An Evaluation of the Relationship of Automobile Door Distortions to Variations in Material Properties and Production Operating Parameters

by

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B.S., Industrial Engineering, University of Washington, 1986
M.S., Industrial and Systems Engineering, Georgia Institute of Technology, 1987

Submitted to the MIT Sloan School of Management and
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ABSTRACT

An important quality attribute of automobiles is the fit of their closure panels, particularly their doors. The door assembly process is complex and may distort a door in such a way that its fit to the automobile will be imperfect. This thesis examines door assembly through the stamping and hemming processes in an effort to identify sources of distortion and variation that arise through this system, focusing on material or operating parameter changes and process controls.

The stamping and hemming processes that make up the door assembly system are detailed. Material properties that are important for both primary and secondary forming operations, and production operating parameters that can induce distortions and variations in door assemblies, are described.

Data is presented from a series of experiments on the stamping process used to make inner and outer door panels. The relationships of steel grade, blank lubrication and draw die cushion pressure to outer panel surface strains, inner panel thickness strains, and inner panel distortions, are quantified. First and second order interactions of the experimental variables are examined along with main effects to determine optimal levels of the process parameters studied. Particularly significant results are the identification that stronger, less formable, grades of steel may make better inner panels and that high lubrication can sometimes improve surface strain for outer panels.

A series of experiments to study the door assembly process through stamping and hemming are presented. In addition to the factors studied in the stamping experiment, the door assembly experiment included the hemmer set point and induction cure cycle. These factors, plus all first order interactions, were studied for their effect on four output measures of door distortion (see Section 3.3.4):

- RMS Flushness, a root mean square measure of the flushness of the automobile door to the body in white;
- RMS x-Gap, a root mean square measure of the gap of the front door to front fender and rear door;
- RMS z-Gap, a root mean square measure of the gap of the front door to the body frame in the up/down direction; and
- Average Hem Gap, the average thickness of the door hem.

Notable results include the finding that an induction cure after hemming may increase door distortion and that the inner and outer steel grades and cushion pressures may interact in significant but unexplained ways.

The results of this research suggest that process parameters will affect different measures of door distortion in different ways. It offers a preliminary quantification of the trade-offs that result. It has also identified situations where stamping process parameters that optimize local objectives may suboptimize the overall door assembly system. Recommendations are made for process modifications and follow-up research based on the results of both sets of experiments.

Recommendations are made for the implementation of process controls based on the results of these experiments. Statistical process controls for critical material properties and production operating parameters are recommended. No opportunities for the application of adaptive process control were identified by this research.

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CHAPTER 1. INTRODUCTION

1.0 Introduction

This thesis describes research performed on-site at a North American automobile assembly plant. The goals of the research were to:

1. Determine material properties and manufacturing process parameters that cause automobile exterior body panel distortions and variation through the automobile body-in-white (BIW) assembly process; and
2. Based on these findings, to recommend process controls that could be implemented to minimize such distortions.

Front doors (left and right-hand side) of a four door sedan were used for the experimental analysis conducted for this research.

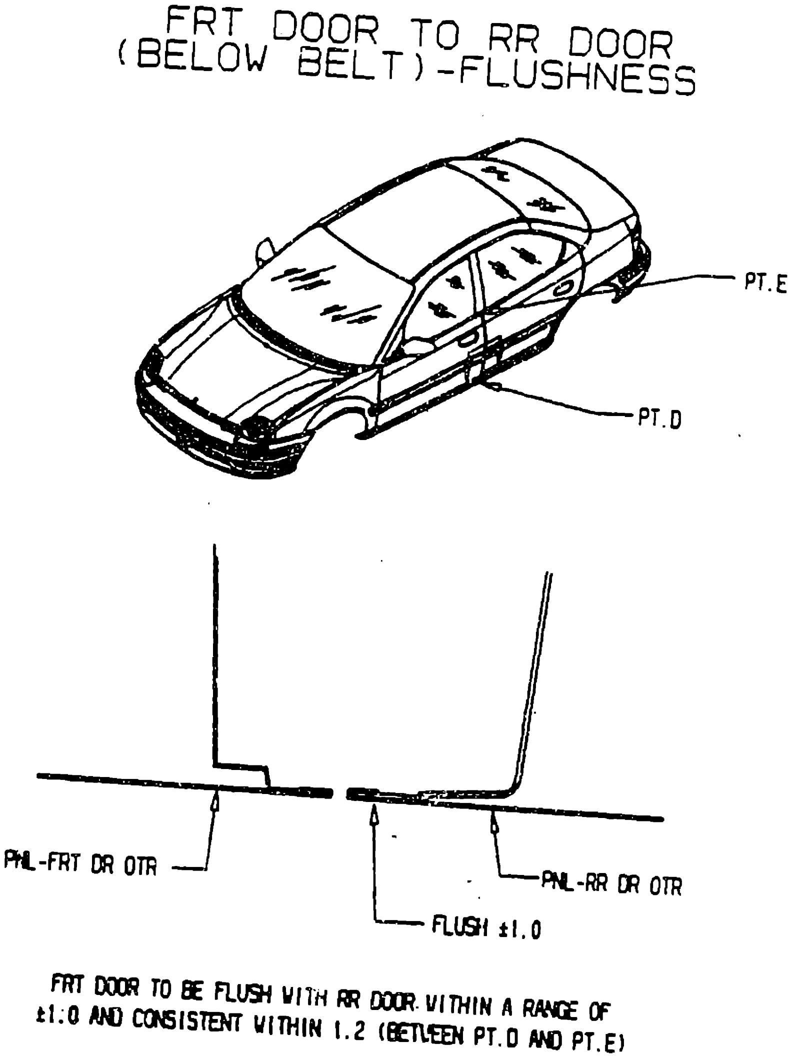
This chapter addresses the importance and characteristics of door distortions, the assembly plant process and the objectives of this research project. Chapter 2 discusses the elements of the stamping and hemming door assembly system. Chapter 3 describes experimental procedures used to study causes of door distortions in the door assembly system. Chapter 4 presents the results of those experiments and Chapter 5 discusses those results. Chapter 6 reviews the implications of this research for process control of the door assembly process. Chapter 7 concludes with an overview of the results of the research project and Chapter 8 presents suggestions for future research.

1.1 The Importance of Door Fits

The fit of exterior panels on automobile bodies is an important quality attribute. Aesthetically, poor panel fits cause excessively large or uneven gaps and/or unattractive flushness differences between panel surfaces. Mechanically, poor panel fits cause increased door closing effort, wind noise and water leakage. Each of these factors has a detrimental effect on perceived automobile quality for the customer [1].

In addition, excessive variations in exterior panel fits impede the productivity of the automobile assembly process. Varying panel dimensions require additional personnel and cycle time allowances on the assembly line to carefully fit and adjust panels to a framed automobile BIW. There could be a significant cost advantage for an assembly operation that eliminates panel variation at the source and avoids these incremental costs.

As used in this paper, the "fit" of a door relates to flushness and gap between adjacent exterior body surfaces. Flushness is the deviation of two adjacent panels from being on exactly the same plane, measured along a surface where the two panels come closest together (Figure 1). Gap is the distance between the two panels perpendicular to


FRT DOOR TO RR DOOR
(BELOW BELT)-FLUSHNESS

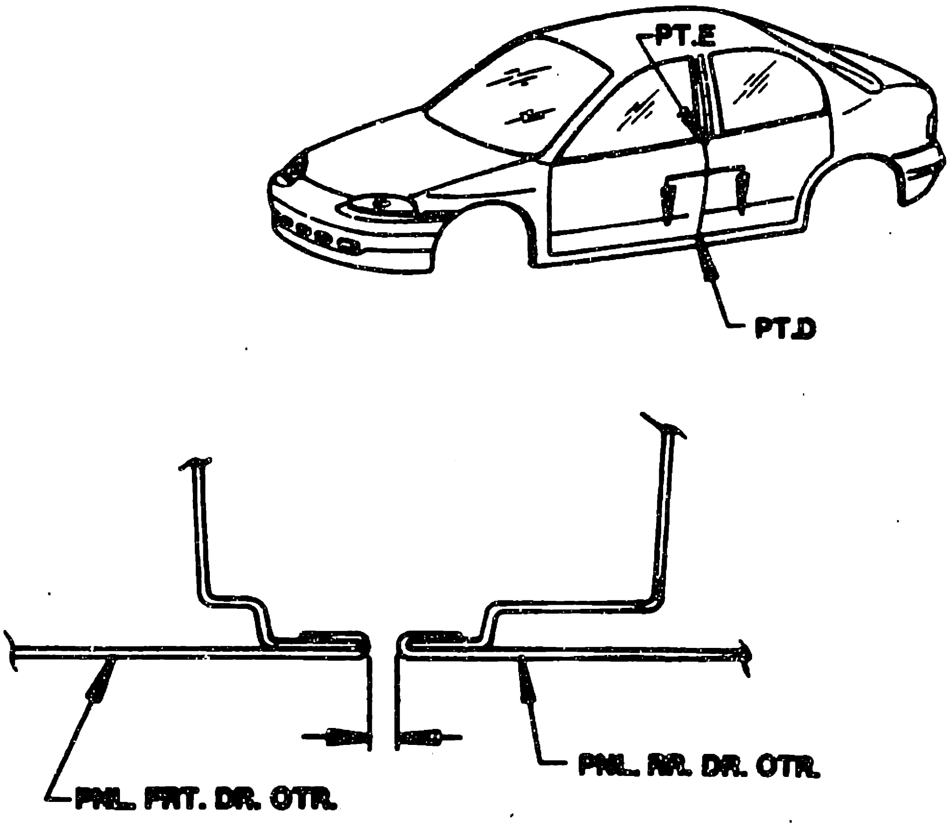
FRT DOOR TO BE FLUSH VITH RR DOOR VITHIN A RANGE OF ±1.0 AND CONSISTENT VITHIN 1.2 (BETVEEN PT.D AND PT.E)

Figure 1. Flushness (dimensions in mm).

that surface (Figure 2). Specifications for door flushness and gap are small and continuously decreasing. Today, world-class automobile assembly requires total fit variation of less than 2 millimeters (mm). Variation of fit between panels on the same vehicle (even when all are within tolerance) are more detrimental to appearance than a gap or flush that is consistently out of tolerance. The key to perceived quality is consistency as well as absolute deviation from nominal design values [2].

The automobile body panels considered in this paper are joined by a series of mechanical (bolting) and metallurgical (welding) operations to a steel frame in a portion of the automobile assembly plant called the Body Shop [3]. All exterior panels must meet

FRONT DOOR TO REAR DOOR (BELOW BELT) - ALIGNMENT
ALL BODYSTYLES



FINAL ASSEMBLED CLEARANCE BETWEEN FRONT AND REAR DOORS
TO BE 5.0 ±1.0 AND PARALLEL WITHIN 1.0 (BETWEEN PT.D AND PT.E)

Figure 2. Gap (dimensions in mm).

process specifications for flushness and gap (among others). Each assembly plant uses a rigorous system of process measurement and control to ensure the fits are within these tolerances on a regular basis. In addition, non-exterior body panels are carefully measured, as variations in the frame of the BIW can make it difficult to fit exterior panels to the required tolerances.

This thesis research concentrated on door distortions that can affect door fits and the factors that can cause these variations. Historically, door fits have been one of the greatest sources of customer complaints. Causes of door distortions are relevant to other BIW closure panels as well. The door assembly process is a complex subassembly prerequisite to fitting the door to the automobile, incorporating most of the processes that are used to produce other exterior body panels.

1.2 Characteristics of Door Distortions

An automobile front door can be visualized as a rectangular box of steel (Figure 3), which must fit inside an opening (defined by the rear door, front fender, roof and body side aperture) of the same dimensions plus a few mm of clearance on each side (Figure 4). Ideally, the gap between the door and each adjacent panel will be at the design specification uniformly across the length of the curved segment between them. The gap between the front door and front fender or rear door is measured in the fore/aft direction of the car, henceforth referred to as the "x-direction." The gap between the front door and roof or body side aperture (at the bottom of the door) is measured in the up/down direction of the car, henceforth referred to as the "z-direction" (Figure 5).

The ideal door would also lie on the same plane as these adjacent panels, such that a straight surface placed across the gap would be perfectly level. In practice, this flushness is difficult to measure precisely on an automobile body because the panels have some design curvature. Nevertheless, the concept remains that the curvature defined by the surface of a panel in one plane should be maintained across the gap and onto the edge

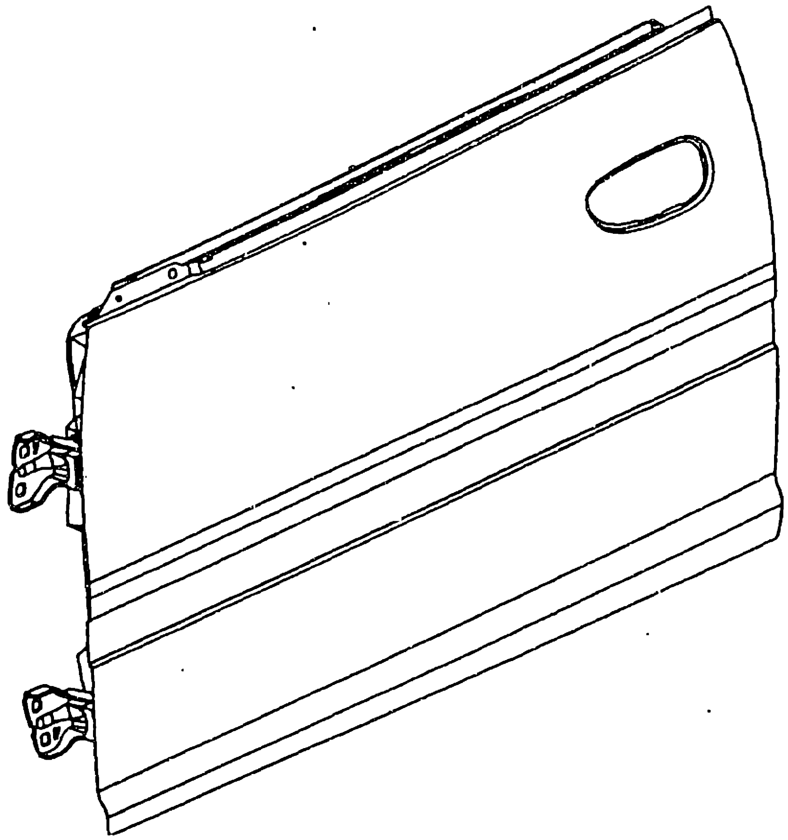


Figure 3. A front door.

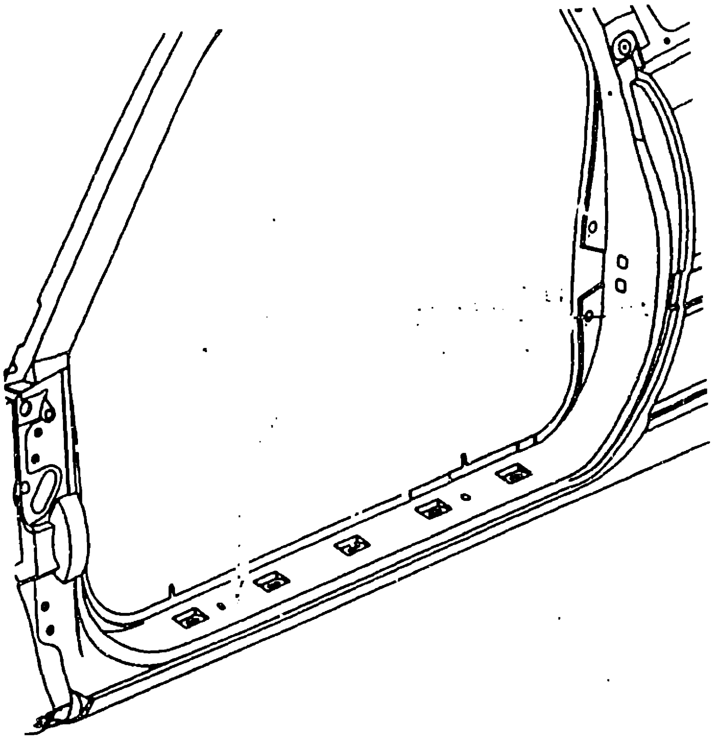


Figure 4. A front door opening.

of the adjacent panel. For doors, this flushness is measured in the inboard/outboard direction of the car, henceforth referred to as the "y-direction" (Figure 5).

The panels of an automobile should appear to form a continuous shaped surface, despite the fact that the surface is made up of dozens of distinct panels. This research assumes that variation reduction is always advantageous. The goal, then, is to consistently produce a door as near to the ideal described above as possible. Fits (both gap and flushness) are measured in mm and the process tolerances may require total process variation of as little as 1.0 mm.

Consistency is critical to the assembly process. Doors are attached to the automobile body by two hinges on the forward edge of the door, which bolt into four holes into a hinge pillar on the automobile frame (Figure 6). When closed, the door is also

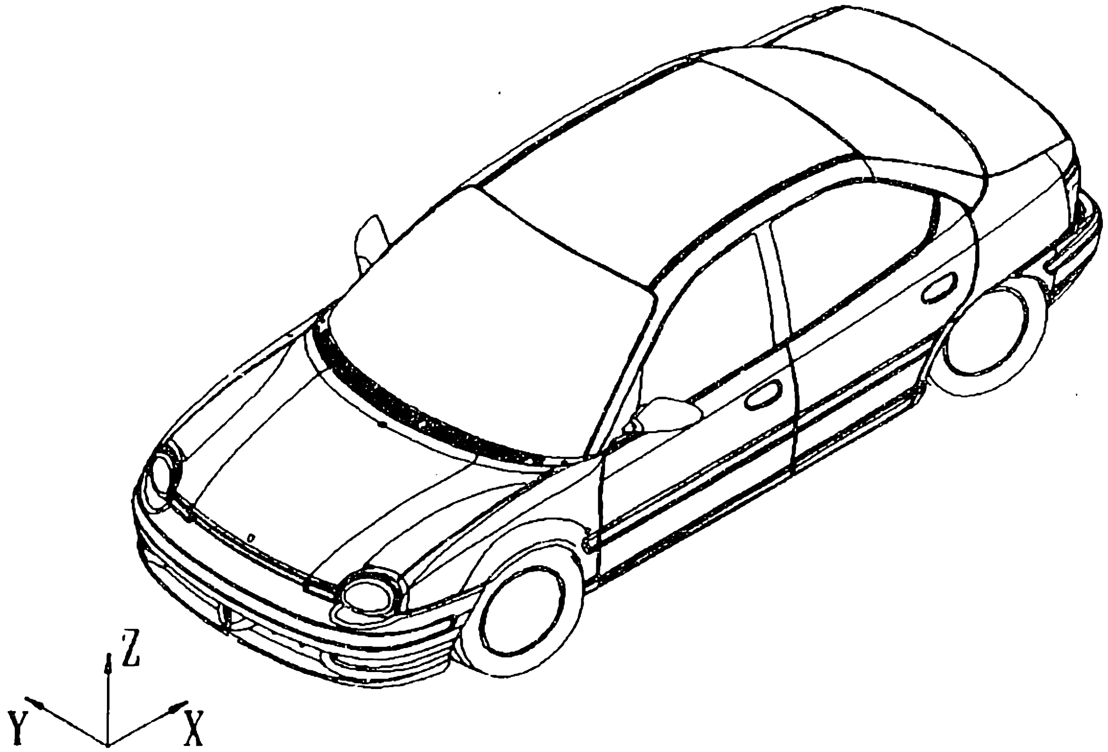


Figure 5. Coordinate axes for an automobile body.

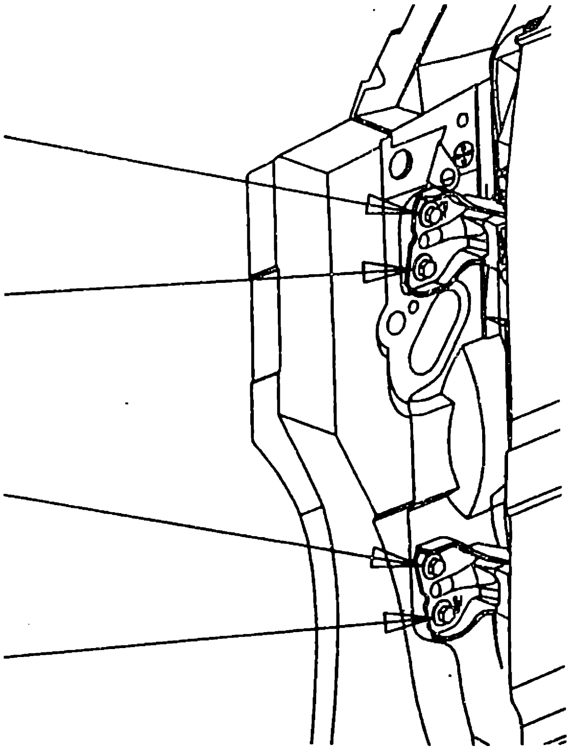
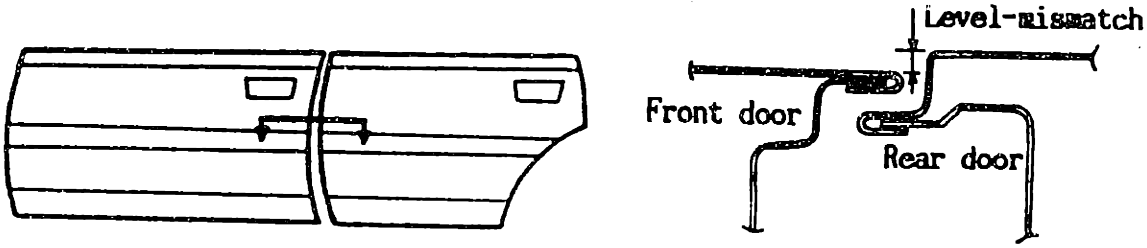


Figure 6. Door attachment to body shell: hinges bolted to hinge pillar.

secured by a striker on its aft edge. Together, these three points position the door in the x, y and z directions. Each of these fasteners has some degrees of freedom, and adjustments to the hinges and/or striker plate can sometimes compensate for deviations of a door from nominal. Therefore, as long as they are within the range of flexibility of these adjustments, doors that are consistently off nominal dimensions may be fit properly by minor tooling adjustments.

Such a fortuitous situation is seldom the case. Typical door distortions are not repeatable, and hence can not be accounted for by a simple tooling adjustment. To further complicate the situation, adjustments will shift the door flushness and/or gap on all four edges. An adjustment to fix a flushness or gap problem in one area is likely to cause a problem in another area of the door perimeter. Therefore, the door fitting process is usually a labor-intensive exercise in adjusting the door set to minimize the maximum error



Inappropriate clearance

Level-mismatch

Figure 7. Typical door fitting defects [2].

in fit, or at least to hide the largest deviations where they are least likely to be noticed (Figure 7).

For example, a gap below tolerance on the door to fender alignment might be compensated for by the addition of a shim beneath one or both door hinges. Yet this will shift the door back in the x-direction and decrease the gap between the front and rear doors. If possible, the door will be shifted back such that both gaps are on the low side of tolerance. In practice, the knowledge and problem-solving skills required to make these adjustments have not been automated, and experienced operators are used for this task in the Body Shop.

It is possible to envision a Body Shop where a door is bolted to the BIW and fits properly with no adjustments every time. This would reduce product variation, labor and cycle time. It is with this vision in mind that this research has been conducted, while recognizing that this is an ideal future state and not easily achieved in the short term.

1.3 Assembly Plant Processes

The automobile assembly plant receives components and subassemblies, and assembles them in three areas, described in order of occurrence. First, the Body Shop receives components (primarily steel stampings) which are assembled into an unpainted automobile body. In some cases, closure panels (doors, decks and hoods) are received as completed subassemblies. In the plant where this research was done, however, the plant was building its own body panels from stamped details. Welding is the primary joining technology employed in this area, although some adhesives and mechanical fasteners are also used. The output of the body shop is an automobile body shell.

Second, the Paint Shop receives the body shell and coats all surfaces with various protective coatings for corrosion resistance and paint for aesthetic appeal. Other than the paints and coatings used (and some sealers used to prevent contaminants from getting into undesired areas of the body), the Paint Shop generally does not add any features to the body shell.

Painted bodies are sent to the third area, Trim, Chassis and Final (TCF) Assembly. The function of TCF Assembly is to add the thousands of parts and subassemblies to the painted body that are required to make a finished car. This includes all interior paneling and carpeting, the engine and transmission, the electrical system, the instrumentation, etc. TCF Assembly may build up a number of significant subassemblies itself or may purchase them complete. Examples include engines, instrument panels, and assembled tires.

Other than subassemblies built up in TCF Assembly, most of the fabrication and subassembly for automobile manufacturing is done at vendor plants (either from the parent company of the assembly plant or from a supplier company). In some cases, however, an automobile manufacturer will choose to locate fabricating operations at or near the plant site. For example, the plant where this research was conducted had a satellite Stamping Plant fabricating a number of the stamped parts required by the Body Shop and a satellite Fascia Plant injection molding large plastic components used in TCF Assembly. The proximity of such operations can reduce handling damage, inventory costs, and coordination costs between the assembly plant and its suppliers of fabricated parts, even if both are part of the same company.

1.4 Research Objectives

The objective of the research project was to examine the variation and distortions of front doors through the door assembly system. The goal was to analyze the relationship of such distortions to the material properties of the sheet steel and the operating parameters of the stamping and hemming processes, and to identify those factors that are critical for reducing door variation. In addition, the goal was to propose a methodology for monitoring and controlling these factors that could lead toward an adaptive process control system based on those results.

The scope of the research was limited to the stamping and door assembly processes to focus on those areas of the plant. It must, however, be recognized that there are many other processes in the plant that affect door fits. These include the thermal and chemical operations in the Paint Shop and a variety of causes of distortions in TCF Assembly. Other important quality characteristics of the doors, such as surface finish, were specifically excluded.

The methodology for the research occurred in four stages. First, literature research and process observation were undertaken to identify the material and process factors that should be studied (Chapter 2). Second, four grades of sheet steel were selected and analyzed. Third, an experiment was conducted to study the stamping portion of the process. Fourth, an experiment was conducted to study the door assembly portion of the process. The procedures for these tests and experiments are described in Chapter 3. The analysis of the results are given in Chapter 4 and discussed in Chapter 5. From this methodology, implications for process control were developed (Chapter 6). Conclusions are presented in Chapter 7, and suggestions for future work are presented in Chapter 8.

CHAPTER 2. THE DOOR ASSEMBLY SYSTEM

2.0 Introduction

This chapter describes the system under study in this research, including the door hemming process and the stamping process for the major parts of the door, the inner and outer panels. One premise of this research is that primary forming operations (stamping) may affect secondary forming operations (hemming). This thesis examines the two processes as a single system.

Most previous research has attempted to locally optimize these two processes rather than understand their linkages. There is a body of literature describing research toward optimizing die design and stamping process parameters to achieve "better" stamped parts. Normally, "better" in this context is defined as parts that will run productively without splits or wrinkles in the stamping process to improve stamping productivity [4, 5, 6, 7, 8, 9]. Few have considered the impact of process variations on the fitness for use of stamped parts in the secondary forming operations used to assemble them into consumer products or subassemblies such as automobile doors [1, 2, 10, 11].

Examining the stamping and hemming process as a single system provides the opportunity to identify process controls that span across production departments. For example, it may be that the Stamping Plant could feed forward process variables to the Body Shop so that they could adjust their process accordingly. Similarly, it could be that the Body Shop would request specific changes to Stamping Plant processes based on particular problems they are having with door fits. In either case, such controls are only meaningful if both processes are in a state of statistical control and capability, such that process variations are not greater than the magnitude of the changes that can be made by slight process adjustments [12, 13].

2.1 Door Assembly Process Description

A flow chart of the door assembly system as defined for this research is presented in Figure 8. It begins with received coils of sheet steel and continues through the blanking press, blank storage, the stamping press line, finished panel storage and received parts, the hemming line, and ends with assembled doors. For each type of part or material, the figure lists a sampling of the numerous part properties that could be important for subsequent operations. For each of the major processes, the figure shows a sampling of the numerous controllable factors that could be important for their effect on the part properties of the process output. These properties and factors are defined in Appendix A.

The lists of properties and factors shown in the figure are not exhaustive, but are potentially important based on discussions with stamping and hemming process experts within the automobile company where the research was done, with equipment vendor process experts, as well as review of the relevant literature [6, 7, 9, 14, 15, 16, 17]. Each of these factors is described in Appendix A. Many of the properties and factors listed are highly correlated to each other; indeed, some are completely specified by the others.

Much more research has been reported in the literature for the stamping process than for the hemming process, either because more has been done in this area or because the automobile manufacturers and equipment suppliers have wanted to keep hemming information proprietary. See [2] for a notable exception.

2.2 Scope of This Thesis

There are many important problems for door assembly beyond the system that is shown in Figure 8. Three primary areas of limitation include:

- upstream processes;
- design processes; and
- downstream processes.

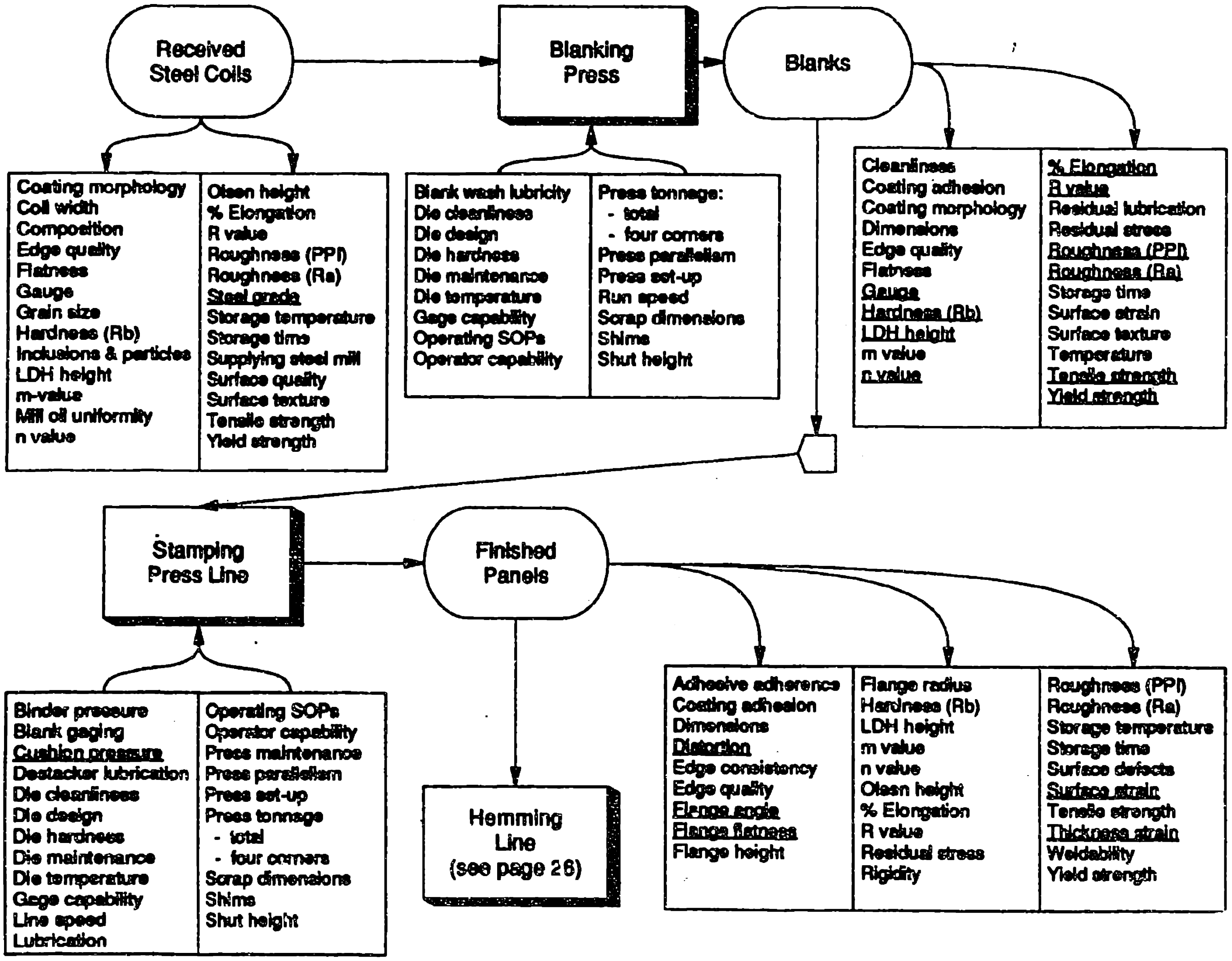


Figure 8a. The door assembly system (p. 1 of 2).

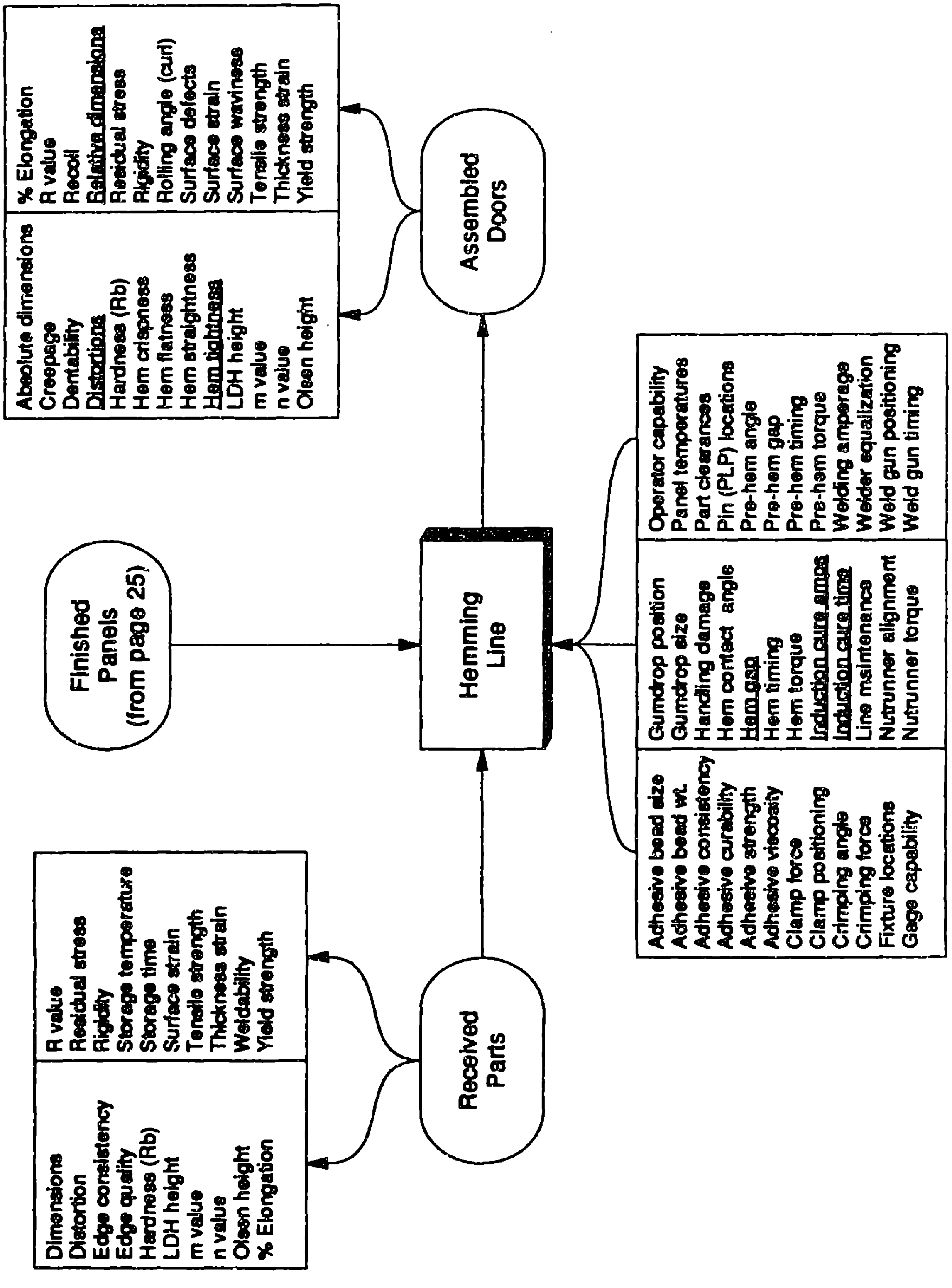


Figure 8b. The door assembly system (p. 2 of 2).

Upstream processes used to produce the sheet steel and stamped details received were not studied. In this thesis, "details" refers to the numerous stampings that are used in door assembly other than the inner and outer panel studied here. The goal of this research was to identify the properties which the stamping and hemming processes may be most robust and those which may be most sensitive. Using this information, it would be possible to work with vendors for better processes, controls or monitoring of those variables that are truly critical.

The intent of this research was to consider how to better control the process that exists, rather than to try to design a substantially different process. Although die design is listed as a controllable input in Figure 8, for the purposes of this study all processes and tooling were taken as given. A better understanding of the interactions of the stamping and hemming system could influence the design of future generations of these systems, but this research did not explicitly set out to address this issue.

Third, the scope of this research included the stamping and hemming processes. The objective was to learn how to make doors that are consistently free of distortions as a necessary, but not sufficient, condition for excellence in door fits. Many downstream processes in the automobile assembly plant can influence door fits, such as the BIW frame build-up and door fitting in the Body Shop, the chemical and thermal operations in the Paint Shop, and all the operations performed to build up the door (glass insert, electrical wiring, trimming, etc.) that occur in TCF Assembly. Some of these processes, particularly the thermal stresses imposed in the Paint Shop, may interact in complex ways with the stamping and hemming system.

2.3 Selection of Properties and Sources of Variation to Study

The properties and sources of variation listed in Figure 8 are extensive. Even so, it is likely that other factors are involved that have a significant effect in complex and unknown ways. There was sufficient experiential knowledge among the engineers at the automotive company where the research was done and sufficient theoretical foundations in the literature to focus this large list down to a few variables for study. The following criteria were used in this selection process.

First, the source of variation had to be significant, as suggested by the literature research and discussions with process experts. There was wide agreement among the process experts and literature on the most significant sources of variation [1, 2, 3, 7, 9, 10, 11, 14, 15, 16, 17, 18]. Interestingly, however, there was some disagreement about the mechanisms by which the variations occurred and how they related to the process variables. This is indicative of the complex nature of these processes and the incomplete theoretical understanding of them [6].

Second, the source of variation had to be controllable. There should be a measurable and repeatable relationship between a process variable or material property and an output characteristic of interest, such that a feed-forward or feed-back control loop could be implemented. Thus, manual processes and irregular events were not selected.

Third, the source of variation had to be a potential cause of door distortions that would hinder the door fitting process. Process parameters and material properties that related primarily to stamping yield, surface quality and paintability were excluded.

Fourth, the source of variation had to be measurable in a production environment. It would not be valuable to recommend a control system that would cost more to implement than it would save in reduced door fitting effort. Factors such as grain size of the steel and panel rigidity that would be difficult to measure regularly in a production mode were eliminated.

Finally, the sources of variation to consider were constrained by the current process. The production process studied was already designed and it was not practical in the short term to retool a significant part of the plant, irrespective of how much it would improve the door fits. Factors such as tooling design and shut height were not considered for study.

On the basis of these criteria, the following factors were selected for study:

- Steel grade;
- Stamping line lubrication level;
- Stamping line draw die cushion pressure;
- Hemming line hemmer set point; and
- Hemmer line induction cure cycle.

Each of these factors is defined in Chapter 3. Blanking press line factors were not selected for study and were held constant.

In addition to these factors, it was agreed that material properties should be measured so that they could be correlated to the factors under study to identify the physical or metallurgical causes of observed effects. Material properties studied for the sheet steel included:

- gauge;
- hardness;
- LDH height;
- n-value;
- percentage elongation;
- R-value;
- surface roughness (PPI and Ra);
- tensile strength; and
- yield strength.

Each material property is defined in Appendix A. The measurement processes used for these properties are described in Chapter 3.

Material properties of the finished panels studied included:

- outer panel surface strains;
- inner panel thickness strains; and
- inner panel distortions.

Each material property and the processes by which they were measured are described in Chapter 3. No material properties were studied for the blanks. No details were used in the study so there was no need to consider their properties.

Finally, dimensions of door assemblies were studied as the ultimate output of the system as defined, including:

- RMS Flushness;
- RMS x-Gap;
- RMS z-Gap; and
- Average Hem Gap.

These measurements are explained in Chapter 3.

CHAPTER 3. EXPERIMENTAL PROCEDURES

3.0 Introduction

A series of experiments was performed to study the effect of the material properties and stamping and hemming process parameters described in Chapter 2 on door distortions. Experimental procedures for materials characterization, stamping experiments and door assembly experiments are described in this chapter.

3.1 Materials Characterization

Four grades of steel were selected for experimental analysis - two for door inner panels and two for door outer panels (Figure 9). Multiple samples from a single coil of

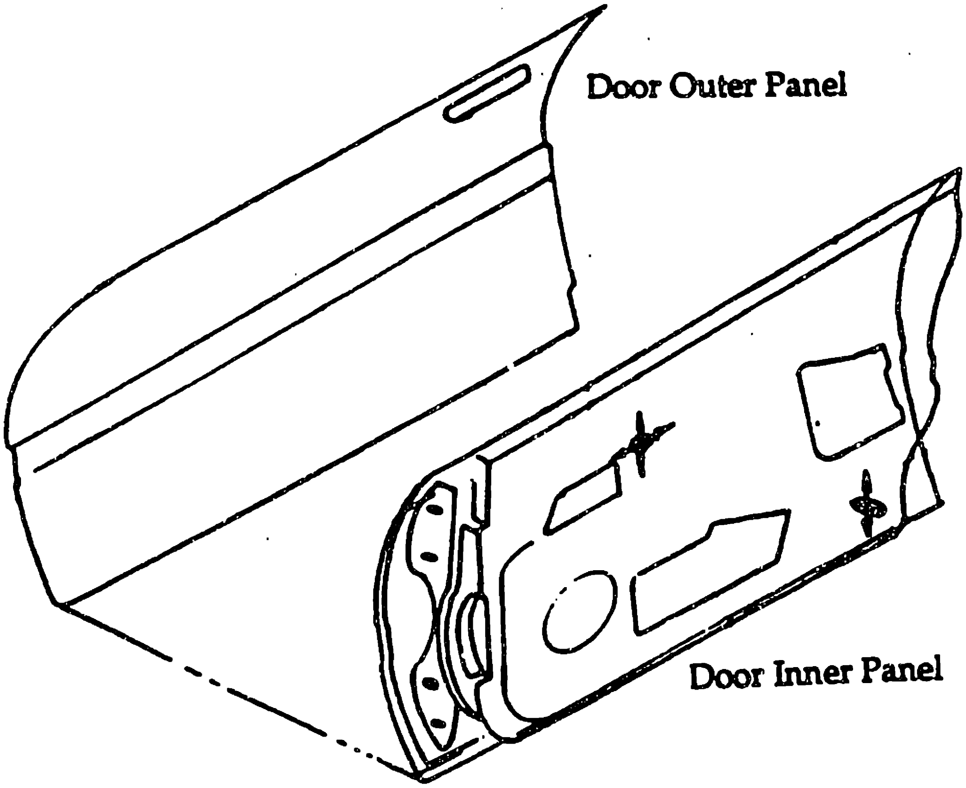


Figure 9. Matching door inner and outer panels [19].

each grade were taken and characterized with the following property tests:

- Tensile test [17, 20, 21, 22, 23];
- LDH test [17, 21, 22, 23];
- Gauge (i.e. sheet thickness);
- Rockwell B hardness [17, 20, 21, 22, 23]; and
- Surface roughness [17, 21].

The testing procedures are described in this section.

"Grade" of steel was chosen as the basis for differentiation for this study. As used in this thesis, a grade of steel refers to a combination of qualities, rather than a single mechanical or metallurgical characteristic.

Steel mill processes such as composition, deoxidization, cold rolling reductions, annealing, temper rolling and coating affect the metallurgical and mechanical structure of the sheet and simultaneously its material properties. For example, the R-value is a mechanical property that indicates the ratio of strain that a sheet will experience in its plane to that it will undergo in its thickness (Appendix A). Any attempt to change the R-value of a coil of steel will also affect its yield strength (the minimum stress required to plastically deform the sheet), n-value (the work hardening exponent of the steel), percentage elongation (the percentage of strain the sheet will accommodate before fracture in pure tension), and other properties (Appendix A) [24, 25].

3.1.1 Selection of Steel Grades

Different grades were used for the inner and outer panels because exposed (outer) grades have different surface coatings (for corrosion protection) than unexposed (inner) grades. These coatings can affect the lubricity and formability of the panels. Therefore, for this experiment, only exposed grades were used for the outer panels and unexposed grades were used for the inner panels.

Several grades of both exposed and unexposed steel were available at the plant with sufficient width to make blanks for the inner and outer door dies. From these, the most different grades available (based on previous property characterization that had been done by in-plant personnel) were selected for the inner and outer panels. For the outer panels, the grades selected are code-named grade 548 and grade 660. For the inner panels, the grades selected are code-named grade 019 and grade 982.

3.1.2 Material Property Measurement Procedures

For each grade of steel selected, 30-40 blanks were cut to the specified dimensions. All blanks for each steel grade came from the same coil. Some of the cuts were made on the blanking press. Other cuts were made to collect samples for material property tests and to cut the blanks to the appropriate width. One longitudinal cut was made with a hand shear for the 660 and 019 grades. One longitudinal and one transverse cut were made with the hand shear for the 982 grade. One longitudinal cut was made with a hand nibbler for the 548 grade. Several square feet of sheet were saved from each blank for material property testing.

The following material property tests were performed for each blank:

- Tensile test (to characterize yield strength, tensile strength, percentage elongation, n-value and R-value);
- LDH test (to characterize limiting dome height);
- Gauge;
- Rockwell B hardness (before and after the tensile test);
- Surface roughness (in peaks per inch and average peak height).

All tests were performed in both the transverse and longitudinal directions of the sheet.

The methodology used for each of these tests is described below. Note that repeatability and reproducibility (R&R) studies were performed for all tests except the destructive tensile and LDH tests to assess the capability of the measurement process [17].

Errors due to operator variability have been minimized, since all tests were performed by the thesis writer.

Tensile Tests. Tensile samples were hand sheared to 1" x 8" and milled to the ASTM standard "dog done" shape for sheet tensile tests. Burrs in the gage length of the sample were removed with a hand file to prevent premature sample failure due to stress concentrations at the burr. The samples were wiped clean with a cloth, their gauge was checked with a hand micrometer and they were cycled to failure on an Instron Tensile Tester (model 4204). This model had the ability to measure changes in gage length and extensometers to measure changes in gage width. Given the hand-measured initial gauge of the sample, the tester automatically calculated the yield strength, tensile strength, percentage elongation, n-value and R-value for each sample.

LDH Tests. LDH samples were hand sheared to 8" by 5" and the corners were clipped with a hand shear to fit the tester, an Amsler BUP 200. The punch and ring of the tester were carefully cleaned with acetone and wiped off with a light lubricant before the start of the testing and each 20-40 samples thereafter. Each sample was cleaned and lubricated with the same lubricant before testing. The samples were cycled to failure. The LDH height was automatically measured by the tester.

Gauge Tests. Tensile test sample gauges were measured as input to the tensile tester. The samples were carefully wiped clean of any dirt, burrs or galvanneal flakes prior to measurement with a hand micrometer. Measurements were made to the nearest 0.001". An R&R test showed reproducibility of +/- 0.00064" using these methods (Table 1).

Hardness Tests. Rockwell B Hardness (HRB) values were collected for the tensile test samples on a Wilson hardness tester. Two tests were made for each sample, once in the grip area (where the indentation would not disrupt the tensile test) before the tensile test and once in the gage length (but away from the neck) after the tensile test. The difference between the values represented the work hardening of the sample that occurred during the tensile test. The samples were carefully wiped clean before each test. An R&R study showed reproducibility of +/- 5.2 HRB for samples prior to tensile testing (Table 1).

Surface Roughness Tests. 1" x 8" samples were tested for roughness on a Taylor-Hobson Surtronic 3P. The samples were carefully wiped before testing. The needle of the tester was placed on a portion of the sample where no apparent scratches or other surface imperfections were within its range of travel. The tester returned two values for each sample. One, labeled Ra, measures peak height on the sheet surface in microinches. The other, labeled PPI, measures the peaks per inch on the surface of the sheet. Both measures have an influence on the frictional resistance of the sheet to die mating surfaces.

This test was very sensitive to small scratches that could not be visually identified and to vibrations of the testing apparatus or slight movements of the sample. When unreasonably high values were obtained, the tester needle was moved to another location on the sample and tested again until a reasonable value was obtained. With these procedures, an R&R study showed that both measures are highly variable, with a reproducibility of +/- 5.33 Ra and +/- 55.3 PPI (Table 1).

Table 1. Measurement R&R Studies

	Gauge	HRB	Ra	PPI
Average	0.0263	40.4	29.1	168.7
Minimum	0.0260	34.0	25.3	121.0
Maximum	0.0269	43.0	32.9	197.0
Range	0.0009	9.0	7.6	76.0
Std. Dev.	0.0002	1.7	1.8	18.4
3 Sigma	0.00064	5.2	5.33	55.3

3.2 Stamping Experiment Procedures

The purpose of this research was not to explore the stamping process independent of the hemming process. Nevertheless, stamped panels were a necessary input for the hemming portion of the overall experiment described in the next section. This section describes the experimental procedures used to make those panels. The results are shown in Chapter 4.

3.2.1 Experimental Design

The factors studied in the stamping experiment included steel grade, lubrication level and cushion pressure. All other relevant factors (Appendix A) were held as constant as possible during the experimental run. One experimental run was done for the inner panels and one was done for the outer panels.

Two levels of each factor were used for each experiment. For the steel grade, the two inner grades and the two outer grades described in Section 3.1 were used. For the lubrication level, the two levels were varied by hand application of lubricant to the blanks prior to the draw die. For the low level, the blanks were run "dry," i.e. no lubricant was hand-applied to supplement the lubrication on the blanks from the mill oil, blanking press line and the feeding system for the stamping press line. For the high level, the blanks were run "wet," i.e. a significant amount of light lubricating oil was hand-sprayed on both the top of the blank and the bottom surface of the draw die.

Given the factors of steel grade and lubrication, the intention was to vary the cushion pressure by running some of the panels at the highest possible pressure without developing splits (the high level) and by running the others at a significantly lower pressure (the low level). A significant number of panels split and/or were run at levels of one or more factors that were not in conformity with the levels to which the experiment eventually converged.

The experiment was designed as a full factorial with four replicates for three factors, each at two levels. As such, 32 panels were required at the "right" combinations of levels for both the inners and outers.

Although normally it would be desirable to randomize the order of the runs, this was not practical in this case for several reasons. First, switching between lubrication levels was not possible without stopping to wipe off all the blank handling equipment and the die each time it was necessary to switch from high to low lubricant. Second, stamping experts questioned the ability of the press to stabilize on set point values until one or two cycles had been completed after the values were changed. Third, since the exact levels of the variables were unknown up front, it was known that some runs would be at the wrong levels. Any attempt to run the experiment in a specific randomized order would be thwarted by the process. Instead, the number of change-overs between lubrication levels and cushion pressures was minimized to best control special causes of variation.

These concerns do not apply to the order in which the steel grades were run. The order of the last 32 blanks of each experiment was randomized with respect to steel grade with the intention that those blanks would end up being at the correct experimental levels for all factors.

3.2.2 Experimental Measurement Procedures

Efforts were made to collect data on important stamping variables during the run. The variables collected included actual cushion pressure, shut height, cushion stroke, line speed (strokes per minute), and total tonnage for the draw press. Press line gage readings were assumed to be accurate. Gage capability was a concern (Appendix A), but in this case there was no gage R&R information available for these lines.

To measure surface strains of the finished outer panels, circles were scribed in the blanks before stamping. After stamping, the minimum and maximum dimensions of those circles allow the major and minor strains in the plane of the panel surface to be determined [17]. An R&R study was performed for scribing and measuring 5" circles (Table 2). Eight 5" circles per hand (left and right) were scribed on each outer blank to be used for the experiment (the dies formed both a left and a right panel from each blank).

Table 2. Five Inch Circle R&R Study

	Single Circle	No Adjustment	Adjust Each
Average	4.986	4.986	5.000
Minimum	4.98	4.98	4.99
Maximum	4.99	5.03	5.01
Range	0.01	0.05	0.02
Std. Dev.	0.005	0.010	0.004
3 Sigma	0.015	0.031	0.011

3.2.3 Outer Panel Experimental Run

A five station Danly tandem press line was used for the experiment. The draw die shut height, cushion stroke and strokes per minute line speed were held constant throughout the run. There was a recurring problem with splits. A split releases stress and prevents a panel from achieving the strains it would otherwise experience. Therefore, splits were undesirable, even in the trim area of the panel. A variety of techniques were implemented to eliminate the splits, including adjustments to the lubrication level and cushion pressure, as well as the use of shims.

It appeared that some of the gages on the press line were not in a state of statistical control and capability [13]. The draw die tonnage periodically spiked up by 200 tons (30%) or more between successive runs for no apparent reason. Likewise, the cushion pressure did not remain steady at the set value. It was unclear whether the actual pressure was fluctuating or if the gage was inconsistent in its measurements. Neither of these gage readings was used for subsequent analysis.

After the run, the 32 trials that best represented the levels of each factor (as those levels were defined during the run) were selected as the experimental outer panels. There were both left and right-hand side panels for each of these trials, so there were 64 total experimental panels available. These are the panels for which the measurements and analysis described later were performed. The other panels were retained for the hemming line experiment.

3.2.4 Inner Panel Experimental Run

A five station Verson transfer press line was used for the experiment. This press line was configured such that the first and second dies were controlled in the same stroke. Therefore, it was not possible to consider the first stamping operation independent of the second. The draw die shut height, cushion stroke and strokes per minute line speed were held constant throughout the run for this first press. The press tonnage for the draw die was not useful, since sometimes the measure included a panel at the second die and sometimes it did not.

As with the outer panel experiment, splits occurred periodically throughout the run. These panels normally had some minor wrinkles in production, and this was observed for the experimental run. Adjustments to the lubrication level and cushion pressure, as well as the use of shims, were again implemented to eliminate the splits.

After the run, the 31 trials that best represented the levels of each factor (as those levels were defined during the run) were selected as the experimental inner panels. Unlike the outer panel experiment, four replicates of one of the conditions was not obtained, so the total was one short of the goal. There were 62 total experimental panels available to measure and analyze, including the left and right-hand sides. As with the outer panels, the extras were stored for the hemming line experiment.

3.2.5 Stamping Output Measures

Several output measures were investigated for the experimental panels. For the outer panels, the surface strains were evaluated and the flanges were qualitatively examined for variation in flange angle and/or waviness. Thickness strains and distortions were measured for the inner panels.

Outer Panel Surface Strains. Of the eight circles placed on each outer door panel, seven could be read. For each circle, the minimum and maximum dimensions were selected as the minor and major strains at that location, respectively. The average major and minor strains were calculated from the 32 outer panels for each hand side (left and right).

Outer Panel Flange Characteristics. It was suspected that different steel grades and/or press operating parameters could cause flange characteristics such as flange angle and waviness to vary for the outer panels (Appendix A). The flanges of the experimental panels from extreme conditions of the run were carefully compared by visual examination and approximate measurements. From this, it was concluded that any possible difference was too small to be measured with available equipment. As a result, no quantitative assessment of the flanges was made and it was assumed they were practically identical.

Inner Panel Thickness Strains. An ultrasonic thickness tester (UST) was used to evaluate thickness strains in several critical locations for each inner panel. An R&R study with the UST demonstrated a reproducibility of +/- 0.001" (Table 3). This is sufficiently accurate to measure thickness strain changes of about 5% for this gauge of sheet. Thickness strain readings for six points on each panel were averaged to yield an average thickness strain for all 31 left and right-hand experimental panels [26, 27].

Table 3. Ultrasonic Thickness Tester R&R Studies

	Thickness (inches)
Average	0.02114
Minimum	0.02000
Maximum	0.02160
Range	0.00160
Std. Dev.	0.00032
3 Sigma	0.00096

Inner Panel Distortions. In addition to the thickness strains, inner panel distortions were characterized. The inner panel provides a good deal of the rigidity of the finished door assembly, so it was postulated that a distorted inner panel would result in a distorted door assembly. A digital caliper was used to measure deviations from nominal in the y-direction of the panel, the inner panel equivalent of an out-of-flush condition. It was believed that any significant bend or twist in the inner panel would manifest itself in these measurements.

The stamping plant had a checking fixture with a surface at the nominal y values around the panel edge. Panels were precisely located on the checking fixture via pins and flushness to the fixture was measured with the digital caliper around the perimeter. No clamps were applied that could hide any distortion in the panel. Three measurements were taken in a standard location for each side of each panel, one in the middle and one near each edge, for a total of twelve measurements per panel.

For each panel, an average absolute deviation from nominal was calculated for the twelve flushness readings to represent the average distortion of the panel. This was done for not only the 31 sets of experimental inner door panels, but also for the 32 sets of inner door panels that were to be used for the hemming line experiment on the outer doors. An R&R study showed that each measurement was reproducible to +/- 0.25 mm on average. Therefore, each average of twelve values is reproducible to +/- 0.07 mm (Table 4).

One problem experienced in collecting these data was the presence of handling damage along the edges of the panels. In some cases the panel had been bent in on one corner, or twisted to give unreasonable flushness values for one or more points. To eliminate these points from the average distortion values, three standard deviation limits were computed for each point and any readings that fell outside those limits were eliminated from the average distortion measure.

3.2.6 Statistical Data Analysis Procedures

For each output measure, the primary analysis technique employed was analysis of variance (ANOVA). Each ANOVA considered all three main effects (steel grade, cushion pressure and lubricant level) plus all two and three way interactions. All main effects and their interactions were screened for significance using a 90% statistical confidence

Table 4. Digital Caliper R&R Studies on Door Inner Panels

Left-hand Side:

	Min. Value	Max. Value	Average	Range	Std. Dev.
Point 1	3.08	3.26	3.16	0.18	0.08
Point 2	5.11	5.33	5.23	0.22	0.09
Point 3	3.66	3.72	3.68	0.06	0.03
Point 4	1.93	2.15	2.06	0.22	0.09
Point 5	2.99	3.10	3.03	0.11	0.05
Point 6	3.72	3.97	3.85	0.25	0.11
Point 7	4.71	4.97	4.85	0.26	0.11
Point 8	5.59	5.64	5.61	0.05	0.02
Point 9	3.89	3.94	3.91	0.05	0.02
Point 10	3.53	3.62	3.58	0.09	0.04
Point 11	2.69	2.77	2.73	0.08	0.03
Point 12	3.13	3.32	3.22	0.19	0.08

Right-hand Side:

	Min. Value	Max. Value	Average	Range	Std. Dev.
Point 1	3.01	3.28	3.18	0.27	0.12
Point 2	2.64	2.78	2.72	0.14	0.06
Point 3	5.35	5.45	5.41	0.10	0.04
Point 4	5.37	5.86	5.72	0.49	0.21
Point 5	5.05	5.83	5.46	0.78	0.34
Point 6	2.01	2.17	2.08	0.16	0.07
Point 7	2.95	3.08	3.03	0.13	0.06
Point 8	4.37	4.46	4.43	0.09	0.04
Point 9	3.91	4.16	4.02	0.25	0.11
Point 10	3.20	3.32	3.27	0.12	0.05
Point 11	2.43	2.59	2.53	0.16	0.07
Point 12	2.89	2.98	2.95	0.09	0.04
Overall Averages				**0.19**	**0.08**

threshold. In addition, t-tests for significance of each variable were performed, one at a time, and the output measure was evaluated for each level of each variable [28, 29].

Since both left-hand and right-hand side data were available from identical experiments, two different analyses were performed for each output measure. Some of the left-hand results differed from the right-hand results. This was not unexpected since the left and right-hand side processes can not be exactly the same, due to small differences in blank gaging, dies, etc.

In consideration of this, the results were screened to report only outcomes that are both significant in at least one of the two hand sides and directionally consistent in the other. In other words, a significant result on one side will be considered to be either a statistical anomaly or due to process differences between the sides unless it is supported by the directional trend for that variable on the other side. Even if it could be proven that one level of one of the factors should be used on one side and the other level of the same factor on the other side, it would not generally be possible to implement such a proposal.

3.3 Door Assembly Experiments

The same panels that were used for the stamping experiment were used as the input to the hemming process. All the factors considered in the stamping experiment were included in the door assembly experiment. In addition, two factors were added for the hemming process, the hemmer set point and the induction cure cycle.

3.3.1 Experimental Design

Initially, the objective was to run separate experiments for the inner and outer panels. With five total factors per experiment (steel grade, cushion pressure, lubricant level, hemmer set point and induction cure cycle), this would produce one sample of each combination of experimental conditions with 32 panels. The plan was to run identical experiments on the left and right-hand sides for the inners (31 panels) and the outer (32 panels). The stamping experiment had already defined the first three factors. Those panels were to be run at the appropriate levels of hemmer set point and induction cure cycle to fill out a full factorial, 1 replicate design.

For the new factors, the levels also had to be selected. The hemmer set point is a computerized parameter that dictates the length of stroke of the hemmer dies. With some experimentation, it was found to be adjustable down from -15.000 to -14.900 without causing any apparent difficulties in the hemming operation. This was believed to be a significant difference, and therefore, a good choice for the two levels of that factor. The two levels are subsequently referred to as -15.0 and -14.9.

The induction cure cycle is characterized by the amount of heat (based on the electrical flow through the induction coils) put into the hem area of the panel and the time over which the flow occurs (on the order of several seconds). The two levels of the induction cure cycle used for the experiment included the normal degree of induction cure, specified by a temperature and time setting, and no induction cure at all. To keep all other factors the same, the panels that were run with no induction cure were still transferred to and from the induction cure station and clamped, but the induction cure controller itself was switched off. Thus, the two levels for this factor were "on" and "off."

One complicating factor was the degree to which the door details were distorted. Some of these parts were very strong and rigid and, if they had a bend or a twist in them, could distort the whole door in the assembly process. Also, a distorted hinge could potentially cause the door to be bent by the nut runner (Appendix A). Therefore, no details were used in these experimental runs.

It was necessary to have both an inner panel and an outer panel for the door assembly process. To satisfy this requirement, panels left over from the stamping experiments were used for the hemming experiments. Thus, for the inners hemming experiments (left and right), the 31 experimental inners were assembled to 31 unused outers of the proper side. Likewise, for the outers hemming experiments, the 32 experimental outers were assembled to 32 unused inners of the proper side.

The risk of this arrangement was that, while the conditions in which these extra panels were run were well documented, they were not always the "experimental" stamping conditions. In addition, there were many more panels run under some conditions than under others. For example, during the stamping experiments more panels were run at high cushion pressures and low lubricant levels since those conditions caused more splits. If there was no interaction between the inner factor levels and the outer factor levels with respect to door assembly distortions, then there would be no cause for concern and the conditions under which the "non-experimental" panel had been run would not be important.

This condition was not met. There was some evidence of significant interaction between the inner and outer panel run conditions for the finished doors. As a result, the analysis methods were changed. Instead of looking at the inner and outer hemming experiments separately, both were combined into one large experiment of 63 panels incorporating eight, instead of five, experimental factors, each at two levels. Those factors included the:

- Inner steel grade (019 versus 982);
- Inner cushion pressure (low versus high);
- Inner lubricant level (low versus high);
- Outer steel grade (660 versus 548);
- Outer cushion pressure (low versus high);
- Outer lubricant level (low versus high);
- Hemmer set point (-15.0 versus -14.9); and
- Induction cure cycle (on versus off).

With this deviation from the original plan, the analysis was significantly altered. The new plan was to use analysis of individual means and variances between the two levels of each factor for each side. Since there were not enough runs (and the design was unbalanced) to consider all factors simultaneously, ANOVA was used to identify all significant first order interactions for each side. Higher order interactions were not considered, because the sample sizes involved were so small that confidence in their implications was highly suspect. Indeed, the first order inner lubricant/outer lubricant interaction could not be analyzed due to the imbalance of the design [28, 30].

Once again, the run order was not randomized. As with the stamping experiment, it was felt that the disadvantages of randomization outweighed the advantages. Primarily, the set-up and test time required to change the levels of the factors would have exceeded the time available to perform the experiments. Instead, the experiments were run in an order that would minimize the number of changes to hemmer set point, and minimize the number of changes of induction cure cycle within that. Therefore, approximately 16 panels were run at the same experimental conditions between each change.

As with the stamping experiment, the basis for drawing conclusions from the data was to be established only after consideration of both sides of experimental data. If a factor or interaction was found to be significant on one side, it would only be reported as such if it was directionally consistent with the results on the other side, whether or not the results were significant on the other side. In this way, the experiments from the two sides served to validate each other. After all, if there is a fundamental physical reason why, for example, induction cure level improves results on the right side, it should at least not make the results worse on the left.

Obviously, the process is not exactly the same for the two sides. It is theoretically possible that it would be best to run the hemmer at a -15.0 set point on the left-hand side and a -14.9 set point on the right-hand side. However, unless the process differences that caused this effect were well understood, it would be likely for them to change over time and these results would no longer be valid. This was consistent with the focus of this research on fundamental physical causes of repeatable distortions, rather than problem solving for tooling or minute differences between the left and right-hand lines.

In this way, the focus of this research differs from much of the work done by the S. M. Wu Manufacturing Research Center [1, 10, 11], which is engaged in research on stamping and hemming processes. The research described in these references is focused toward solving specific problems with tooling or stamping dies that can eliminate existing process variations. Indeed, they estimate that about half the total variation from preproduction phase to post-production phase are caused by tooling maintenance and installation. The other half, however, is caused by stamping panels and process/product design. It is this second source of variation that this research addresses.

3.3.2 Experimental Measurement Procedures

The hemming line process that was used for this experiment was highly automated. As a result, there was little risk that uncontrolled factors varied significantly during the run.

Both the hemmer set point and induction cure cycle were changed by electronic controls. For the induction cure cycle, the controller was switched on and off for the different conditions during the experiment. For the hemmer set point, a controller set point change was required, but it was believed that the changes were quite repeatable. No gage capability study was done for this controller, but there was no evidence of poor repeatability.

The steel grade and stamping process conditions were known for each panel based on the records kept from the stamping experiments. The sequence in which the panels would be run was determined in advance with full knowledge of the history of the panels to be used.

3.3.3 Door Assembly Experimental Runs

The sequence of the runs on the hemming lines was as follows. First, the left inner experiment was run, followed by the left outer experiment. These runs were then followed by the right inner and outer experiments, respectively. The left and right side hemming lines used were supplied by Litton Industries and featured double action electric hemming machines, robotic part handling and both geometry and pedestal welding stations.

During the experimental runs, many of the welds normally used to assemble the doors were not required since the details had been left out. The weld guns for these stations were not cycled, such that they would not distort the panel in any way by poor weld gun equalization. This was a particularly significant risk given that the details were not there to make the panel more rigid and better able to resist deformation. At the end of the door hemming lines, the experimental doors were diverted to a conveyor from which they were manually racked.

3.3.4 Door Assembly Output Measures

Several output measures were taken for the finished door assemblies. "R1" assembly gages were available where each door assembly could be measured for gap and flushness to a nominal surface. These R1 gages are complicated fixtures that allow a door assembly to be located via two principal locating points (PLPs) in three dimensions (Figure 10). The R1s also have a surface representing the ideal door

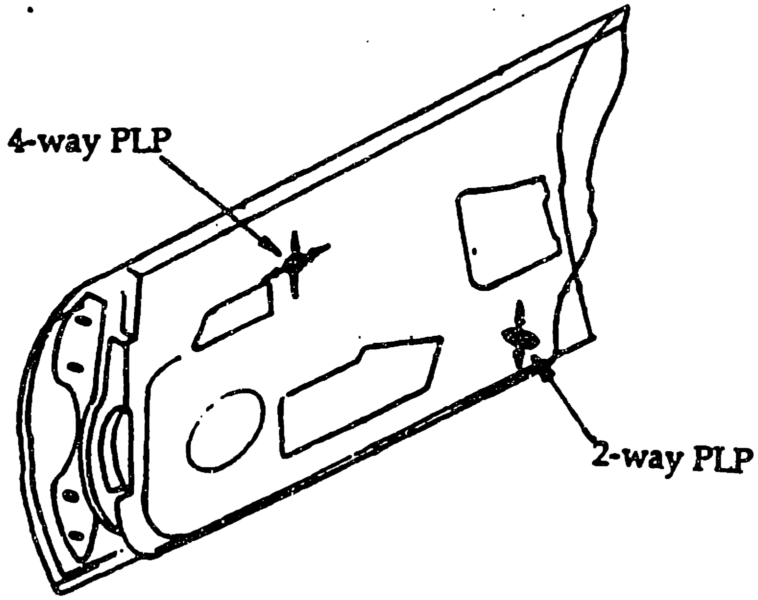


Figure 10. Principal Locating Point (PLP) positions on a door assembly.

opening for the BIW, cut to the precise engineering design specifications relative to the PLPs. Thus, a door set to the PLPs can be readily compared to nominal flushness and gap dimensions on these R1 gages.

Measurements were taken at twelve points for each panel, three points per side with one near the middle and one near each corner. The panels were located via two PLPs and were not clamped. This was done to make sure that the clamps did not obscure any bend or twist in the doors, even though it made it more difficult to locate the panels properly in the y-direction. All measurements were made with a digital caliper that read the gap and flushness to the nearest 0.001".

R&R studies were done for these measurements with the digital caliper (Table 5). On the basis of 25 measurements of the same point, the three sigma measurement process capability was +/- 0.08 mm for gap and +/- 0.37 for flush.

The "hem gap," i.e. the distance from the outside edge of the outer panel flange to the outside edge of the outer panel surface, was also measured for each door assembly. (Figure 11) [2]. These measurements were taken with the same digital caliper in nine locations. These locations were the same as the points where the gap and flush measurements were taken, except that no measurements of hem gap were made on the top

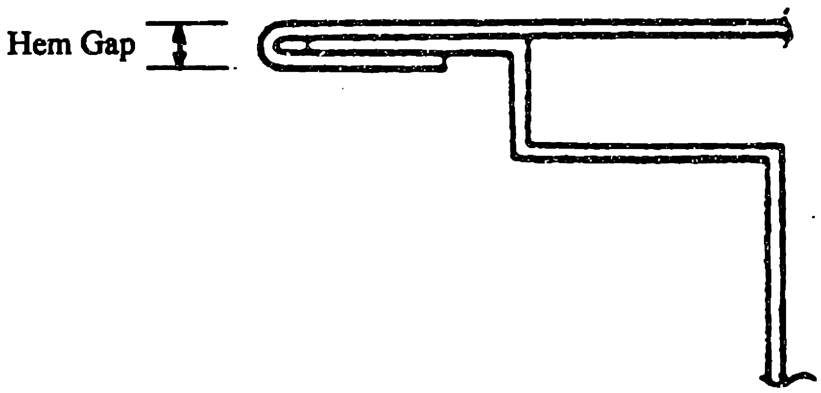


Figure 11. Hem gap [2].

of the door since there was no hem on that side. No gage was required for the hem gap measurements. An R&R study showed a three sigma measurement process capability of +/- 0.26 mm for hem gap using the digital caliper (Table 5).

Table 5. Digital Caliper R&R Studies on Door Assemblies

	Gap (inches)	Flush (inches)	Hem Gap (inches)
Average	3.26	2.09	2.63
Minimum	3.22	1.88	2.52
Maximum	3.32	2.27	2.80
Range	0.10	0.39	0.28
Std. Dev.	0.03	0.12	0.09
3 Sigma	0.08	0.37	0.26

These measurements were then consolidated into four output measures for each door. They are the RMS Flushness, RMS x-Gap, RMS z-Gap and Average Hem Gap. Each of these measurements will be described in turn below.

RMS Flushness Measurements. The RMS Flushness is a root-mean-squared computation of the measured flushness values around the perimeter of the door. Each measured value was subtracted from the nominal value for the flushness and squared. These squares were summed and the square root of the sum was taken and divided by the number of points to obtain the RMS Flushness:

$$\text{RMS Flushness} = (\Sigma_{\text{all } i} (\text{flush}_i - \text{nominal}_i)^2)^{0.5} / N.$$

Since there were twelve flush measurements taken on the door (three each on each of the four sides), i = 1, 2,..., 12 and N = 12 for these data.

The logic of the RMS Flushness is that deviations from nominal are important, regardless of the direction in which the deviation occurs, so sign is not retained. The deviations are taken from nominal and are squared to indicate an increasing penalty for nonconformity. The square root of these sums is taken and divided by the sample size to convert the measure back into units of millimeters of deviation per point. The drawback of this measure is that it does not distinguish in any way between a door where all twelve measures are either overflush or underflush (a potentially easy condition to fix during fitting), and a door where six of the measures are overflush and six are underflush (a difficult if possible condition to fix by fitting).

RMS x-Gap Measurements. The RMS x-Gap is a similar root-mean-squared computation of the measured gaps in the x-direction, i.e. the front door to front fender and front door to rear door:

$$\text{RMS x-Gap} = (\Sigma_{\text{all } i} (\text{gap}_i - \text{nominal}_i)^2)^{0.5} / N.$$

Since there were six gaps taken in the x-direction (three each on the fore and aft edges of the door), $i = 1, 2, \ldots, 6$ and $N = 6$ for these data.

RMS z-Gap Measurements. The RMS z-Gap is another root-mean-squared computation, this time of the measured gaps in the z-direction, i.e. along the top and bottom of the door:

$$\text{RMS z-Gap} = (\Sigma_{\text{all } i} (\text{gap}_i - \text{nominal}_i)^2)^{0.5} / N.$$

Since there were six gaps taken in the z-direction (three each on the up and down edges of the door), $i = 1, 2, \ldots, 6$ and $N = 6$ for these data.

The logic of the RMS z-Gap was the same as that for the RMS x-Gap. The two measures were separated, rather than combined into one RMS Gap type of measurement in recognition of the fact that, to a large extent, the x-Gap and z-Gap may be independently adjusted when the door is fit to the BIW. In a specific situation, it would be desirable for an assembly plant to focus on those factors that have the most impact on whichever gap is most variable, or the one that is the most difficult to adjust for in fitting the door due to process or design constraints. To the extent that the factors which control x-Gap differ from those which control z-Gap, a particular plant can determine which measure is most critical for its own situation.

Average Hem Gap Measurements. The Average Hem Gap measure was the simplest of the four output measures. In this case, there was no nominal value or particular standard to achieve. The goal was a tight, crisp hem, such that a smaller average hem gap was preferred [31]. Since there was no design value, the parabolic Taguchi loss function concept did not apply and was not used for this measure. Also, since the measure was inherently positive, no adjustment was needed for the sign of the values. Instead, the hem gap measures were simply averaged to arrive at the Average Hem Gap:

$$\text{Average Hem Gap} = \Sigma_{\text{all } i} (\text{hem gap}_i) / N.$$

Since there were nine hem gaps taken along the hemmed edges of each door (three for each edge of the door except the top), $i = 1,\ldots,9$ and $N = 9$ for these data.

Since there were no clear design specifications for the average hem gap, this measure is considered to be of secondary importance for process optimization. To the extent that factors necessary to improve the average hem gap conflict with what is best for the other output measures, it would normally be preferable to favor the other measures.

3.3.5 Statistical Data Analysis Procedures

Two primary tools were used to analyze each factor with respect to each output measure. First, the mean and variance for each level of each factor were compared and statistical tests were used to identify significantly lower means and/or variances at a 90% confidence level. This analysis of means was used to identify the preferred levels of the main effects by considering each factor one at a time.

Second, all first order interactions were checked for significance via ANOVA except for the inner lubricant level / outer lubricant level interaction, which could not be evaluated due to an imbalance in the data. Again, a 90% confidence level was used to identify significant results. No higher-order interactions were considered due to low sample sizes and difficulties with the unbalanced nature of the data set.

For both main effects and first-order interactions, no results were reported as significant unless they were directionally consistent between the left and right-hand sides.

In this way, the two identical experiments, one on each side, were used to validate each other. In addition, impractical and/or transient recommendations to use different levels of the same factor on the opposite sides were avoided.

CHAPTER 4. EXPERIMENTAL RESULTS

4.0 Introduction

This chapter summarizes the results of the materials characterization, stamping experiments and door assembly experiments described in Chapter 3.

4.1 Materials Characterization Results

The results of the tensile tests are summarized in Table 6 and the other material property test results are shown in Table 7. Statistically significant differences between the two levels of the inner and outer grades and between the different directions (longitudinal and transverse) tested are discussed below for each test procedure.

4.1.1 Tensile Test Results

Inner Grade Yield Strength. The 019 grade had a substantially higher yield point than the 982 grade in both directions. For the 019 grade, the transverse yield strength was higher than the longitudinal yield strength.

Outer Grade Yield Strength. The 660 grade had a significantly higher yield point than the 548 grade in both directions. For both grades, the transverse yield strength was slightly higher.

Inner Grade Tensile Strength. The 019 grade was stronger in both directions, although the advantage over the 982 grade was much less than the yield strength advantage. The 019 grade had a higher tensile strength in the transverse direction. The 982 grade had a lower variance of tensile strength in both directions.

Outer Grade Tensile Strength. There was no difference between the tensile strength of the two grades in either direction. The 660 grade was slightly stronger in the longitudinal direction.

Table 6. Tensile Test Results

	019 Grade	982 Grade	660 Grade	548 Grade
Yield Strength (ksi)				
Longitudinal Mean	26.62	21.51	25.42	22.64
Longitudinal Std. Dev.	0.82	1.07	0.42	0.40
Transverse Mean	28.98	21.74	26.63	23.95
Transverse Std. Dev.	0.80	0.48	0.75	0.77
Tensile Strength (ksi)				
Longitudinal Mean	45.31	44.28	45.41	45.14
Longitudinal Std. Dev.	0.97	0.22	0.24	0.49
Transverse Mean	46.31	44.12	44.40	44.88
Transverse Std. Dev.	0.58	0.24	0.25	0.40
Elongation (percentage)				
Longitudinal Mean	42.81	47.39	43.56	46.00
Longitudinal Std. Dev.	1.66	1.32	1.58	1.31
Transverse Mean	40.44	45.38	39.27	43.51
Transverse Std. Dev.	1.93	1.95	1.27	2.06
n Value				
Longitudinal Mean	0.2031	0.2634	0.2185	0.2518
Longitudinal Std. Dev.	0.0038	0.0021	0.0039	0.0019
Transverse Mean	0.2030	0.2551	0.2160	0.2467
Transverse Std. Dev.	0.0027	0.0044	0.0036	0.0029
R Value				
Longitudinal Mean	1.580	1.844	1.791	1.905
Longitudinal Std. Dev.	0.085	0.106	0.066	0.077
Transverse Mean	1.898	2.333	2.024	2.537
Transverse Std. Dev.	0.095	0.104	0.081	0.098

Inner Grade Percent Elongation. The 982 grade elongated substantially more than the 019 grade in the tensile test in both directions. Both grades had greater elongations in the longitudinal direction.

Outer Grade Percent Elongation. The 548 grade had significantly greater elongations than the 660 grade in both directions. For both grades, the longitudinal elongation was greater.

Inner Grade n-Value. The 982 grade had a substantially higher n-value than the 019 grade in both directions. The 982 grade had a slightly higher n-value in the longitudinal direction.

Outer Grade n-Value. The 548 grade had a substantially higher n-value than the 660 grade in both directions. The 548 grade had a slightly higher n-value in the longitudinal direction.

Inner Grade R-Value. The 982 grade was superior in both directions. For both grades, the R-value was substantially higher in the transverse direction.

Outer Grade R-Value. The 548 grade had a higher R-value in both directions. For both grades, the transverse R-value was substantially greater.

4.1.2 LDH Test Results

Inner Grade LDH. Both grades were more formable (higher mean LDH value) and less variable (lower LDH variance) in the transverse direction. The 982 grade had a lower LDH variance in both directions.

Outer Grade LDH. The 660 grade was significantly more formable than the 548 grade in both directions. The 548 grade was significantly more formable in the longitudinal direction than in the transverse direction.

4.1.3 Gauge Test Results

Inner Grade Gauge. The transverse samples were significantly thicker than the longitudinal samples for the 019 grade. Most likely this was due to the crown of the sheet, as the transverse samples were cut from a location farther from the edge of the coil. Gauge variation was almost twice as great for the 019 coil.

Outer Grade Gauge. The average gauge of the 548 coil was 0.0001" thicker than the 660 coil.

Table 7. Other Material Property Test Results

	019 Grade	982 Grade	660 Grade	548 Grade
Limiting Dome Height (inches)				
Longitudinal Mean	1.281	1.279	1.297	1.270
Longitudinal Std. Dev.	0.034	0.021	0.009	0.011
Transverse Mean	1.310	1.324	1.298	1.260
Transverse Std. Dev.	0.024	0.007	0.011	0.010
Sheet Gauge (inches)				
Longitudinal Mean	0.02587	0.02668	0.02964	0.03054
Longitudinal Std. Dev.	0.00041	0.00015	0.00019	0.00028
Transverse Mean	0.02653	0.02656	0.02949	0.03057
Transverse Std. Dev.	0.00026	0.00019	0.00020	0.00020
Pre-tensile Hardness (HRB)				
Longitudinal Mean	49.8	37.0	48.3	40.8
Longitudinal Std. Dev.	2.3	1.1	0.8	1.3
Transverse Mean	53.1	38.8	47.2	41.1
Transverse Std. Dev.	2.0	1.4	1.3	1.2
Post-tensile Hardness (HRB)				
Longitudinal Mean	72.3	72.2	68.6	77.0
Longitudinal Std. Dev.	5.1	10.2	10.0	8.3
Transverse Mean	76.5	74.0	78.0	80.5
Transverse Std. Dev.	4.5	6.5	5.9	3.4
Average Peak Height (Ra)				
Longitudinal Mean	41.58	31.07	33.48	33.30
Longitudinal Std. Dev.	4.31	3.25	3.88	3.23
Transverse Mean	36.61	36.07	35.29	34.71
Transverse Std. Dev.	3.83	4.19	3.91	3.74
Peaks Per Inch (PPI)				
Longitudinal Mean	181.5	141.7	86.3	153.7
Longitudinal Std. Dev.	32.1	29.6	17.7	31.1
Transverse Mean	146.2	159.1	82.5	139.1
Transverse Std. Dev.	28.8	32.3	19.9	27.5

4.1.4 Hardness Test Results

Inner Grade Hardness. The 019 grade was significantly harder than the 982 grade. The 982 grade has significantly lower hardness variation. For both grades, the HRB values were higher for the transverse direction samples.

Inner Grade Hardness Increase. The average hardness of both grades in both directions was substantially greater after tensile testing. The 982 grade hardened much more during the tensile test.

Outer Grade Hardness. The 660 grade was significantly harder than the 548 grade in both directions. The 660 grade demonstrated a higher average hardness in the longitudinal direction.

Outer Grade Hardness Increase. The average hardness of both grades in both directions was greater after tensile testing. The 548 grade exhibited a greater hardness increase. The 660 grade hardness increased much less in the longitudinal direction than in the transverse direction. Although the post-tensile hardness was higher for every sample, the variance of the hardness increase for the 660 longitudinal samples was so high that there was only limited statistical confidence that this grade had hardened in that direction.

4.1.5 Surface Roughness Test Results

Inner Grade Ra Values. Ra was higher in the transverse direction for the 982 grade, whereas Ra was higher in the longitudinal direction for the 019 grade. The 982 grade had lower values in the longitudinal direction.

Inner Grade PPI Values. PPI was higher in the transverse direction for the 982 grade, while the 019 grade had higher longitudinal values. The PPI values were higher for the 019 grade in the longitudinal direction.

Outer Grade Ra Values. Both grades and directions were statistically equivalent.

Outer Grade PPI Values. The 660 grade demonstrated much lower PPI values and variances than the 548 grade in both directions. Both the average and variance of the PPI count for the 660 grade were only slightly more than half the values of the other three grades.

4.2 Stamping Experiment Results

Results of the stamping experiment described in Chapter 3 are summarized in Tables 8-13. They are described below for each of the following output measures: major and minor outer panel surface strains, inner panel thickness strains and inner panel distortions. Appendix B presents the data for the experimental interactions in graphical form.

Table 8. Outer Panel Surface Strain Main Effects

	660 Grade	548 Grade	Difference	Sig. Level*
Left Major Strain (percent)	3.269	3.869	0.600	0.000
Right Major Strain (percent)	3.344	3.956	0.612	0.000
Left Minor Strain (percent)	1.031	1.238	0.207	0.000
Right Minor Strain (percent)	0.875	1.056	0.181	0.000

	Low Cushion	High Cushion	Difference	Sig. Level*
Left Major Strain (percent)	3.519	3.781	0.262	0.000
Right Major Strain (percent)	3.356	3.781	0.425	0.000
Left Minor Strain (percent)	1.100	1.169	0.069	0.045
Right Minor Strain (percent)	0.975	0.956	-0.019	0.490

	Low Lubricant	High Lubricant	Difference	Sig. Level*
Left Major Strain (percent)	3.563	3.575	0.012	0.772
Right Major Strain (percent)	3.356	3.781	0.425	0.000
Left Minor Strain (percent)	1.106	1.163	0.057	0.096
Right Minor Strain (percent)	0.956	0.975	0.019	0.490

* Significance level may be thought of as the probability that the difference observed is due to chance, rather than a physical phenomenon [28, 29].

4.2.1 Outer Panel Major Strain Analysis

For both left and right-hand side ANOVAs, the most significant factor was the steel grade. On both sides, the 548 grade resulted in an 18% higher major strain than the

Table 9. Outer Panel Surface Strain Interactions

	Factor 1	Factor 2	Factor 3*	Sig. Level**
Left Major Strain	Grade	Cushion		0.004
	Grade	Lubricant		0.007
	Cushion	Lubricant		0.007
	Grade	Cushion	Lubricant	0.156
Right Major Strain	Grade	Cushion		0.179
	Grade	Lubricant		0.309
	Cushion	Lubricant		0.023
	Grade	Cushion	Lubricant	0.011
Left Minor Strain	Grade	Cushion		0.849
	Grade	Lubricant		0.001
	Cushion	Lubricant		0.569
	Grade	Cushion	Lubricant	0.003
Right Minor Strain	Grade	Cushion		0.817
	Grade	Lubricant		0.000
	Cushion	Lubricant		0.254
	Grade	Cushion	Lubricant	0.046

* Factor 3 only applies to three-way interactions.
** Significance level may be thought of as the probability that the difference observed is due to chance, rather than a physical phenomenon [28, 29].

660 grade. This result is consistent with expectations based on the higher n-value, higher R-value, lower yield strength and higher percentage elongation of the 548 grade.

Also on both sides, the second most important factor was the cushion pressure. Use of a higher cushion pressure (75 psi versus 60 psi) increased the major strain by 13% on the left-hand side and by 7% on the right-hand side. This is also an expected result, since a higher binder pressure will put a greater restriction on slippage of the sheet over the draw beads, and thus force it to strain more.

The lubricant level was not significant on either side. Conventional wisdom would indicate that more lubrication would increase the amount of slippage of the sheet and result in a lower major strain, yet this effect was not observed in this experiment.

All three first-order interactions were significant on the left-hand side, while only the cushion pressure/lubricant level interaction was significant on the right. The boxplots in Appendix B demonstrate that the general trend was the same for both sides, despite the difference in significance. Since higher surface strains are preferred for outer panels, the 548 grade steel is preferred over the 660 grade, as noted from the main effects. Also consistent with the main effects, the higher cushion pressure yields higher major strains. Finally, from the cushion pressure/lubricant level interaction, which is directionally consistent and significant for both sides, we can see that at the high cushion pressure a low lubricant level is preferred.

The three-way interaction between steel grade, cushion pressure and lubricant level was significant on the right-hand side. Again, there was excellent directional consistency between the sides. The results agree with what has been shown above for the main effects and two-way interactions. Specifically, the best results were found with the 548 grade steel, high cushion pressure and low lubricant level.

4.2.2 Outer Panel Minor Strain Analysis

As with the major strains, the steel grade was the most significant factor for both sides. The 548 grade minor strains increased by more than 20%. The cushion pressure was significant on the left-hand side, but directionally inconsistent on the right. The lubricant level was significant on the left-hand side and directionally consistent on the right. High lubricant level improved minor strain by a little more than 5% on the left and about 2% on the right.

Only the steel grade/lubricant level interaction was significant, but its significance was strong for both sides. From Appendix B, clearly a low lubricant level is preferred for the 660 grade, but for the 548 grade the high lubricant level is best. Since the 548 grade is clearly superior, this reinforces the weak main effect suggestion for the use of a high lubricant level.

The three-way interaction was significant on both sides. The results were very consistent between sides and with the results from main effects and two-way interactions. The data indicate that the 548 grade should be used with a high lubricant level. It is unclear whether cushion pressure has any significant effect, although it appears to be best at the low level based on the right-hand side results.

4.2.3 Inner Panel Thickness Strain Analysis

Thickness strain is a relatively inconclusive output measure (as compared to surface strain), because it is not clear whether it should be increased or decreased. Increasing it too much can result in a high percentage of splits in the line. On the other hand, increasing thickness strain indicates that the metal stretched more and will therefore be more likely to have developed sharp, clear formations without wrinkles or buckles. This analysis assumes that it is desirable to increase thickness strain, although this will not always be true [15, 32].

For the main effects, the cushion pressure was highly significant on both sides. A higher cushion pressure increased thickness strain by 12% on the left-hand side and by 7% on the right-hand side. This is consistent with the expected effect of a higher cushion pressure. The other main effects were not significant on either side.

The results from the two-way interactions were different between the two sides. On the left, the cushion pressure/steel grade interaction was highly significant and indicated that the 019 steel grade at a high cushion pressure is preferred. Although the right-hand side data did not show the interaction as significant, it was directionally consistent. It was obvious during the runs that the 982 grade was more difficult to form for this part, because all the splits occurred in the panels formed from the 982 grade.

Table 10. Inner Panel Thickness Strain Main Effects

	019 Grade	982 Grade	Difference	Sig. Level*
Left Thickness Strain (percent)	12.5762	12.3020	-0.2742	0.182
Right Thickness Strain (percent)	13.2550	13.0827	-0.1723	0.540

	Low Cushion	High Cushion	Difference	Sig. Level*
Left Thickness Strain (percent)	11.7694	13.1627	1.3933	0.000
Right Thickness Strain (percent)	12.7600	13.6107	0.8507	0.019

	Low Lubricant	High Lubricant	Difference	Sig. Level*
Left Thickness Strain (percent)	12.5162	12.3660	-0.1502	0.454
Right Thickness Strain (percent)	13.2056	13.1353	-0.0703	0.760

* Significance level may be thought of as the probability that the difference observed is due to chance, rather than a physical phenomenon [28, 29].

Table 11. Inner Panel Thickness Strain Interactions

	Factor 1	Factor 2	Factor 3*	Sig. Level**
Left Thickness Strain	Grade	Cushion		0.004
	Grade	Lubricant		0.076
	Cushion	Lubricant		0.812
	Grade	Cushion	Lubricant	0.595
Right Thickness Strain	Grade	Cushion		0.346
	Grade	Lubricant		0.321
	Cushion	Lubricant		0.010
	Grade	Cushion	Lubricant	0.767

* Factor 3 only applies to three-way interactions.
** Significance level may be thought of as the probability that the difference observed is due to chance, rather than a physical phenomenon [28, 30].

The second most significant was the cushion pressure/lubricant level interaction, significant on the right side. On this side, the high cushion pressure/low lubricant level combination was preferred. This combination also appears to be advantageous on the left-hand side.

Finally, the steel grade/lubricant level interaction was significant on the left-hand side. On this side, the 982 grade steel at a low lubricant level is preferred. Although this result is consistent with the general trend of the data on the right-hand side, it conflicts with the more significant interactions and therefore is not considered further. The three-way interaction was not significant on either side so was not considered.

As a result, this analysis indicates that the 019 steel grade, a high cushion pressure and a low lubricant level will increase thickness strain for these door inner panels.

4.2.4 Inner Panel Distortion Analysis

For distortion analysis, the meaning of the output measure is more obvious. The objective is to minimize distortion of the inner panels that could cause the door assembly to be distorted during hemming.

For the main effects, both the cushion pressure and lubricant level were significant on both sides. For the cushion pressure, the high level decreased the average distortion by 7% on the left-hand side and by 14% on the right-hand side. This is consistent with expectations since more stretch of the panel should increase both its strength and its dimensional accuracy. For the lubricant level, the high setting increased distortion on the left-hand side but decreased it on the right-hand side, an inconclusive result.

No two-way interactions were significant on the right-hand side, although two were on the left. The most significant was the cushion pressure/lubricant level interaction. A low level of both cushion pressure and lubricant level minimized the average distortion. The right-hand results were inconsistent, however, so this interaction was not considered further. The second significant interaction was the steel grade/lubricant level. On the left-hand side, the preferred levels appeared to be the 019 steel grade at a low lubricant level. Again, the right-hand side results are inconsistent, so this interaction was also dropped from further consideration.

Table 12. Inner Panel Distortion Main Effects

	019 Grade	982 Grade	Difference	Sig. Level*
Left Avg. Abs. Dev. (mm)	0.6975	0.6900	0.0075	0.712
Right Avg. Abs. Dev. (mm)	0.5862	0.6247	0.0385	0.282

	Low Cushion	High Cushion	Difference	Sig. Level*
Left Avg. Abs. Dev. (mm)	0.7188	0.6673	-0.0515	0.039
Right Avg. Abs. Dev. (mm)	0.6481	0.5587	-0.0894	0.010

	Low Lubricant	High Lubricant	Difference	Sig. Level*
Left Avg. Abs. Dev. (mm)	0.6588	0.7313	0.0725	0.007
Right Avg. Abs. Dev. (mm)	0.6319	0.5760	-0.0559	0.090

* Significance level may be thought of as the probability that the difference observed is due to chance, rather than a physical phenomenon [28, 29].

Table 13. Inner Panel Distortion Interactions

	Factor 1	Factor 2	Factor 3*	Sig. Level**
Left Average Absolute Deviation (mm)	Grade	Cushion		0.274
	Grade	Lubricant		0.031
	Cushion	Lubricant		0.006
	Grade	Cushion	Lubricant	0.075
Right Average Absolute Deviation (mm)	Grade	Cushion		0.207
	Grade	Lubricant		0.614
	Cushion	Lubricant		0.486
	Grade	Cushion	Lubricant	0.876

* Factor 3 only applies to three-way interactions.
** Significance level may be thought of as the probability that the difference observed is due to chance, rather than a physical phenomenon [28, 29].

The three-way interaction was highly significant on the left-hand side, but far from significant on the right. These results were not consistent between the left and right-hand sides.

This analysis suggests that high cushion pressure is favorable over all combinations of steel grade and lubricant level for both sides.

4.3 Door Assembly Experiment Results

Results of the door assembly experiment described in Chapter 3 are described below for each of the following output measures: RMS Flushness, RMS x-Gap, RMS z-Gap and Average Hem Gap. The goal was to determine the levels of the experimental factors that minimized the values of all these measures.

Statistical tests of the mean and variance of each output measure for each factor are shown in Appendix C and displayed graphically in Appendix D. Interactions that were significant on at least one hand are shown in Appendix E. The data in Appendices C, D, and E are useful for interpreting directional consistency.

4.3.1 RMS Flushness Analysis

For both the left and right-hand sides, there was a significant interaction between the inner steel grade and inner cushion pressure. In both cases, the preferred level of these variables was the 982 grade steel and a low inner cushion pressure. This was a highly consistent and significant result, decreasing RMS Flushness by about 0.08 (18%) on the left-hand side and 0.06 (10%) on the right-hand side.

Other statistically significant effects supporting the use of a low inner cushion pressure on the left-hand side were directionally consistent on the right-hand side. First was a lower mean for inner cushion pressure at the low level, for a decrease of 0.05 (9%) on the left-hand side and 0.02 (4%) on the right. Second was an interaction with outer cushion pressure that favored the inner cushion pressure low and the outer cushion pressure high, for a decrease of 0.10 (19%) on the left-hand side and 0.05 (9%) on the right. Third was an interaction with the hemmer set point that favored the inner cushion pressure low and the hemmer set at -15.0, for a decrease of 0.09 (17%) on the left-hand side and 0.01 (2%) on the right.

The 548 outer steel grade is recommended, as its mean was lower (significant on the right-hand side). The decrease was 0.03 (6%) on the right-hand side and 0.02 (4%) on the left. The variance was reduced with the outer lubricant level at the high level (significant on the left-hand side). The standard deviation reduction was 0.03 (38%) on the left-hand side and negligible on the right.

4.3.2 RMS x-Gap Analysis

The RMS x-Gap was minimized with the 982 inner steel grade, based on a reduction in the mean value (significant on the right-hand side), for a decrease of 0.03 (11%) on the right-hand side and 0.02 (8%) on the left. This was consistent with an interaction with outer cushion pressure (significant on the left-hand side) that favored the 982 grade and a high outer cushion pressure. The decrease associated with this interaction was 0.04 (14%) on the left-hand side and 0.03 (12%) on the right.

For the outer steel grade, a lower mean (significant on the left-hand side), lower variance (significant on the right-hand side) and an interaction with inner cushion pressure (significant on the left-hand side) all favored the 548 grade. The mean was 0.04 (13%) lower on the left-hand side and 0.01 (7%) lower on the right. The standard deviation was 0.02 (33%) lower on the right-hand side and 0.01 (11%) lower on the left. The interaction reduced the RMS x-Gap by 0.07 (22%) on the left-hand side and 0.01 (4%) on the right.

A low inner cushion pressure was preferred based on a lower mean (significant on the left-hand side) as well as the interaction with the outer steel grade mentioned above. The mean was 0.04 (12%) lower on the left-hand side and 0.01 (2%) on the right. A high outer cushion pressure is recommended, given a lower variance (significant on the right-hand side) and the interaction with the inner steel grade mentioned above. The standard deviation was 0.02 (29%) lower on the right-hand side and 0.01 (13%) on the left. Finally, a low outer lubricant level resulted in a lower mean RMS x-Gap (significant on the left-hand side). The decrease was 0.05 (15%) on the left-hand side and 0.01 (3%) on the right.

4.3.3 RMS z-Gap Analysis

The RMS z-Gap variance was decreased by:

- using the 019 inner steel grade (significant on the left-hand side), for a standard deviation decrease of 0.03 (28%) on the left-hand side and 0.003 (6%) on the right;
- using the 660 outer steel grade (significant on the right-hand side), for a standard deviation decrease of 0.01 (27%) on the right-hand side and 0.01 (8%) on the left;
- using a high inner cushion pressure (significant on the left-hand side), for a standard deviation decrease of 0.05 (35%) on the left-hand side and 0.003 (6%) on the right;
- using a low outer cushion pressure (significant on both sides), for a standard deviation decrease of 0.04 (30%) on the left-hand side and 0.02 (29%) on the right; and
- using a -15.0 hemmer set point (significant on the left-hand side), for a standard deviation decrease of 0.03 (22%) on the left-hand side and almost none on the right.

The mean RMS z-Gap was reduced by turning off the induction cure cycle (significant on the left-hand side). The decrease was 0.07 (16%) on the left-hand side and negligible on the right.

4.3.4 Average Hem Gap Analysis

The Average Hem Gap analysis was the only case in which conflicting results were found. From the main effects, the variance was reduced by a low inner lubricant level (significant on the left-hand side) and a high outer lubricant level (significant on the right-hand side). The standard deviation decrease was 0.01 (24%) on the left-hand side and 0.01 (10%) on the right with the low inner lubricant level, and 0.02 (27%) on the right-hand side and negligible for the left with the high outer lubricant level. When interactions of these factors were considered, however, these levels were seen to be suboptimal.

An interaction between inner lubricant level and induction cure cycle showed that the high inner lubricant level and induction cure off is preferred (significant on the left-hand side). The decrease was 0.02 (1%) on the left-hand side and 0.07 (3%) on the right. The majority of the variation from the high lubricant level occurred when the induction cure was on.

Similarly, the outer lubricant level was reversed by an interaction with the hemmer set point that recommended a low outer lubricant level and a hemmer set point of -15.0 (significant on the right-hand side), for a decrease of 0.07 (3%) on the right-hand side and 0.05 (2%) on the left. On the left-hand side, the results with the -15.0 hemmer set point were roughly equivalent regardless of the level of outer lubricant used. On the right side, however, the low outer lubricant level showed a clear advantage. The variance was lower with the high outer lubricant on the right-hand side because of the low variance achieved with that lubricant level at a -14.9 hemmer set point. Since the evidence supporting the use of a -15.0 hemmer set point is strong (as shown below), this portion of the results is not useful, and therefore a low outer lubricant level is recommended to reduce Average Hem Gap.

The -15.0 hemmer set point was verified by a lower mean (significant on both sides). This result was expected since by definition the -15.0 hemmer set point will close the hem tighter than the -14.9 hemmer set point. The decrease was 0.05 (2%) on the right-hand side and 0.04 (1%) on the left.

CHAPTER 5. DISCUSSION OF RESULTS

5.0 Introduction

This chapter discusses the results of the material property tests, stamping experiment and door assembly experiment.

5.1 Materials Characterization

This section describes processing differences for the grades of steel used in the experimentation. It then discusses the tensile test, LDH test, hardness test and surface roughness test results for these grades.

5.1.1 Processing of the Steel Grades Studied

The 548 and 982 grades were interstitial-free (IF) steel. This is an industry designation for steel in which the concentration of free carbon is extremely low. Usually this is done by blowing oxygen through a basic oxygen furnace while the steel is liquid (thus driving off carbon in the form of carbon dioxide) and by tying free carbon in equiaxed precipitates by the addition of niobium or titanium. In addition, different rolling and annealing practices are used at the steel mill to give the interstitial-free steel a crystallographic anisotropy that enables large in-plane strains with minimal thinning (i.e., a high R-value) [25].

The 019 and 660 grades were aluminum-killed-draw-quality (AKDQ) and draw-quality-special-killed (DQSK) steel, respectively. These grades are less expensive because they do not use expensive alloying elements like niobium or titanium to tie up free carbon, although they do use aluminum to tie up free nitrogen into precipitates. Free nitrogen, like free carbon, resides in the interstices of the steel lattice and helps to pin dislocations.

Rolling and annealing practices at the steel mill are different from IF grades as well, with usually less cold reduction taken on AKDQ/DQSK grades to avoid making the sheet too hard. This lowers the R-value for the grade. Although the AKDQ/DQSK steels are low in carbon and relatively soft, they still have more free carbon available to pin dislocations and hence are stronger and less formable than the IF steels [25].

Another difference in the processing of these grades was in their coatings. The 660 grade had an electrogalvanized coating for rust prevention. This type of coating has a low lubricity, i.e. the coefficient of the friction of the sheet is relatively high, which lowers formability. In contrast, the 019, 548 and 982 grades had a galvanneal coating with a higher lubricity. All four grades were coated by different suppliers, so differences in the surface morphology of the galvanneal coatings would also be expected. All grades had the same coating thickness specification [21, 25].

A final difference between the processing of the steel grades was the annealing practice. The 660 grade was a batch-annealed product, whereas the 019, 548 and 982 grades were in-line annealed. The in-line anneal is done on the coil in strip form while the sheet is unwound, whereas the batch anneal is done in coil form while the sheet is wound. This should result in a more consistent product along the length of the in-line annealed coils, whereas a batch anneal generally results in a more complete recovery of the grain structure than an in-line anneal due to the greater annealing times involved.[25].

5.1.2 Tensile Test Results

The IF grades justified their higher cost with lower yield strengths, greater elongations, higher n-values and better R-values. At the same time, they demonstrated nearly equal tensile strength. The evidence from the tensile tests suggests that the IF grades should be more formable than the AKDQ/DQSK grades. This is especially true for the inner grades tested, where a more dramatic difference in properties was observed.

One interesting result was the directional differences in the properties across the grades. In some cases, the results were consistent. For example, R-value was significantly greater in the transverse direction of all four grades. In some cases, however, there were differences in the directional behaviors of the different grades. For example, the tensile strength of the 019 grade was significantly higher in the transverse direction, whereas the similar 660 grade had a significantly higher tensile strength in the longitudinal direction.

This result implies two responses. First, in selecting tensile samples from a coil, inspectors must be careful to ensure that they are oriented in a standard direction (or set of directions) that is consistently applied by all inspectors over all coil for that specification. It could make sense to test different specifications in different directions, depending on the directional characteristics of the part and the steel grade.

Second, when selecting the optimal steel grade for a particular part, consideration should be made of the direction in which formability problems (splits or wrinkles) are most likely to be an issue, given the design of the dies. This knowledge enables an automobile stamping plant to work with the steel supplier to select a grade that will have the directional properties that they need, even if they have to rotate the blanks 90 degrees from the rolling direction before loading them into the press line.

5.1.3 LDH Test Results

During the LDH testing, it seemed that the LDH values were highly autocorrelated. The values drifted up or down, regardless of the grade of steel run. The position of the ring on top of the sample seemed to be important. When it was rotated, frictional differences in different parts of the ring (presumably) caused significant changes in LDH for otherwise apparently identical samples. Other factors such as sample width and sample and tool cleanliness also appeared to be important, as expected [33].

From the data obtained, the LDH test appears to be highly variable, confirming the allegations made by stamping experts in the literature and in discussion [34]. If an automotive stamping plant wants to use this test, an average of multiple LDH samples (in the same direction) should be obtained for each coil. As with the tensile test specimens, a decision should be made on the most important direction in which to measure the LDH for each part. All samples should be taken with the same orientation to the rolling direction as the steel grades may form differently in the transverse and longitudinal directions.

It was postulated that some of the differences in the LDH sample results were due to gauge variations. To test this theory, linear regression models were used to check for a significant effect of gauge on LDH for each grade of steel. None of these four models had an adjusted R^2 greater than 0.1. As a result, it was concluded that the gauge deviations were not responsible for the LDH variations observed.

5.1.4 Hardness Test Results

On the basis of the experimental results, it appears that Rockwell B hardness values can be used to distinguish between grades of steel that are substantially different in their properties. The test appears to be justified in its intended use as a rough check of material properties. There was a statistically significant difference, however, in the average hardness in the different directions from which the samples were cut for three out of four grades of steel. Since the indenter does not measure any directional property of the steel, this result is not explained.

As expected, the hardness increased substantially after work-hardening the samples in the tensile test. Also as expected, the IF steel grades, with their higher n-values, work-hardened much more than the AKDQ/DQSK grades. In all cases, there was a great deal more variability in the HRB values after tensile testing than before. The post-tensile test standard deviations of HRB ranged from about three to twelve times their pre-tensile test values. It appears that the hardening effects are highly localized in the samples at failure, such that some points work-harden considerably while other points are only slightly affected. Alternatively, the galvanneal coatings may have deteriorated differentially, causing some of the different hardnesses observed. This phenomenon was particularly observed for the 660 grade in the longitudinal direction.

5.1.5 Surface Roughness Test Results

For the inner grades, the 982 coil was significantly smoother than the 019 coil in the longitudinal direction, but not in the transverse direction. Conventional wisdom implies that this will enhance the formability of the 982 steel in the rolling direction as compared to the 019 steel. Surface friction, however, can actually increase formability if it allows lubrication to be better adsorbed to the surface of the sheet (Appendix A) [35].

For the outer grades, the 660 coil had a much lower mean PPI and PPI variance than the 548 grade, though their average Ra values are not different. Again, conventional wisdom indicates that this would tend to make the DQSK 660 coil more formable relative to the IF 548 coil than it otherwise would be. As with the inner grades, however, such a conclusion can not be drawn from these data alone.

As with the LDH tests, the Surtronic appears to be a highly variable material characterization device. With many samples, the device seems to be capable of detecting differences between steels, but it would be difficult to draw any meaningful conclusions from a single reading of Ra and/or PPI from a coil.

5.2 Materials Characterization Summary

The following discussion summarizes the material properties of the four grades of steel tested.

5.2.1 Inner Grade 019

This AKDQ product was stronger and less formable than the 982 grade. It exhibited more strength (both yield and tensile), less elongation, a lower n-value and a lower R-value in both directions. It was significantly harder before tensile testing, although about the same hardness after. It was significantly rougher in the longitudinal direction.

5.2.2 Inner Grade 982

This IF product yielded at lower stress and elongated more before fracture. It work-hardened significantly during plastic strain in the tensile test to make up most of its original strength disadvantage. It differed somewhat from the 019 grade in its directional properties. Whereas the 019 coil was stronger in the transverse direction, the 982 coil was equally strong in both directions. Conversely, it had a higher n-value in the longitudinal direction, whereas the 019 grade had the same n-value in both directions. Finally, the 982 grade demonstrated a larger increase in R-value from the longitudinal to the transverse direction than did the 019 grade.

5.2.3 Outer Grade 660

This DQSK, batch annealed product was stronger and less formable in both directions than the 548 grade. Its yield strength was higher, it demonstrated less elongation to failure, and it had lower n-values and R-values. It was 0.001" thinner in gauge and achieved higher LDH values in both directions. It was significantly harder before tensile testing, although not after. Its electrogalvanized surface had much lower PPI values than those of the galvannealed 548 grade.

5.2.4 Outer Grade 548

This IF, in-line annealed product had better formability properties than the 660 grade, although the differences were not as pronounced as they were for the inner grades. It had a lower yield strength, yet made up the difference by work-hardening, such that its tensile strength and post-tensile hardness were equally high as those for the 660 grade. Directional differences existed between the outer grades. Unlike the 660 coil, the 548 coil had higher LDH and n-value in the longitudinal direction. In addition, its R-value increase in the transverse direction over the longitudinal direction was much larger.

5.3 Stamping Experiments

The results of the stamping experiments are discussed with respect to the experimental factors for both the outer and inner panels in this section.

5.3.1 Outer Panel Summary

Putting the results from the major and minor strains together, the following suggestions can be made for the steel grade, cushion pressure and lubricant level.

Steel Grade. It is apparent that the 548 grade will yield better surface strains, as expected given its higher n-value and lower yield strength. The objective of maximizing strain is primarily to increase dent resistance of the outer panels. Dent resistance was not evaluated from these experimental panels [36].

The 660 grade is initially stronger, yet the additional strain for the 548 steel could enable it to work-harden to the point where the two grades have similar dent resistance in a finished panel. In this case, however, the surface strains in the middle of the panel are sufficiently low that it is not expected that the 548 grade work-hardened enough in this area to match the dent resistance of the 660 grade. As a result, the stronger 660 grade should better resist denting both on a finished automobile and, relevant to the purposes of this study, in handling during the door assembly process.

An earlier study characterized the yield strength in several areas of a panel formed from the 660 steel (Figure 12). As expected, the formed panel was stronger near the edges and had work-hardened less near the middle. This is because the panel had experienced greater strain around the edges of the panel, as observed in the surface strain analysis. From the figure, it is apparent that there are significant strain gradients for the finished panel as the yield strengths vary by as much as eight ksi in different areas.

The 548 grade, with its greater n-value, would be expected to have a more homogeneous surface strain as work-hardening in an area of higher initial strains will tend to spread the strain to other areas of the panel more uniformly (Appendix A). As a result,

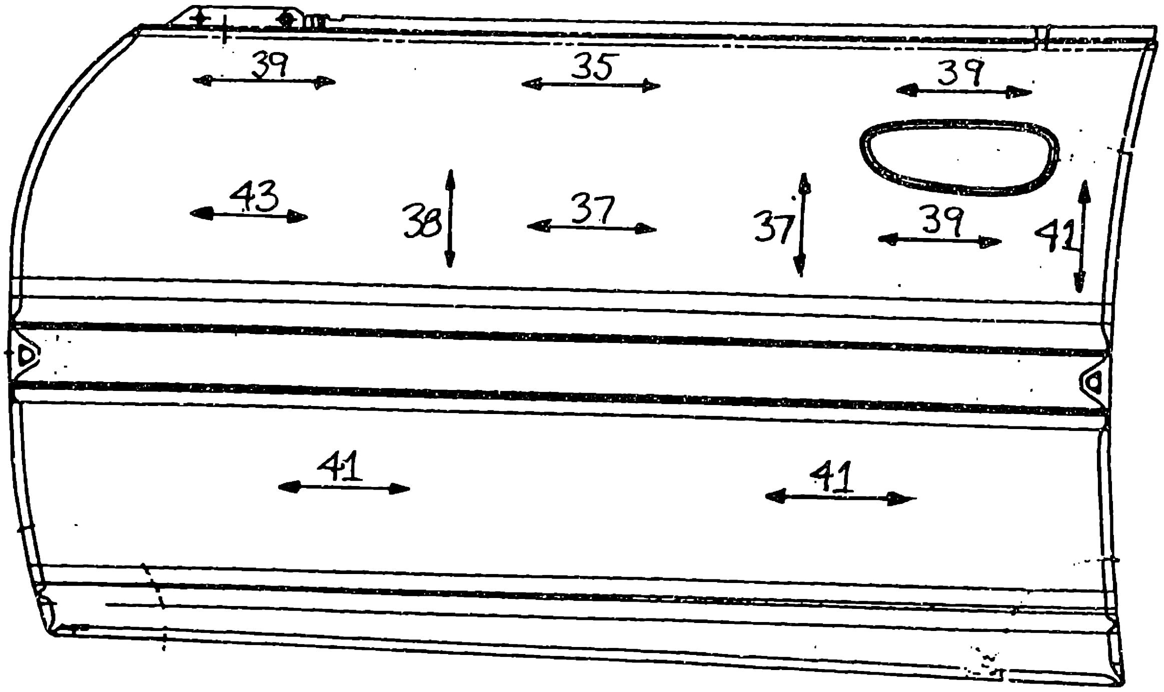


Figure 12. Yield strength distribution of a formed door panel (ksi).

the yield stress and surface strain gradients for the 548 grade would be smaller than those for the 660 grade. Since these strain gradients internal to the sheet cause residual stresses, the result is that the more formable 548 grade would be expected to have lower residual stresses than the less formable 660 grade. These residual stresses could lead to panel distortions in cutting (trim dies), bending (hemming) and stress relieving (thermal treatment) operations.

In conclusion, there is a trade-off between more formable and less formable outer steel grades. More formable grades such as the 548 grade will have lower residual stresses and be less likely to deform in post-forming stamping operations (such as trimming) and the hemming process (bending). On the other hand, stronger grades such as the 660 grade will have higher dent resistance and are thus less likely to be distorted during the handling required for door assembly.

It should also be noted that the 660 grade was more robust to deviations from the preferred cushion pressure and lubricant levels. From the charts in Appendix B, it is clear that, although the strains were higher for the 548 grade, the variability of the strains for that grade was very high relative to the 660 grade when the cushion pressure or lubricant level were low.

Cushion Pressure. Since a high cushion pressure was preferred for the major strains and had little effect on the minor strains, a high cushion pressure is recommended. Current practice in automotive stamping is to run outer panels at the highest possible cushion pressure to maximize work-hardening for increased dent resistance [16].

Lubricant Level. The lubricant level suggested was inconsistent between the major strain analysis, which benefited from a low lubricant level, and the minor strains, which were increased when the lubricant level was high. In this case, increasing the minor strain is more important than improving the major strain, especially where the major strain is comfortably high (over 3%) and the minor strain is low (under 1%).

Several reasons exist for desiring minor surface strains of at least 2%. Most important, relatively large, flat surfaces have a tendency to buckle unless there is sufficient tension in the sheet to pull it taut in all directions. Such so-called "low spots" of only a few microinches in depth can be seen on a painted door with the naked eye. In addition, greater strain in the panel reduces the blank size required to form a part for a potential material savings. Finally, greater strain minimizes the amount of metal draw in over the drawbeads, which makes for a cleaner panel surface.

Thus, the data presented suggest that a high lubricant level should be used for these panels. Note that this is inconsistent with current practice of minimizing lubricant for automotive stamping [16]. Automobile stamping plants attempt to avoid excess lubrication because it increases material costs, increases environmental emissions, decreases the consistency of stamping results and may negatively impact downstream welding and painting operations.

The results from this experiment were very consistent between the sides. This provides a check for the data and suggests that the analysis is valid. On the basis of this study, these suggestions could be implemented with confidence for these particular panels, and could be used to reconsider lubrication practices and/or steel grade selection for other exterior panels.

5.3.2 Inner Panel Summary

From the thickness strain and distortion results, the following suggestions can be made for the cushion pressure, steel grade and lubricant level.

Cushion Pressure. High cushion pressure may be strongly recommended for the inner panels. A high cushion pressure resulted in greater thickness strains and reduced distortion, as expected.

Steel Grade. The surprising result for the inner panels is the recommendation to use the 019 steel grade. Conventional wisdom suggests that the more formable 982 grade IF steel is necessary for an inner panel, which is difficult to form due to its deep draw and many tight formations.

Given the 019 and 982 grade properties compared earlier, a few hypotheses may be developed to explain why the 019 grade outperformed the 982 grade for these panels. First, the 019 grade had a rougher surface texture in the longitudinal direction (all the splits occurred in this direction). It may be that the higher roughness improved adsorption of lubrication, thus decreasing friction and improving flow for this grade in that direction.

Second, the strength difference between the grades may have caused the difference in performance. The material properties suggest that the 982 grade will not be as strong as the 019 grade even after work-hardening. The higher strength 019 grade would resist splits while the 982 split if the stress in that area of the panel during forming was between the tensile strength of the 982 grade and that of the 019 grade (after adjusting for more thinning of the 019 grade due to its lower R-value and greater work-hardening of the 982 grade due to its higher n-value). The greater strength of the 019 panels may help them resist dents and dings during handling as well, although the distortion results did not demonstrate a clear reduction in average distortion for 019 grade inner panels.

Third, with respect to the thickness strains, it appears clear that the 019 grade will thin more than the 982 grade given its low R-values. By definition, a lower R-value means that the 019 grade will strain more in the thickness direction for a given amount of surface strain than the 982 grade. Since the surface strain is primarily controlled by the die geometry for this panel (as deep draws and steep formations act like draw beads in the panel), it is not surprising that the 019 steel was thinner in those areas after forming.

Finally, since these grades came from different steel suppliers with different coating processes, it is entirely possible that the lubricity of the 019 grade surface was higher, particularly when the lubricants used during this study were added at the stamping plant.

On the other hand, the results in Appendix B clearly demonstrate that the 982 grade was more robust to deviations in cushion pressure and lubricant level than the 019 grade for the distortion measure. The worst distortion values were obtained with the 019 grade. The variation of the 019 grade distortions were higher, and the difference between the average distortion between the levels of the cushion pressure and lubricant level were greater, than for the 982 grade.

In conclusion, the 019 grade appears to be better with respect to thickness strains and average distortions. The results, however, may be more variable than those for the 982 grade, particularly when other factors are not held consistently at their desired levels.

Lubricant Level. The evidence suggests that the low lubricant level may be preferable. As discussed for the outer panels, current practice in the automotive stamping industry is to maximize cushion pressure and minimize lubricant level (up to the point where splits become a problem), so these results are consistent with respect to those factors [16].

5.4 Door Assembly Experiments

The door assembly experiment results are summarized in this section. In addition, significant results related to the induction cure cycle and the steel grade / cushion pressure interaction are discussed.

5.4.1 Summary of Results

Table 14 summarizes the results on the data analysis. Note that for each output measure, only those factors for which one level could be recommended over the other are shown. Of the eight factors in the experiment, only four to six were significant for any given output measure. This implies that the process should be robust to either level of the other factors tested in this experiment. For example, the RMS x-Gap appears to be robust to the hemmer set points of -14.9 and -15.0. This does not, of course, guarantee what will happen with intermediate levels of the factors, such as -14.95, since the relationships between the variables involved are complex and likely nonlinear. Nor does it suggest what will happen if levels beyond the ones tested are used, such as -15.05.

Table 14. Door Assembly Experiment Data Analysis Summary

	RMS Flush	RMS x-Gap	RMS z-Gap	Avg. Hem Gap
Inner Steel Grade	982	982	019	-----*
Outer Steel Grade	548	548	660	-----
Inner Cushion Pressure	Low	Low	High	-----
Outer Cushion Pressure	High	High	Low	-----
Inner Lubricant Level	-----	-----	-----	High
Outer Lubricant Level	High	Low	-----	Low
Hemmer Set Point	-15.0	-----	-15.0	-15.0
Induction Cure Cycle	-----	-----	Off	Off

* ----- indicates that there was no significant difference between the levels of the factor for this output measure.

The table demonstrates the level of each factor recommended to minimize each output measure. On the basis of these results, trade-offs can be seen to exist between output measures. For example, the low outer lubricant level was preferred for two output measures (RMS x-Gap and Average Hem Gap) and, in contrast, the high outer lubricant level was preferred for one output measure (RMS Flushness). This is not to imply, however, that a low outer lubricant level would always be recommended.

An interesting aspect of these results was the degree of conformity for the levels of the factors between the output measures. In some cases, the results were very consistent. For example, the preferred levels to optimize RMS Flushness and RMS x-Gap are almost identical, with only the outer lubricant level in contradiction. On the other hand, some cases were very contradictory. For example, the inner and outer steel grades and cushion pressures preferred by the RMS z-Gap measure are the exact opposites of those preferred by the RMS Flush and RMS x-Gap measures.

The results for the inner lubricant level, hemmer set point and induction cure cycle appear to be clear cut, as no trade-offs are suggested by this experimentation. The analysis presents no evidence that the hemmer set point should be run at -14.9, which was not a surprise since the process was designed to run at a set point of -15.0.

Another clear result is that the inner lubricant level should be run low. This result is informative because automotive stamping plants have generally been trying to reduce the amount of lubricant used to improve strain in stamped panels and reduce problems that may be caused in downstream operations (such as the Paint Shop) by excessive residual lubrication.

5.4.2 Discussion of Induction Cure

Potentially the most significant result is that the induction cure cycle should not be used. The adhesive that was used at the plant was supposed to cure quickly at room temperature, and there was some debate about whether an induction cure would be worth the cost. To be safe, it was decided to put in the induction cure system. Although some experts felt that the induction cure system was unnecessary, no one went so far as to speculate that the induction cure process might actually <u>increase</u> distortion of the doors.

Some hypotheses were investigated as to why the induction cure cycle caused an increase in distortion, even though conventional wisdom suggests it should lead to a decrease. It was considered that perhaps the heat in the panels acts to release residual stresses. When these stresses are released, the panels will warp and hence those that are put through this thermal cycle will tend to be more distorted. Stress relief temperatures for low carbon steels such as the ones studied in these experiments, however, are normally greater than 1,000 degrees Fahrenheit [21]. Temperatures achieved in the panel during the induction cure process are an order of magnitude lower. Therefore, this is an implausible hypothesis.

Another potential cause is related to thermal expansion. The induction cure process would be expected to heat only the outer panel, as the inner panel is insulated from the outer by a layer of air and adhesive. Thermal expansion is given by:

$\varepsilon = \delta T\,\alpha = (70\text{ K}) \times (12\times10^{-6}/\text{K}) = 0.084\%$; and

$\delta L = \varepsilon\,L = (0.00084\text{ m}) \times (1\text{ m}) = 0.84\text{ mm}$;

where:

ε = thermal strain in the hem area due to induction cure;

δT = temperature increase in the hem area from the induction cure (70 Kelvin);

α = coefficient of thermal expansion for low carbon steel (12×10^{-6}m/mK) [21];

L = length of the hem area heated (approximated by 1 m); and

δL = thermal expansion of the outer panel in the hem area.

The values used in the formulation above are approximate and have been used only for a rough calculation. This calculation is sufficient, however, to note two important points. First, the thermal strain is relatively small and will not result in any significant plastic deformation of the outer panel. Second, the thermal expansion is very significant compared to the tolerances for gap and flushness.

As a result, it seems that thermal expansion may be the cause of additional distortion for panels subjected to an induction cure. The following mechanism is hypothesized for this condition. First, the outer panel expands as it is subjected to the induction cure, while the inner panel does not, causing the outer panel to slip significantly relative to the inner panel. Second, the hemming adhesive may cure and lock the outer panel in place before it returns to its ambient length. Third, the outer panel cools to ambient temperature and would normally contract to its original length. As it is locked by the adhesive, however, it will be unable to contract and will be put into compressive stress. This causes buckling or other distortion around the hem.

The length of the door is greater than its height, so the thermal expansion will be greater in the x-direction than in the z-direction. In addition, there is no hem on the top of the door (where there is an opening for the window). As a result, the door would be expected to distort in complex ways that would affect the x-gap, z-gap and flushness. Interestingly, the induction cure did not have a detrimental effect on the x-gaps in this experiment.

5.4.3 Discussion of Steel Grade / Cushion Pressure Interaction

Another question is why the more formable steel grades (982 inner and 548 outer) with a low inner cushion pressure and high outer cushion pressure were preferred for the RMS Flush and RMS x-Gap measures, but the less formable grades (019 inner and 660 outer) with a high inner cushion pressure and a low outer cushion pressure were preferred for the RMS z-Gap measure. The hypothesis developed in this section relates to the trade-off for outer steel grades presented in Section 5.3.1.

Looking first at the x-direction, the outer panel formed with the 548 grade and a high cushion pressure will have relatively high surface strain. It will also have a relatively low level of residual stress in the sheet and an intermediate level of strength (lower than for the 660 grade, but higher than if it had been run with a low cushion pressure). The 660 grade, with its higher strength and greater resistance to dings and dents that could distort the hem, will have a higher residual stress. In the x-direction, with a hem on both the fore and aft edges of the door, the residual stresses appear to dominate the potential distortion effects.

On the other hand, in the z-direction it appears that the lower strength of the 548 panels may have been more of an issue since they were more distorted. In this case, the lower strength 982 inner panel, which provides most of the structural rigidity for the door, may have hindered the door's resistance to distortions caused in the z-direction during handling and the hemming process.

It was expected that residual stress or lower strength effects would have consistent results in both the x-direction and z-direction, yet these data suggest they do not. Hemmer timing or the fact that the unhemmed top edge of the door is less rigid than the mechanically locked edges could subject the panel to greater stress in the z-direction, hence making strength more important in that direction. Such strength-related issues may be less of a factor when the details are included in the door assembly, since they provide the majority of the structural strength of the door.

There are two hems to bend over in the x-direction, both subject to distortion from residual stresses. In contrast, there is only one hem in the z-direction (on the bottom edge). This difference could account for the greater role of residual stresses in the x-direction.

The steel grade / cushion pressure interaction is a complex phenomenon since four factors (two steel grades and two cushion pressures) are interacting at once. As the experimental design did not permit for the evaluation of four-way interactions, it is difficult to be precise about the mechanisms involved or the optimal levels of each factor.

CHAPTER 6. IMPLICATIONS FOR PROCESS CONTROL

6.0 Introduction

This chapter considers control of material properties, control of important stamping process parameters, control of hemming process parameters and control of significant stamping/hemming process interactions [4, 14, 15, 17].

6.1 Material Property Control

On the basis of the material property tests performed on the four grades of steel used for this research, the following recommendations are made for maintaining control of material properties.

The optimal strategy is to carefully measure and monitor a few important process control variables. Every coil received should be tested, either at the stamping plant or in the steel mill before shipment [17]. All major suppliers of steel coils to the automotive industry check their own coils for material properties before shipment and can provide the results of their tests to their stamping plant customers, although the stamping plants may want to certify the mills' testing processes.

Previous research discusses the development of a "window of properties" for received steel via stamping plant testing [16, 18]. This approach uses the first 30 coils received for each steel specification to develop an acceptable range for the properties of interest. Subsequent coils that do not fall within the range established by the first 30 coils are not accepted. The drawback to such an approach is that it is not clear whether the properties of those first 30 coils were in a state of statistical control.

An adaptation of this methodology that overcomes this handicap would be to develop a Shewhart (x-bar and R) control chart for the most important material properties based on the first 30 coils. The chart should be examined for evidence of statistical control [2, 7, 13, 15]. Deviations from the control limits should be investigated to examine the root cause of the problems, working in partnership with the steel supplier. Subsequent coils should be rejected if they fall outside the control limits only after statistical control has been demonstrated and the control limits are within the specification limits for the material properties. Up to that point, they should only be rejected if they fall outside some predetermined specification limits (based on the best available estimate of the range of variation that may be tolerated by the process).

Not all of the tests performed in this research would need to be used in production. Most importantly, tensile tests should be performed for either the longitudinal or transverse directions (or both) of the coils. From these tests, at a minimum the yield strength, n-value and R-value should be monitored. The tensile strength and percentage elongation could also be tracked, since they would be available from the tensile test results, although they are closely correlated to these other factors. The gauge of the coils should also be monitored over time.

Many of the other tests described seem to have limited value for production. The hardness test would be useful if no tensile tester was available, but otherwise is unnecessary. The LDH test, although a theoretically superior predictor of sheet formability, appears to be too variable to be reliable unless numerous samples are taken and averaged per coil. In addition, roughness tests to determine Ra and/or PPI have limited value unless additional research is performed to determine whether high or low roughness is preferred for a given part and coating type.

6.2 Stamping Process Controls

The stamping and door assembly experiments indicate that both the cushion pressure and lubricant level are important press line parameters for inner and outer panels. On this basis, CUSUM control charts [13, 19, 30] are recommended to monitor these parameters during and between production runs. This should be straightforward for cushion pressure, as modern press lines provide actual cushion pressure data on their computerized display screens. The gages used for measuring cushion pressure must be in control and capable.

Lubricant level measurement is another matter. It may be possible to adequately gauge the flow of lubricant onto the blanks as they are loaded onto the stamping press line, but the distribution of lubricant across the sheet is more important than the total amount of lubricant applied. This is a critical factor that is difficult to measure. In addition, it would be necessary to eliminate or somehow measure any extra lubricant applied manually before the draw press.

The use of CUSUM control charts is deliberately recommended for these variables, rather than the Shewhart control charts recommended for the steel material properties. As described in detail by James [19], the CUSUM control chart can identify small shifts of the mean of a process more rapidly than the Shewhart chart. In addition, the Shewhart chart is technically only appropriate for statistically independent samples. In the case of a single sample from each coil of steel, this is a good assumption. In the case of cushion pressure on successive strokes of the same press, this is a very poor assumption. For these reasons, CUSUM charts are a preferred method of process control for processes (like stamping or hemming lines) where process parameters are likely to trend slowly up or down over time.

6.3 Hemming Process Controls

This research identified the importance of controlling the hemmer set point. The hemmer set point is unlikely to change significantly over a short period of time unless a problem occurs such as a "crash" of the hemmer dies. Eventually, the dies will wear or a linkage in the machinery will slip and an adjustment will be required to bring the hem gap back to the exact distance called for by the hemmer set point.

Because of the expected slow nature of such degradation, it is not necessary to monitor the hem gap in real time. Rather, this parameter should be monitored periodically over time. A CUSUM chart would be useful for this process because the wear would be expected to follow a gradual trend. Therefore, hem gap measurements are likely to be highly autocorrelated.

This research does not imply that the induction cure cycle should be monitored in any way, it implies that it should be turned off. Follow-up research, or other considerations, however, may suggest that an induction cure is required. In this case it may become necessary to monitor panel temperatures periodically to ensure that they do not drift out of control. A variety of devices could be used to measure surface temperature in the panels, although some investigation would be required to determine the capability of these measurement processes.

It would not be practical to measure every panel. Instead, a periodic test of panel temperature should be made. A CUSUM chart would be the most appropriate monitoring device, since the process would be expected to drift out of control slowly over time and subsequent measurements are likely to be autocorrelated.

6.4 Stamping / Hemming Process Interaction Controls

Finally, the research looked to identify opportunities where data could be fed forward from the stamping process to control the hemming process. Although several instances of significant interactions were found between stamping and hemming process parameters, none were sufficiently strong to suggest an advantage by such adaptive process controls (APC).

For example, the significant interaction between outer lubricant level and hemmer set point for the average hem gap suggests that the hemmer set point should be set at -15.0, regardless of the outer lubricant level used in the stamping plant. The advantage provided by this hemmer set point was significantly different depending on the outer lubricant level, but the direction of the effect is still the same.

Although it would be interesting to find opportunities for APC, it is noteworthy to see that such a complex system development may not be necessary in this environment.

Despite the fact that the stamping and hemming process parameters interact in significant ways, the door assembly process appears to be designed to be robust to such interactions.

No APC is recommended based on the results of this research. This does not mean, however, that such opportunities do not exist. It may be advantageous to develop an information system that can integrate readings between the stamping and hemming processes. Such a variable monitoring system could be used to correlate large quantities of actual production process data that could be used to suggest opportunities for implementation of APC that would be robust to the normal variations of the production environment.

CHAPTER 7. CONCLUSIONS

7.0 Introduction

This chapter summarizes the recommendations from this research for improving steel characterization and minimizing door distortions through the door assembly system. Observations from the experiments important to future research in this area are presented.

7.1 Improving Steel Characterization

1. Limited resources available for testing material properties for steel should be focused on performing the few most important characterization tests. The tensile test is recommended where available.
2. Whatever tests are used, statistical process control (SPC) with Shewhart (x-bar and R) charts should be used to monitor trends of material properties over time and identify coils that should be rejected. This method has advantages over the "window of properties" approach.
3. All material sampling and testing of directional properties should be done in a standardized direction, preferably the direction that is most critical for the part based on die and material considerations.

7.2 Experimental Results for Minimizing Door Distortions

1. Highly formable inner and outer steel grades proved to be best for RMS Flush and RMS x-Gap measures, but stronger and less formable inner and outer steel grades were best for RMS z-Gap.
2. Low inner cushion pressure and high outer cushion pressure were optimal for RMS Flush and RMS x-Gap, but the preferred levels were reversed for RMS z-Gap.
3. A high inner lubricant level was best for the Average Hem Gap.

4. A low outer lubricant level was best for the RMS x-Gap and Average Hem Gap, but a high outer lubricant level was best for the RMS Flush.
5. The hemmer set point should be maintained at -15.0. A set point of -14.9 increased the RMS Flush, RMS z-Gap and Average Hem Gap.
6. The induction cure cycle should not be used as it increased RMS z-Gap and Average Hem Gap.
7. Trade-offs exist between these variables and should be resolved depending on plant-specific priorities or concerns.

7.3 Other Recommendations

This section prescribes other recommendations for future efforts to reduce door distortions in automobile assembly plants. These recommendations are based on the data analysis from the experiments in this research.

7.3.1 Global Versus Local Optimization

The different results from the stamping and door assembly experiments serve as a reminder for thinking globally, rather than concentrating on local optimization. The stamping plant exists to satisfy the requirements of downstream assembly processes, including the door fitting operation. The parameters that are known to be important to downstream operations are used to define the objectives of the stamping plant. The door assembly experiment suggests that some of the stamping parameters that will help the body shop optimize door fits are in conflict with these local stamping objectives.

For example, the door assembly experiment identified a preference for a low outer lubricant level for some output measures, whereas the stamping experiment led to the recommendation to use a high outer lubricant level. Likewise, the inner panel stamping experiment showed a preference for a high inner cushion pressure, 019 steel grade and a low lubricant level. Yet two out of three door output measures were better off with a low inner cushion pressure and the 982 steel grade, and the Average Hem Gap was improved with a high inner lubricant level.

These specific examples indicate the need for supplier processes to understand their customer requirements and measure their performance against those requirements. Of course, the stamping plant has multiple customers, and those customers (including the hemming process) have competing requirements. If a high outer lubricant level improves panel dent resistance, that may be preferred over a low outer lubricant level that reduces door distortions. Those trade-offs should be made explicitly with a full understanding of the consequences of these parameter choices. Much work remains to obtain that level of understanding of how stamping process parameters affect downstream operations.

7.3.2 Variable Interactions

Another important lesson from this research is the need to consider the interactions between variables. The physical and metallurgical properties of the steel, the process and tooling design and maintenance and the stamping and hemming line run parameters all interact in complex and little understood ways. Any serious effort to define the optimal level for one or more process parameters, even if in different stages of the production process, should consider the interactions of these process parameters rather than optimizing each variable independent of others.

The Average Hem Gap output measure is an example. In two cases, a preliminary assessment of the means and variances indicate that a certain level would be preferred. Yet after looking at the significant interactions involved, it became clear that those were not the best levels of those factors to consider.

The problem with looking at interactions is that there are so many potential factors to be considered (Appendix A) that not all of them can possibly be analyzed in one experiment. Nevertheless, a careful examination of relevant research and survey of expert knowledge can help define some of the more likely candidates. That was the approach taken in this research.

A related caution is to be careful with the experimental design [12]. The unbalanced design and limited sample size that was achieved in the door assembly experiment prevented the assessment of interactions of higher order than the two-way interactions considered. This limited the results of this research. Due attention should be paid to experimental design and planning for contingencies (such as splits in the stamping press or bent panels in the hemming line) that can disrupt experimental objectives.

The door assembly experiment results illustrate this point. The differences between the levels of the factors for the two-way interactions shown in Appendix E are generally easier to observe than for the main effects shown in Appendix D. The main effects, of course, include both levels of all factors except the one directly compared, and these factors may create a great deal of variation in the data that can mask the significance of these main effects. The more factors that can be broken out from the data, the more easily the effects of the levels of each factor may be distinguished, although the number of data values required increases exponentially to achieve this increased resolution.

7.3.3 Reducing Variances Rather than Means

In the analysis of experimental results, it is important to consider the effect that each level of each factor has on the variance of the output measures, rather than to focus principally on the impact on their means. In general, it is easier to adjust process tooling or assembly procedures to shift the mean of a process output than it is to reduce the inherent variability in that process.

Problems requiring a change to the mean of a process often required significant investigative work to determine the source of the problem and make an appropriate tooling adjustment, but are generally solvable [10, 11]. Variation reduction, on the other hand, may be rendered inherently insolvable once the process has been designed, installed and is running in a production mode. Variations of door shape lead to costly manual door fitting in the body shop, while a consistent problem can often be corrected with a shim or the move of a tooling pin. Therefore, improvement programs would do well to focus on variation first and to consider the mean of the process as a secondary criterion.

As a result of such considerations, it may be best to choose a material that is less desirable on average, but exhibits less variation. For example, the 982 grade inner steel had a higher average distortion than the 019 grade. Yet it is more robust to process variations for cushion pressure and lubrication level and had a lower distortion variance.

7.3.4 Other Sources of Variation

Finally, it is important to keep the importance of this research in perspective. Although statistically significant relationships were found for these factors, it is not clear how important the magnitude of their effects are in the overall environment of the assembly plant. The experimental panels were carefully monitored and as many sources of variation as possible were eliminated. Although the effects found in this study were significant under these conditions, it may be that they are only a minor factor in the overall scheme of door fitting variation.

One study was done to assess door fit process capability at the assembly plant where this research was conducted. It suggested that the variation that can be explained by the factors considered in this study is approximately 10-30% of the total variation in the process through the body shop. Additional variation occurs downstream in the paint and trim shops. This is not to say that these results are unimportant. It does, however, indicate that there may be higher priorities for gaining control of the process to improve door fits than those presented in this paper for that particular assembly plant.

CHAPTER 8. SUGGESTIONS FOR FUTURE WORK

8.0 Introduction

This chapter describes the need for future research. Suggestions for future work are summarized for material characterization, stamping and door assembly. It closes with suggestions for using a process improvement team to study door distortion issues.

8.1 Suggestions for Material Characterization

The LDH test was highly variable and multiple samples would be required to properly characterize a coil. If an automotive stamping plant intended to make use of LDH results for material sampling and control, it should study the causes of variation for this test and work to reduce them [33, 34, 37].

The surface profilometer results were also highly variable. The literature suggests the draw bead simulator test as a potentially preferred method of characterizing surface friction [17, 38]. This test can consider sheet surface morphology, coating type and lubricant adsorption together with their interactions. Although this thesis did not evaluate this test, it could be productive to investigate such a method for characterization of material frictional properties.

This research demonstrated that directional properties will differ for different steel grades, primarily as a function of different processing methods at the steel mills where the coils are produced. As a result, standardized sample orientations should be established for all material testing of directional properties. The samples should be oriented in the direction that is most critical for the part(s) to be stamped from a given coil based on die and material considerations.

8.2 Suggestions for Stamping

The consistency and low variation of the stamping experiment results offer substantial confidence that they are valid. Suggestions for future work are presented for outer panels, inner panels and overall stamping plant issues.

8.2.1 Suggestions for Outer Panels

This study confirmed the need to maximize cushion pressure. It left open the question of whether the 548 or 660 grade would have better dent resistance based on the 660 grade's higher initial tensile strength and the 548 grade's higher rate of work-hardening and greater surface strain. Follow-up research on the dentability of panels formed with these two grades could be beneficial. This result could be extended to other exterior panels as well [36].

In addition, the study rejected the notion that low levels of lubrication are necessary to achieve acceptable surface strains. On the contrary, it appears that high lubricant may allow higher minor strains to be achieved. There could be reasons why lubricant level should be minimized other than strain, of course, such as reduced material expenditures, reduced emissions and disposal, and improved paint adherence. Nevertheless, high lubricant levels are worth further investigation and/or implementation for these and other exterior panels where surface strain is important.

8.2.2 Suggestions for Inner Panels

The inner panel research confirms the need for high cushion pressure and low lubricant for inner panels, consistent with current objectives. On the other hand, it suggests that, in some cases, a higher strength, lower formability product may actually have greater thickness strains and less distortion than the more formable, and expensive, types of steel normally selected for these applications. Some causes of this result have been hypothesized above, but additional research is required to determine exactly what factors are important.

8.2.3 Other Stamping Suggestions

During the experimental runs, substantial variation in press gage readings were observed, particularly on the Danly tandem press line used to run the outer door panels. Efforts to improve gauge repeatability would assist efforts to maintain a consistent process on this line [12, 17].

A more fundamental problem was the transient start-up behavior exhibited by the stamping lines during the experimental runs. Both lines had been idle for hours immediately prior to running the experiments, and the first few panels ran without difficulty. Less than ten panels into the run, however, conditions that generated no splits the first few panels resulted in splits every time. Plant stamping experts and the literature did not provide a good explanation for this behavior. It would be worthwhile to engage in research to understand the causes of this phenomenon.

8.3 Suggestions for Door Assembly

The inconsistency between the left and right-hand sides and the high variability of results observed in the door assembly experiment is an area of concern. Although the left to right consistency check increases the confidence in these results, follow-up experimentation is recommended to confirm the major conclusions before implementing any of the suggested changes to the levels of the factors. This section suggests follow-up research for the induction cure process, the steel grade/cushion pressure interaction and to check for nonlinear effects. Confirmation experiments are recommended before adopting any of the door assembly conclusions obtained from this research.

8.3.1 Suggestions for Induction Cure

This research indicates that the induction cure cycle should not be used. Elimination of the requirement for induction cure stations in hemming lines could save millions of dollars in future vehicle programs for automotive assembly plants. In addition, it could immediately decrease hemming line cycle time, electricity costs and maintenance effort if the existing induction cure systems were removed or shut off from the line. Consistent with the objectives of this study, door fits should improve due to reduced door distortions.

A conclusion with such broad implications should not be taken lightly. Additional research on doors with and without induction cure is recommended. A simple experiment could be devised to test doors using the full hemming line process (with all details included) but no experimental factors other than running some with induction cure on and some with it off. Such an experiment should be run on both sides for a validation check. The panels could then be checked for flushness and gap on the R1 gage and the conclusions of this experiment could be either supported or refuted with a larger sample size for greater confidence.

8.3.2 Suggestions for Steel Grades and Cushion Pressures

A largely unexplained result was the divergent results between the RMS Flush and RMS x-Gap measures on the one hand, and the RMS z-Gap on the other, with respect to steel grades and cushion pressures. An experiment could be run to test the two combinations supported by this experiment against each other with respect to gap and flush of finished door assemblies. The two combinations are:

1. 982 inner steel grade, 548 outer steel grade, low inner cushion pressure and high outer cushion pressure; and
2. 019 inner steel grade, 660 outer steel grade, high inner cushion pressure and low outer cushion pressure.

Preferably, a factorial experiment testing all combinations of these levels of these factors (and their interactions) could be employed, although such a design would require more samples [12]. In either case, it would be useful to understand if there really is a trade-off between these combinations of factors, as suggested by this research. It would seem that the same combination of factors should be best for all output measures, and such a follow-up experiment would be able to identify that combination.

8.3.3 Suggestions to Check for Nonlinear Effects

It is important to consider that only two levels of the factors were evaluated in this experimentation. It is likely that nonlinear effects are involved for many of these variables and that the relationships between them are quite complex. Employing three levels of some factors for follow-up experiments would test for such nonlinearities and assist with process optimization. The sample sizes required would be larger, so factors to include at more than two levels should be judicially selected based on these results and sound physical principles [12, 28].

8.4 Suggestions for a Process Improvement Team

A team of personnel including experts in metallurgy, mechanics, controls, stamping, hemming and statistics should be formed to study the problem of door distortion. Representatives from stamping diemakers, hemming toolmakers and the hemming line process could contribute their experiential knowledge and assist in running the experiments.

One of the above team members should serve as a full-time team coordinator. It is very difficult for a person with line responsibilities to devote adequate effort to such a long term improvement program over the pressures of an automobile assembly plant in production. A dedicated team resource who is responsible for getting it done and has no formal production responsibilities may be necessary to maintain a reasonable pace of progress. It may be best for such a person to report out of the normal Stamping Plant or Body Shop organizations to preserve their independence.

Academics, either faculty or student researchers, could be useful on such a team and could even serve as the team facilitator. They should not, however, become the primary keepers of the team knowledge, as a myriad of small pieces of relevant information will be lost when their necessarily limited time to be at the plant is over. Maintaining this knowledge in an improvement team will help retain this information and facilitate organizational learning.

The follow-up research suggested in this thesis would be expected to account for only a portion of the total variation in door fits. As with any improvement activity, the team should prioritize its efforts on those factors that are most significant. Although this research attempted to identify the most important factors to consider, there may be others that have a larger influence on the process variability. If such factors are found, they should be prioritized appropriately.

APPENDIX A. PROPERTIES AND SOURCES OF VARIATION

The most significant sources of variation for the production processes and material properties of the door assembly system were shown in Figure 8 (Chapter 2). These factors are described in this appendix. They are divided by stage of the process:

- sheet steel properties;
- blanking process parameters;
- blank properties;
- stamping process parameters;
- finished panel characteristics;
- detail parts properties;
- hemming process parameters; and
- assembled door properties.

A.1 Sheet Steel Properties

- Hardness. Hardness tests (such as Rockwell or Brinell) measure resistance to plastic indentation, which has been shown to correlate with tensile strength. The hardness test is much easier to implement in a production environment than a tensile test and is used often in practice to roughly characterize sheet steel. Hardness is a poor predictor of material formability since the nature of the strain imposed in a hardness test is different from that experienced during stamping. However, it can be useful as a rough guide to compare sheet properties [16, 21, 22].
- Limiting Dome Height. This test measures the point of fracture of a sheet subjected to stress from a circular punch. The sheet is constrained by a bead in one direction, which simulates the binder action in the dies. The literature suggests that the LDH test is a theoretically preferred way to evaluate formability as compared to many of the other tests discussed here, because it is more representative of the actual stamping process. However, the test is not highly reproducible in practice, so the automobile stamping industry has taken a skeptical approach to the LDH [14, 16, 22, 34].
- Microstructure. Grain sizes and orientations, and dislocation density, have an effect on many of the specified properties. These parameters are controlled by the steel mill to give the sheet the properties requested by the plant. Inclusion and second phase particle content and distribution is likewise carefully controlled by the steel mill to impart the desired properties and prevent fracture during stamping. Localized stresses at inclusions and second phase particles may cause sheet splits at stamping, particularly for relatively thin gage sheet. Although important, such factors are difficult to

measure in a production environment and automobile stamping plants rely instead on the macroscopic property tests described in this section [24, 25, 39].

- Percentage Elongation. The greater elongation that a sheet can accommodate before fracture, the less chance of failure during the forming processes of drawing and stretching. A sample of the sheet may be checked for percentage elongation in the gage length by the tensile test. A variety of methods can be used to check the strains developed in the sheet during production. These include thickness strain analysis and circle grid analysis for off-line inspection [8, 16, 20, 21, 22, 39, 40].
- Strain aging. The paint baking operation may cause sheet steel panels to strain age after hemming. Bake-hardenable steels are available that will show a substantial increase in yield stress due to strain aging at these temperatures for this amount of time, although they will not strain age in normal storage, even after long periods of time. However, most galvanneal and electrogalvanized sheet steel in use will not significantly strain age in the paint bake process. Automotive sheet is not exposed to high enough temperatures to cause dynamic strain aging or blue brittleness in the normal manufacturing process [9, 39].
- Strain rate sensitivity (m-value). The literature suggests that the m-value could be an important parameter for stamping operations. A higher m-value leads to more uniform deformation. The metal will strain at a higher rate and thus harden more in the areas of greatest strain, helping to prevent necking and fracture. The forming rates used in automobile stamping, however, may not vary enough to make the m-value of practical significance. In addition, the m-value is temperature-dependent, which could make it difficult to apply as a predictor in practice. For these reasons, as well as the difficulty of measuring the m-value in a production environment, it is not used in practice [9].
- Strain to fracture. This test is often used as an estimator of yield strength. The Olsen test is similar to the LDH test described above, but in this case there is no binder ring to prevent metal flow. The literature indicates that this test is a poor predictor of formability, although it does a better job of simulating the actual biaxial strain condition of a sheet in the stamping process than a single axis tensile test. It is more of a drawing test than a stretching test. In practice, the Olsen test has been found to be highly variable [22].
- Surface cleanliness. The surface of the sheet should have an even layer of mill lubricant to prevent rusting and decrease friction. Not only must the steel mill carefully control coating thickness, but also the lubrication can dissipate over time so surface cleanliness may be a function of coil size and storage time. The sheet surface should be free of excessive surface carbon and microscopic surface defects [15].

- Surface Coating Adhesion. A Double Olsen test can be used to check surface coating adhesion on received coils to minimize this problem. The test forms a bubble on a small sample in one direction, then reverses the bubble without fracture. The degree of flaking in this severe deformation is contrasted with standards to check the acceptability of the coil [18].
- Surface coating morphology. Surface coatings (such as galvanneal) will have an effect on friction. Downstream, these may also affect the efficacy of adhesives at the hemming operation and the performance of welding guns. For galvanneal and electrogalvanized steel sheet, the frictional forces on the sheet are higher than for uncoated sheet. Hot dip galvanized sheet, however, has lower frictional forces [9, 14, 16, 23, 41, 42].
- Surface quality. This term represents the visual uniformity of the sheet, including such defects as slivers and roll marks. In general, automotive customers identify more problems with surface quality than the mechanical properties of the coils they receive [15].
- Surface (macroscopic) Texture. The surface roughness can have two different effects on formability. On the one hand, greater roughness increases frictional forces between the sheet and the die surfaces and can therefore restrain the flow of the steel for a given press tonnage. Conversely, roughness may improve lubricant adsorption on the sheet and lead to a net decrease in these frictional forces. The overall impact on friction could be positive or negative [14, 16, 40, 42].
- Temperature dependence. This can be a factor, particularly for heavy gauge parts that generate substantial heat during cold working. The tensile strength of the steel varies inversely with temperature, and the die may expand as it heats, thus decreasing part clearances. These and other effects may result in splits as the dies get hot, even though the press may have been forming perfect parts at start-up [31].
- Tensile strength. Higher tensile strength steel can accept more stress and hence better resists fracture during stamping. However, springback and distortions become a greater problem when more residual stress exists in the panel. The ratio of tensile strength to yield strength is desired to be as high as possible, and is positively correlated with the n-value of the material [9, 17, 19, 22].
- Through-thickness plastic anisotropy/drawability ratio (R-value). The R-value is a measure of normal plastic anisotropy defined by the ratio of the true width strain to the true thickness strain of a sample in a tensile test, i.e. $R = \varepsilon_{width} / \varepsilon_{thickness}$. This is particularly important for drawing operations. When the strain in the plane of the sheet is positive in one direction and negative in another, the crystallographic

microstructure affects the strain that occurs in the plane of the sheet versus the thinning involved. The higher the R-value, the less the sheet will thin and therefore the less chance there is for necking and fracture. The R-value can also be measured by a tensile test [9, 14, 16, 17, 22].

- Variations between suppliers and locations. It is expected that the same steel (in terms of specifications) will vary (in terms of properties) depending on the supplier from whom the steel is ordered and the location at which it was produced. This is largely a result of different equipment capabilities and operating practices at the different mills. To minimize variations, most suppliers try to ship each specification from a particular mill on a consistent basis.
- Work hardening exponent/Stretchability (n-value). This is particularly important for stretching operations. In a state of biaxial stretching in the plane of the sheet, the metal will thin. The higher the n-value, the more the sheet will work harden as it thins and therefore the deformation will be more evenly distributed within the plane of the sheet, reducing the chance of necking and fracture. The n-value varies inversely with carbon content and is correlated with the percentage elongation. A tensile test can be used to determine the n-value [9, 14, 16, 17, 22].
- Yield strength. In stamping, lower yield strength enhances formability. The higher the yield strength, the greater the press tonnage and the less binder pressure required. As yield strength increases, elastic strain increases and springback becomes a bigger problem. However, a low yield strength in a finished panel has a negative impact on dentability. Therefore, it is desirable to increase yield strength from a low value prior to stamping to a high value afterwards, due to work-hardening and, (in the case of bake-hardenable steels), thermal treatments [9, 14, 16, 20, 22].

A.2 Blanking Press Parameters

- Die cleanliness. The dies must be cleaned regularly for at least two reasons. First, dirt particles and grinding dust on or inside the dies can blow onto the surface of either the die or panel due to the air velocities developed within the die cavity. These can score the die and/or panels. Second, the dies can rust, leading to dimensional changes in the die and an increase in the coefficient of friction for rusty mating parts [9, 14].
- Die maintenance. The condition of the dies is critical to part consistency. The steel surfaces that will be in contact with the sheet will eventually wear, although this may be mitigated by chromium plating. Slow wear implies that the blanks would be expected to have a very slight progressive trend in their dimensional properties. It is

necessary to maintain the dies so they do not wear to the point where critical dimensions of the finished blanks go out of tolerance [9].

- Line speed. The faster a blanking press line is run, the more parts that can be made in a given time period. Naturally, the plant wants to maximize their productivity, so they want to run the blanking line as fast as possible. The press and sheet handling equipment capability constrains the line speed at which the blanker may be run. There is a window of line speeds at which a given part can be formed. If that window is exceeded, metal surface distortions can result. The factors influencing this window of line speeds include the strain rate sensitivity of the steel and the thermal expansion of the die as less time becomes available for heat produced by the friction and shearing operation to dissipate [9, 15, 16].
- Lubrication. Lubricants are added at the blanker to clean the sheet and decrease the frictional forces developed during the blanking operation. The sheet also has a coating of lubricant put on the coil by the steel supplier to prevent rust. These lubricants reduce friction and facilitate metal flow in the blanking and (later) stamping operations [9, 15, 16, 43].
- Press capability. To produce consistent parts, the press should have appropriate tonnage, speed, indexing and gauging capabilities. Presses must be carefully specified to match the requirements of the parts they will be running. Good maintenance is essential to maintaining press capability over time [16, 32].
- Press gage capability. To properly control a complex process like a blanking or stamping press, you must have accurate measurements of the process control variables. Modern presses provide frequent data on process parameters. If the gages that make the measurements are either off nominal or have a high degree of variation in their readings, they could induce variation in the process by causing the operators or the press PLCs to make adjustments that they should not be making [13, 14, 16, 17].
- Press parallelism (levelness) and flatness. Parallelism or levelness measures the degree to which the surface of the bolsters that hold the bottom dies are parallel to the main slide of the press that holds the top dies. Over a shut height of several feet, a very slight out-of-level condition can cause a significant difference in the force applied at one side of the die versus another. Likewise, if either the bolsters or the main slide has a crown or other off level condition, the middle may hit harder than the edges, or some other uneven force may be applied during the stroke. For these reasons, press levelness and flatness are carefully measured and controlled over time with a periodic maintenance program [14, 17, 31].

- Press tonnage. This is the amount of force applied to the ram that actually guides the top half of the die to mate with the bottom and hence to shear the steel sheet. The press tonnage is measured in each corner of the die, as well as a total value, in order to see if the force is applied evenly across the die. Press tonnage is measured and may be used as a process monitoring parameter, but it is not set directly. Some of the tonnage is absorbed by the bottom blocks of the press and some is used to form the blank [16, 17, 31].
- Standard Operating Procedures (SOPs). The blanking process is sensitive to shifts in a number of process parameters. Detailed SOPs for set-up are critical to consistency between runs. This is increasingly important as blanker batch sizes are decreased and set-ups become more frequent [14, 15, 16].
- The work group. Primary controllable attributes of the work force are its training, experience, skill and stability. These factors are closely related. More training and stability will increase experience and skill of the work group that must support the blanking press. Proper incentives can insure adherence to set-up and running SOPs and an emphasis on product quality and equipment maintenance [16].

A.3 Blank Properties

All the properties of the incoming steel are still relevant in the blank stage, although they may have been altered somewhat in the blanking, handling and storage processes. In addition, the following characteristics are important to the stamping press lines.

- Blank dimensions. The width and length of the blank are critical, especially for the draw operation. The amount of material in the binder affects the frictional force required to draw material in from the binder area. Too much force can result in insufficient metal drawn in (causing splits), while too little force can result in too much metal drawn in (causing wrinkles, buckles and pinches) [9, 14, 16].
- Blank edge quality. Burrs and other sharp discontinuities at the edge of the blank may initiate splits or other problems in the stamped part [9, 14, 16].
- Blank flatness. If the blank is wavy, it can sit poorly in the blank gauging for the draw die, leading to inconsistent forming, wrinkles or splits. If the gauge is inconsistent, the friction and yield force effects listed for blank gauge can cause local problems in the panel. Interestingly, all steel coils have some crown to them so the blanks will never be perfectly flat. Dies should be designed for a normal crown [14, 15].
- Blank gauge. The gauge has a significant influence for two primary reasons. First, the forces required for drawing, stretching and fracture vary with the gauge. Thicker

gauges shift the forming limit diagram (FLD) up but require additional force to form. Secondly, the dies are designed for a certain gauge. Variations off this gauge will cause frictional binding forces to differ from design intent as the part will not fit properly to the binder. Blank gauge may vary along the length of a coil (particularly near the head and tail) and from coil to coil [9, 14, 16].

A.4 Stamping Press Parameters

All of the critical parameters discussed above for the blanking press apply to the stamping press as well. Other factors that must be considered for the stamping press line are described below.

- Blank placement (gauging). The placement of the blank is critical, especially for the draw operation. As discussed for blank dimensions under material properties, the amount of material in each side of the binder affects the frictional forces required to draw material in from that side of the binder area. If the blank is placed too far to one side or another, it will result in excessive frictional force (potentially causing splits) on that side and insufficient frictional force (potentially causing buckles) on the other side [9, 14, 15, 16].
- Cushion and binder pressure. These pressures are among the most critical press settings. The binder pressure is set by a "cushion" of nitrogen or air pressure under the bolster. The compressed nitrogen pushes a steel plate up, which in turn pushes a set of cushion pins up. These cushion pins contact the bottom of the binder and move it up in relationship to the rest of the die. Hence, the binder holds the steel sheet tight between itself and the top half of the die. As the cushion pressure is increased, the binder pressure also increases and a greater amount of force will be applied normal to the sheet. This will increase the frictional force between the sheet and the binder and decrease the tendency for metal to flow from the binder into the die.

  If the binder pressure is too low the sheet will flow excessively into the die and will buckle as compressive stresses are applied. This may cause "oil canning," where the metal flows without any residual tension and work-hardening being imparted to the sheet. In this case long, flat surfaces of the panel readily deform, causing low spots and dents in outer body panels such as doors, hoods and roofs. Increased binder pressure increases strains in the panel and resistance to denting. As a result, stamping plants attempt to maximize binder pressure for outer closure panels. On the other hand, too much pressure will prevent the required plastic deformation of the sheet, causing it instead to neck and split. For inner panels, which typically have more radii and formations, less binder pressure is usually desired because metal flow is more important than developing good strain across the panel [9, 14, 15, 16, 31, 37, 44].

- Die hardness. Soft mating surfaces can lead to increased friction and galling as the die hits the panel. Chrome plating or other methods to increase the hardness of mating die surfaces may increase their lubricity, decrease friction and improve part flow. Silicon from die grinding operations or other hard particles are also less likely to become imbedded in the working area of a harder die, helping to prevent gouges in the galvanneal coating on the sheet and pimples and dings on the finished panels. Dirt on finished panels is often a function of the dies being too soft, as well as the cleanliness of the work area and the incoming steel sheet [35].
- Die and binder maintenance. The condition of the dies and binder will be critical to part consistency. Trim and cam dies tend to require more frequent maintenance than forming dies. The steel surfaces that will be in contact with the sheet will eventually wear. In addition to chromium plating (mentioned for blanking press parameters), the dies must be carefully ground to smooth radii to avoid stress concentrations that can initiate cracks in the panels.

  Die and binder wear can have one of at least two potential effects in the long term. First, the binder rings or other critical surfaces used to control metal flow could wear to the point where they are ineffective and the panels would develop splits or buckles. More likely, the panel could continue to be formed successfully but eventually the dimensions would drift out of tolerance for the finished panels. Dies are maintained so they do not wear to either of these conditions, and preferably much less in order to obtain the desired uniformity in the critical dimensions of the finished panels [9, 15, 16].
- Die temperature. It was noted under material properties how the die temperature can have an influence on the stamping process. During a run, significant amounts of heat will be released as the sheet is plastically deformed and this will tend to heat the dies. As the temperature increases, the die will thermally expand, distorting the dimensions of the panels created and closing the gaps between the mating die surfaces [14, 15].
- The line on which the part is run. Even "identical" press lines have slight differences in press levelness and flatness, bolster positions, etc., that inhibit the ability to casually move dies between presses at one plant or between plants and achieve consistent results. The dies must be tuned to the particular press and bolsters on which they are to be run.
- Line speed. Two limiting factors affect the line speed for the stamping press line other than what was mentioned for the blanking press. These are the speed at which the part

transfer equipment (frequently referred to as "press automation") can index the parts from one press to the next in the line and the time it takes to dump the air out of the cavity of the die, due to the high pressures and resultant high air velocities in the die cavity during the stamping process. Sometimes holes must be milled into the dies to vacate this air more rapidly and speed up the line [9, 15].

- Lubrication. Lubricants may be added to the steel blank to decrease the frictional forces developed during the stamping operation. This can increase metal flow and help prevent splits. Two types of lubricant may be added at the stamping press, including lubricant applied at the entry to the press line and manually applied lubricant (drawing compound or "dope") squirted onto critical radii, where the operator believes the "dry" metal might split, as it goes into the press. Each of these lubricants can be individually specified (amount and type), although their quantities are difficult to control or measure and the amount of lubrication may vary greatly, even across different areas of the same blank [15, 16, 38].
- Press shut height. This is the distance that the main slide of the press travels downward in its stroke from its fully upright position. For the draw die, the top die will be separated from the bottom die only by the thickness of the sheet at the bottom of the stroke. The press is controlled by setting the shut height and the tonnage of a given hit is a result of that setting. Thus, gauge variations in the part will result in different force applied during the press stroke.

  The press is "home" if the stroke goes completely to the bottom (full contact) position where there is no gap anywhere between the top die, sheet and bottom die. Forming dies (draw and restrike) must bottom, whereas trim and pierce dies do not necessarily have to go all the way to the bottom. The dies have indenters that scribe a circle in a scrap area on the panel when the die is home. Press tonnage may also be used to determine whether or not a press went all the way home on a given hit.

  Steel blanks will vary in gauge (usually specified to +/- 0.001"), so for a given shut height the force on the part will vary proportionally to gauge. The press shut height could thus be controlled as a function of the gauge of the sheet to give a consistent press tonnage and hence a consistent panel.

  To minimize set-up effort and variability, the goal for a stamping plant is to set up a press and its dies to close enough tolerances that all dies can be run with the same shut height setting on the press. High variations of blank gauge and tensile strength (usually specified to +/- 2 ksi) could make this difficult, or require setting the shut height as a function of blank properties [16, 17, 31].

- Press tonnage. This is described above for the blanking press. A minimum press tonnage is required to overcome the yield strength of the metal and cause the required plastic deformation of the sheet. Consequently, press tonnage usually must be higher for inner panels that have numerous beads and formations or outer panels with deep draws [14, 16, 17].
- Shims. Shims are thin, flat pieces of steel of a known thickness that are placed in one or more of the corners of the die (on the bottom blocks) to change the shut height in those corners. This redistributes the force in the die across the panel and is used to make up for situations where the die hits too hard on one side but not hard enough on another. The need for a shim is an indicator of a problem with the die and/or press and will have an impact on the properties of the panel formed [14, 16].
- Standard Operating Procedures (SOPs). Set-ups must be done exactly the same way every time for consistent stamping results, making the existence of SOPs essential. Set-up procedures must be established for the dies, the press automation (indexing equipment), blank feeding and press controls. As for the blanking press, this is especially important as stamping batch sizes are decreased and set-ups become more frequent [14, 15, 16].
- Timing. The timing of a draw die is the time delay between the time when the binder engages to hold the blank secure and the punch engages to form the panel. It is critical that the binder fully engage before the punch begins to form the part [14, 44].

A.5 Finished Panel Properties

The material properties mentioned for the received steel sheet are still important to the finished panels, although they will have been significantly changed by the stamping process. In addition, the following factors are important to the hemming line.

- Adhesive adherence. Adhesives are applied to the outer panel prior to the hemming operation. Immediately after the hemming operation, the panel temperature is raised via an induction cure process to cure the adhesive. Certain stamping plant outputs may affect the strength of the bond developed by the adhesive in this operation. These include the surface roughness of the sheet and the presence of residual lubricants or other coatings [18].
- Crisp lines. One of the most critical requirements is that the panels have crisp, sharp break lines, hem edges and character lines. The radii should be tight for the character lines and flanges. The character lines must look good for the finished car body, while the quality of the break lines and hem edges are critical for the hemming process in the body shop [2].

- Dent resistance. The primary factors influencing the dentability of a finished door panel are its strength after forming (stress before the onset of plastic deformation) and gauge. The yield strength of the finished panel is influenced by the yield strength of the steel purchased, the work-hardening developed in the press line (primarily at the draw die), and the thermal history of the panel processing. For closure panels that have long, flat surfaces, it is difficult to achieve enough strain to initiate substantial work-hardening and build up tension in the sheet. Sheet gauge is minimized within the constraints of adequate resistance to denting in order to minimize weight [22, 36].
- Dimensional integrity. The panels must conform to dimensional specifications for the size and location of holes, slots and other features as well as overall surface dimensions and flange depths. Even more important, they must be consistent from one run to the next. The body shop can easily adjust to make good cars out of panels that are consistently off specification, but it is costly to be flexible enough to be capable of making good bodies out of variable panels. Flange depths and PLP hole accuracy are especially critical for the hemming and fitting operations [4, 15, 19].
- Edge consistency. The edge of the flanges must be of high quality, with no burrs. The shear cut must be very clean and sharp, especially around corners [31].
- Flange angle. Ideally, the flanges should come up from the plane of the panel surface at a 90 degree angle. In practice, such an angle is impractical due to the need for easy part removal from the die and springback of the flange (Figure 13) [31]. It should, however, be consistent and less than 110 degrees [2].

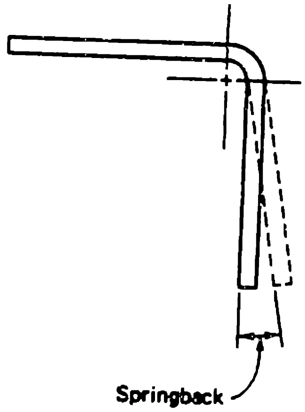


Figure 13. Flange springback [31].

- Flange flatness. The flange should not be wavy since waves may show through to the outer panel surface after hemming. If the geometry of the panel is such that excess metal in the flange causes waves, the flange length is decreased and/or the flange design is modified (by the addition of scallops) to remove the waves (Figure 14) [2].

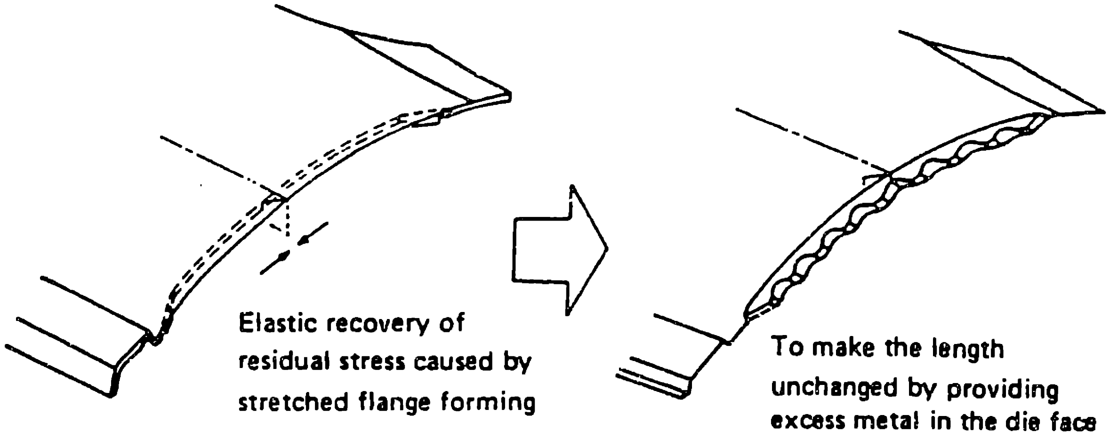


Figure 14. Reduction of flange waviness [2].

- Flange length. The length of the flange should be consistent and no longer than necessary to properly lock the inner panel after hemming. Usually a length between 5 and 10 mm is optimal [2].
- Flange radius. The radius of curvature of the break line where the flange rises up from the surface of the panel should be as small as possible. This will result in a crisp hem with minimal creepage in the hemming process (see door assembly properties) [2, 31].
- Flatness. The resistance of an area of a panel to deflection when a load is applied normal to its surface is largely determined by the radius of curvature of the panel at that point. If a panel is too flat, it may have little resistance to elastic deformation - a phenomenon referred to as the "oil canning" effect. On the other hand, too much curvature in a panel could make it too resistant to elastic deformation and thus make it more likely to be dented instead of deflected by an applied normal force. Flatness is primarily a function of panel design, but will also vary with springback and process variations [31, 36].
- Paintability. The coatings applied by the paint process must readily adhere to the panel surfaces. The surface texture of the finished panels (measured by a profilometer in peaks per inch and/or average peak height) has a significant effect. Another factor is residual drawing compound, which can impede paint adherence. The corrosion-

resistance coating method used at the steel mill (electrogalvanizing, hot-dip galvanneal, etc.) is also important [18].

- Production rate. Clearly one of the most important and most carefully scrutinized variables is the rate at which good panels are produced by the stamping plant. It is important to make improvements that will not have a detrimental impact on the productivity of the plant [16].
- Residual stress. Some downstream operations may release residual stresses and cause distortions. Heat from operations such as hemming induction cure, welding and paint bake could cause such a phenomenon. Mechanical forces such as the load placed in the doors when the body is run through the dip tanks prior to paint, the hemming operation itself, and various bangs and dings the parts incur during handling could also release residual stresses. Unfortunately, it is difficult to measure these stresses directly and most methods are destructive to the part [2, 45].
- Rigidity. The propensity of a panel to bend and twist about either a fore/aft axis or an up/down axis is known as its rigidity. The thicker the finished panel gauge and the greater the finished panel yield strength, the more rigid it will be. Rigidity is important for the resistance of finished panels to deformation during subsequent processing in the Body Shop, Paint Shop and TCF Assembly processes, although there are no standard tests for measuring rigidity in a production environment [19].
- Scrap dimensions. Although a part may have been formed to the proper dimensions, the dimensions of the scrap from the trim operations can provide additional information about the process. Consistent scrap dimensions indicate consistent blank size and placement as well as consistent strain in the plane of the sheet [4, 14, 15, 16, 40].
- Strain. After stamping, the panels must have some residual strain, both through the thickness of the sheet and along its plane in the width and length directions of the part. The plastic portion of the strain is critical for the properties of the panel as well as its dimensions. Thickness strain can be measured relatively easily and quickly with an ultrasonic thickness gauge. Techniques to measure strain in the plane of the sheet, however, require time consuming marking of the blanks before stamping and measurement after stamping [4, 8, 14, 15, 17, 42].
- Surface coating adhesion. It is critical that the galvanneal coating on the sheet does not flake off during the deformation process. Flaking at the draw die, for example, can cause pieces of the coating to be imbedded into a restrike die, causing surface quality problems. In addition, flaking reduces the corrosion resistance of the finished panel and can ruin the appearance of the finished body after paint [18].

- Surface defects. The panel must be free of any number of surface distortions. These include pimples and dings, wrinkles, buckles and pinches, hard marks, low spots, "mouse ears" and a variety of other problems. Normally, these are the result of foreign matter stuck to the dies or blanks, lubrication problems, inadequate surface strain or poor die mating [2, 15, 17].
- Weldability. Body panels are primarily joined by resistance welding operations. As such, it is essential that the steel be highly weldable. Sheet coatings can have a big effect, as can the composition of the steel, especially its carbon and phosphorous content [25].

A.6 Detail Parts Properties

The requirements for detail parts vary with their nature. In general, these are not surface parts and so have little requirements for surface appearance and dentability. Nonetheless, they must normally be dimensionally accurate, weldable, paintable, sufficiently rigid, free of excessive residual stresses, and have adequate material properties in their as-formed condition. These conditions are described above and are not repeated here.

A.7 Hemming Parameters

- Adhesive application. Adhesive is applied to the hem surface of the outer panel before mating with the inner panel. In order for the adhesive to work properly, it is applied with a consistent bead size along a consistent path.
- Adhesive properties. It is important that the adhesive have the required properties of consistency, curability, strength and viscosity. This depends on storage, handling and dispensing practices as well as chemical formulation of the adhesive.
- Clamping, fixtures and pins. At each welding station where the door assembly is built, clamps, fixtures and pins are used to position the panels and hold them securely during welding. It is critical that the fixtures and pins be located properly and that the clamps secure the panel with adequate, but not excessive, force [19].
- Crimping. After the inner and outer panels are mated, they must be moved to the hemmer for hemming. To temporarily hold them together prior to hemming, the outer is crimped over the inner in a few selected positions. It is important that the crimper be properly aligned such that it strikes the panel at the proper angle and crimps it over by the specified amount, without excessive force that can warp the assembly.

- Gage capability. As described for the press lines, it is essential that hemmer line controls and measuring devices be capable of accurate, repeatable performance or it will not be possible to implement any system of process control [12, 19].
- "Gumdrop" application. "Gumdrops" refers to large drops of adhesive that are applied to the outer panel to damp noises or vibrations and provide additional structural support for details inside the door. These gumdrops should be the proper diameter and height and centered in the specified position on the panel.
- Handling damage. All door parts are subjected to considerable handling from the press line or other fabrication source to the hemmer lines. Normally they are manually inspected and loaded into a rack or bin, transported to the hemmer area, and manually loaded on the hemming line. Each of these steps can result in dents or dings that distort the panels, particularly along their edges or on their corners. Such distortions can subsequently distort the assembled door.
- Hem angle. The hemming operation takes place in two stages. The first is a pre-hem, which bends the flange over to approximately a 45 degree angle off the outer panel. The second is the hem, which bends the flange over the rest of the way such that it makes contact with the inner panel. Since the flange has already been bent over by the pre-hem, the angle of approach for the final hem is critical for proper bending of the flange to its final position (Figure 15) [2].

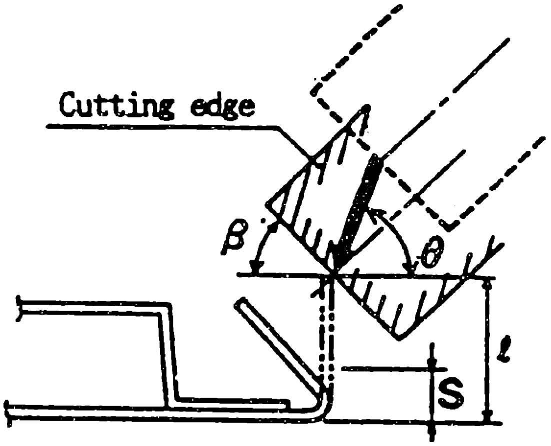


Figure 15. Hem angle [2].

- Hem gap. The second critical characteristic of the hem is the gap between the steel and anvil of the hemmer at the end of its stroke. This distance defines the thickness of the final hem, other than any springback that occurs. Since the hemmer does not exert enough force to reduce the thickness of the steel, the hem is constrained to a minimum hem gap equal to twice the gauge of the outer panel plus the gauge of the inner panel plus twice the diameter of any incompressible material in the adhesive (Figure 11) [2].

- Hemmer timing. The hemmer will not necessarily contact all sides of the hem at once. Often, one or two sides will be hemmed first, followed by one or two more. The sequencing and timing of these hemming steps can cause the panel to be distorted in a particular way, which should be repeatable as long as panel dimensions and locations are constant.
- Hemmer torque. The hemmer must apply a certain amount of torque to deform the flange into a hem. If the hemmer is set so that it will close to a prespecified hem gap, the magnitude of this force will indicate significant changes in the process, such as gage variations of the steel, material property variations, or misalignment. Thus, the hemmer torque may be used as a process control variable to detect a wide range of possible problems with the process [2].
- Induction Cure Cycle. The induction cure process uses an electric current through a coil to locally heat the panel in the hem area after hemming to cure the adhesive. The primary controlling factors of the induction cure are the amperage of electricity applied to the coil and the cycle time over which it is applied. An increase of either will increase the temperature achieved in the hem area. The goal is to achieve a high heat to effectively set the adhesive without creating so much heat that the panel warps from release of residual stresses or partially anneals and loses strength.
- Line maintenance. As with the press lines, it is essential that the hemming line be properly maintained to ensure consistency of product and capability of process control gauges.
- Nut runner. The nut runner screws the door hinges to the hemmed door. Since the hinges are used to attach the door to the BIW, proper alignment of the nut runner is crucial. In addition, the nut runner must apply the correct amount of torque such that the nuts are tight but the hinges are not twisted by an overtorque condition.
- Operator capability. As for the press lines, the work force must be properly skilled to maintain consistent, quality production through the hemming line.
- Panel location. The inner panel must be located in exactly the right place relative to the outer panel in the hemmer before they are married by the hemming operation. Any shift of the panels relative to each other in the hemmer will affect the relative dimensions of the finished door (see door assembly properties). Pimples on the inner panel can help to prevent shift of the panels relative to each other after hemming.

- Panel temperature. As mentioned above for the induction cure cycle, localized hot spots in the panels will cause areas where the material properties are affected. This will certainly be true in the heat affected zone around the welds, although it may also be true in the hem area after induction cure. Care must be taken that the panel is not allowed to get so hot that significant material degradation, such as strain aging, occurs over a large portion of the door.
- Part clearances. To minimize distortion of the panels, care must be taken to make sure that there is adequate clearance for all parts in the hemming line, whether the parts are handled automatically or manually. Otherwise, repeated or periodic collisions of parts against machinery or hard tooling will distort the doors, and can damage the equipment. Of particular importance are the PLPs that positively orient the parts in three dimensions. If there is not adequate clearance to remove the part from the pin, the PLP hole on the part can be distorted, causing improper location for that part in all subsequent operations. Even worse, the pin itself could be bent, causing location problems for all subsequent parts on that station [19].
- Pre-hem angle. The pre-hem will usually need to bend a flange that is at an angle greater than 90 degrees from the outer panel surface. Therefore, it is critical that the angle of approach of the pre-hem dies is designed to crisply bend the flange without distorting the panel or causing excessive creepage [2].
- Pre-hem gap. The stroke length of the pre-hem dies is critical for bending the hem to the proper angle for engagement by the hem dies. The stroke length will need to bend the flange to a smaller angle than that required by the hem steels in order to account for the springback that will occur, particularly for stronger steels [2].
- Pre-hem timing. As with the hem timing, the sequence with which the pre-hem dies engage the flange can cause distortions in the door if the panels are not properly fixtured or if the timing is inappropriate.
- Pre-hem torque. The pre-hem torque can indicate changes in the flange strength, steel gage or other process variations and hence can be used to help monitor the hemming process [2].
- Welder amperage. The weld guns must be supplied with the proper amperage such that the welds are strong and secure, yet not so hot that they create an excessive heat affected zone around the weld (see panel temperatures, above). In addition, the welding tips must be properly cooled and dressed to maintain solid welds.
- Welder equalization, positioning and timing. It is critical that the welders be properly located and positioned with respect to the panel such that, at full extension, they make contact with the panel without bending or distorting it. Even small distortions will be

locked in place by the weld. The sequencing and timing of the weld guns should be designed to minimize distortions of this nature as well.

A.8 Assembled Door Properties

As with every other stage of the process, the material properties after door assembly can affect the door's susceptibility to distortions in downstream operations. Such critical properties as yield strength and gauge will have been significantly altered from the time when the steel sheet was first received at the plant as a result of all the forming operations that have been performed. Some of the finished panel properties such as dentability, rigidity and residual stresses are also important at this stage in the process. Other important door assembly properties are listed below.

- Absolute dimensions. This refers to the overall dimensions of the panel - its height, width, etc. Each of these dimensions must be within design tolerance for the door to be properly fit to the BIW. Often, a coordinate measuring machine (CMM) or a specially designed R1 gauge is used to measure absolute dimensions of assembled doors.
- Creepage. When a flange is hemmed, ideally it will not pull in (such that the overall panel length is reduced) or push out (such that the overall panel length is increased), but will fold over exactly on the break line of the outer panel. In practice, a certain amount of creepage may occur, defined as the distance that the break line moves when the flange is folded over. The pre-hem and hem angles and flange length and radius should be carefully designed to minimize this creepage, or the panel dimensions should be adjusted to account for it [2].
- Distortions. Any bends, twists or localized deflections (dents) will make it difficult to properly fit the door to the BIW [2, 19].
- Hem crispness. Hem crispness is the radius of the fold at the hemmed edges of the door assembly. Different hem designs will have different radii by design. For example, a tear-drop hem is designed to have a large, smooth radius for the hemmed edge (Figure 16) [31]. Most hems, however, are designed to have as tight a radius as possible [2].
- Hem flatness. The finished hem should ideally be perfectly smooth. Sometimes this is difficult in practice, especially if the designed curvature of the panel results in the natural occurrence of excess flange that must somehow be folded over into the plane of the panel. In such a situation, the hem will be wavy, which may show through on the outside surface of the door. Changes to the flange length and/or design (such as the addition of metal gainers or scallops) may be required in such a case [2, 31].

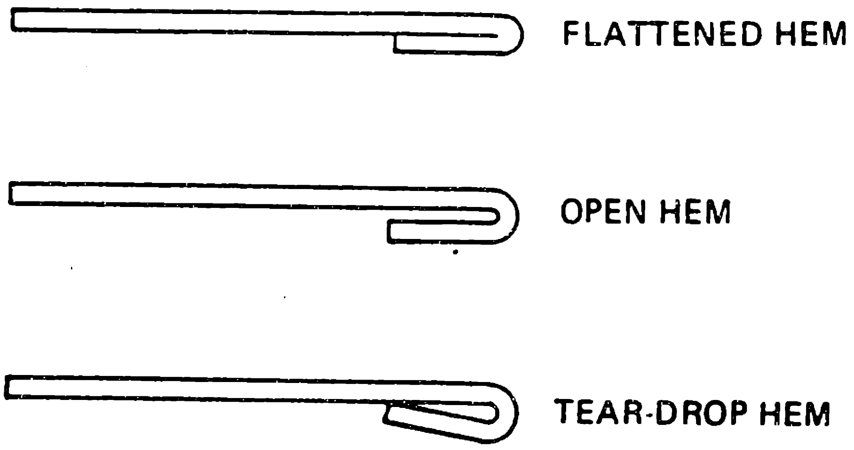


Figure 16. Hem designs [31].

- Hem straightness. It is important that the hem be free of pinches, squirts, flat spots and other similar defects caused by an improperly designed or adjusted hemming process [2].
- Hem tightness. The hem should be as tight as possible, resulting in the best mechanical interlocking of the inner and outer panels together. This minimizes the opportunity for water penetration of the hem that can corrode the door in service. The tightness is essentially controlled by the hem gap from the hemming process, but may loosen up due to a poor design or springback of the flange [2, 46].
- Recoil. Another potential problem is that the hemming process will cause the outer panel to become concave in the area near the hem. Such a "low spot" is caused by compressive stresses placed in the outer panel near the hem due to the plastic deformation in the hem area. Recoil can be visually observed and degrades the surface appearance of the door. In some cases, it may also be sufficient to distort the shape of the door at the edges, making it difficult to fit the door to the adjacent body panels (Figure 17) [2].
- Relative dimensions. In addition to the absolute dimensions of the door mentioned above, it is also critical that its relative dimensions are accurate for proper fit. This refers to the distances between the door PLPs (which define the location of the door in three dimensions and are used to fit the door to the BIW) to the edges of the door.

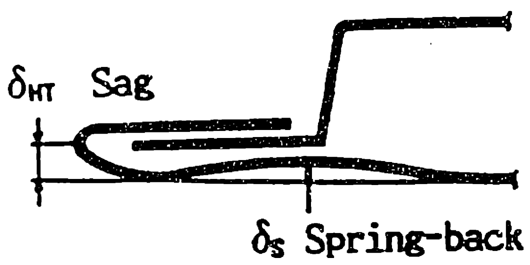


Figure 17. Recoil [2].

Even if the door is properly sized in absolute dimensions, it will be difficult to fit properly if the inner and outer have shifted relative to each other, thus distorting its relative dimensions [19].

- Rolling angle (curl). This is a condition whereby the door assembly actually folds up away from the hem area, such that the edges are overflush to their design dimensions. Like recoil, it is caused by compressive stresses in the outer panel that plastically deform the panel. Higher yield strength panels are more resistant to curl [2].
- Surface waviness. Other than near the hem area, the surface of the outer panel may be subjected to a number of distortions through the hemming process that will cause it to appear wavy. Greater surface strain in the panel will minimize this waviness [2].

APPENDIX B. STAMPING EXPERIMENT INTERACTIONS.

This appendix presents boxplots that graphically display the stamping experiment interactions. The boxplots show the distributions of the individual data values for each output measure for each combination of input factor levels. Each box represents half the data values, from the first quartile to the third quartile. The whiskers extending out on either side of the box represent the remainder of the data. In certain cases where one or more points were outliers, those points are shown beyond the whiskers.

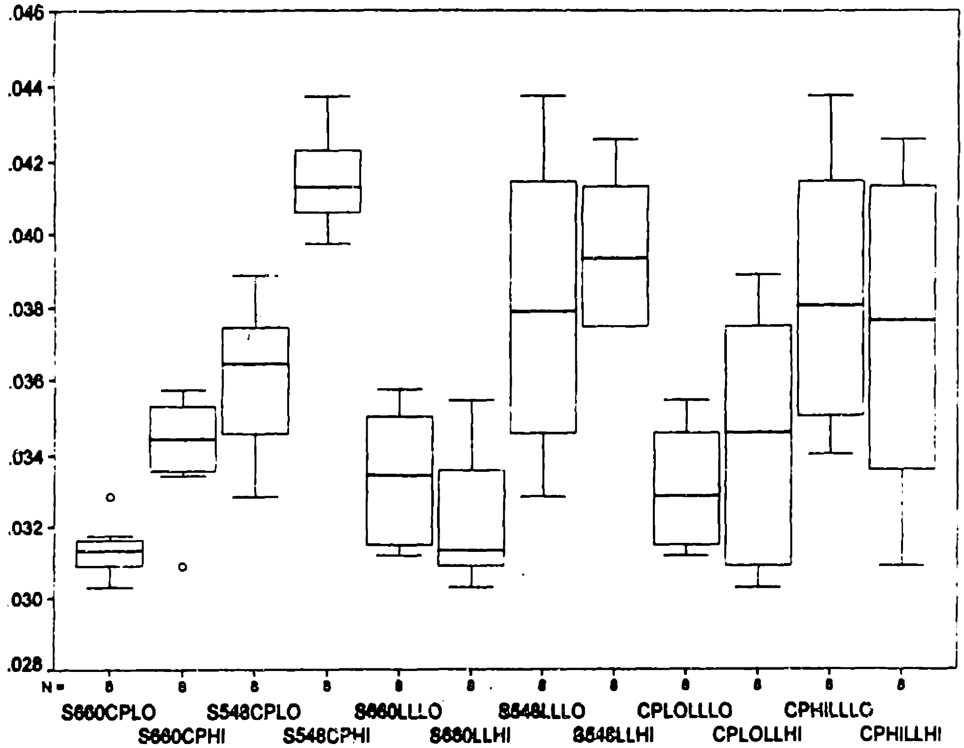
Note that the estimated variance is also a function of the sample size for the data. Factors with low sample sizes have higher estimated variances than is apparent from the charts. The sample size for each combination of factors is shown below the corresponding box on the chart. Also note that the solid line in the box represents the median, not the mean, of the data values. For a skewed distribution, the mean will be closer to the extreme data point(s) than the median [29].

For the two-way interactions, each box is labeled with an eight character code that specifies the level of each of the two factors. The first four characters specify the level of the first factor, while the last four characters specify the level of the second factor. Steel grades are designated as S019 and S982 for the 019 and 982 inner steel grades and S660 and S548 for the 660 and 548 outer steel grades, respectively. Cushion pressures are specified as CPLO for the low cushion pressure and CPHI for the high cushion pressure. Likewise, lubricant levels are specified by LLLO for the low lubricant level and LLHI for the high lubricant level.

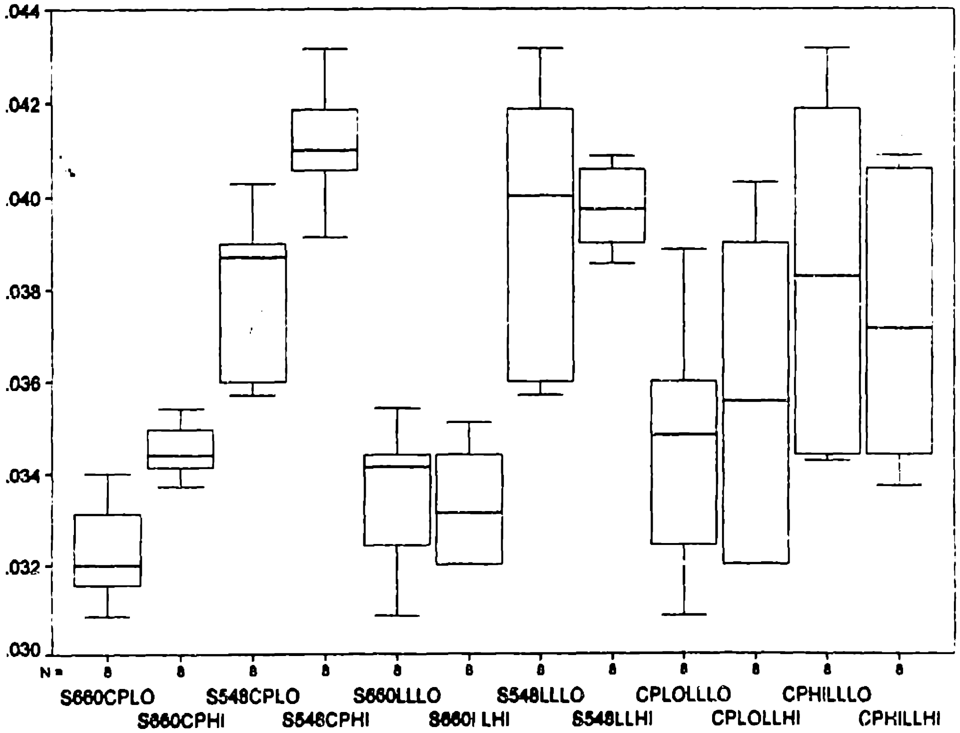
For example, S660CPHI represents the data values for those experimental runs where a high cushion pressure was used on 660 grade outer panels. Similarly, CPLOLLLO represents the data values for those experimental runs where both the cushion pressure and lubricant level were at their low levels.

For the three-way interactions, the boxes are still labeled with an eight character code. In this case, however, the levels of three factors are indicated. Steel grade codes are compressed to two characters; S0, S9, S6 or S5 for the 019, 982, 660 and 548 steel grades, respectively. Cushion pressure codes are three characters; CPL or CPH for the low and high levels. In the same way, lubricant level codes are three characters; LLL or LLH for the low and high levels.

For example, S6CPLLLH represents the three-way interaction among the 660 steel grade, the low cushion pressure and the high lubricant level. Likewise, the three-way interaction among the 019 steel grade, high cushion pressure and low lubricant level is designated as S0CPHLLL.



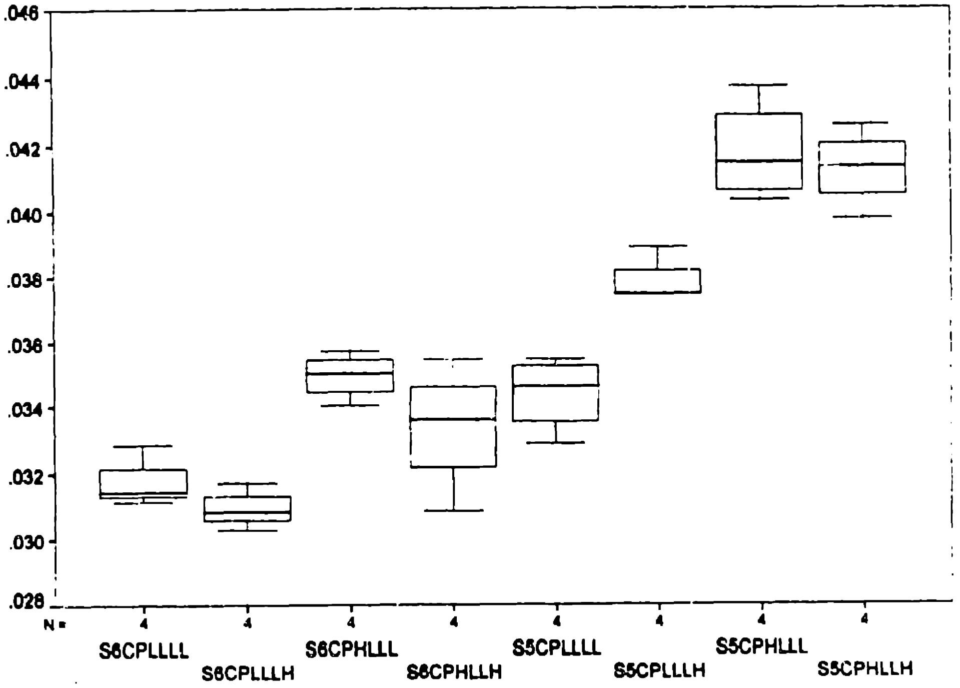
Left Hand Outers Major Strains



Right Hand Outers Major Strains

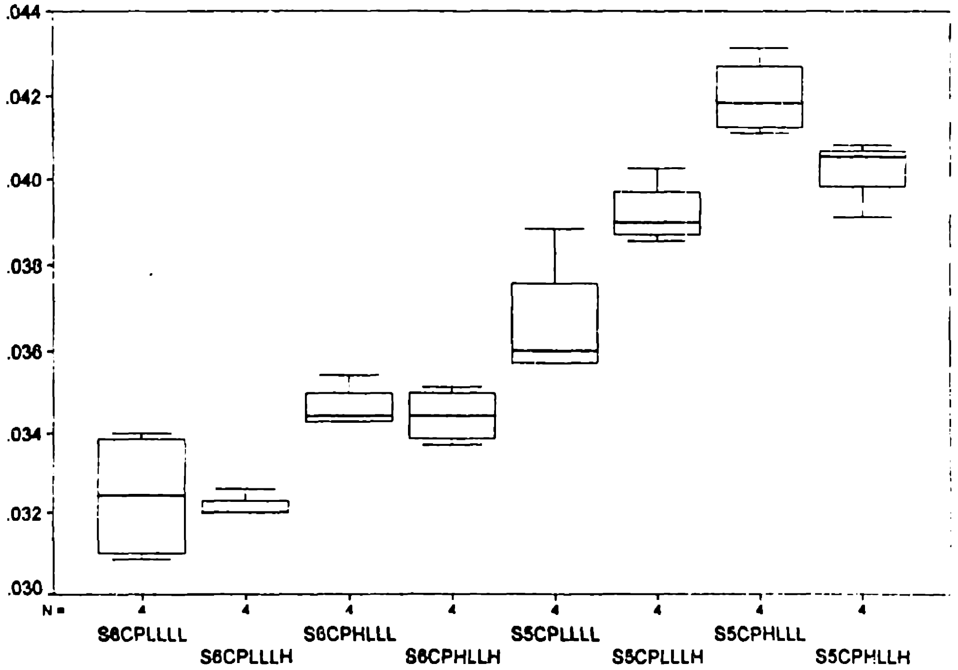
Left Hand Outers Major Strains

3-Way Interactions



Right Hand Outers Major Strains

3-Way Interactions



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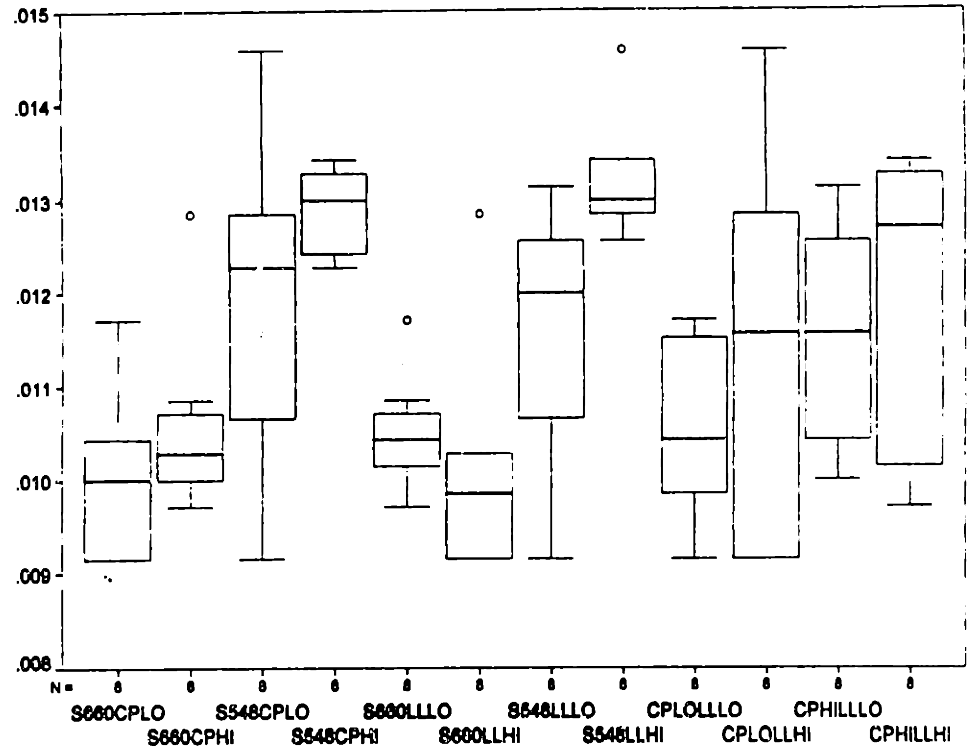

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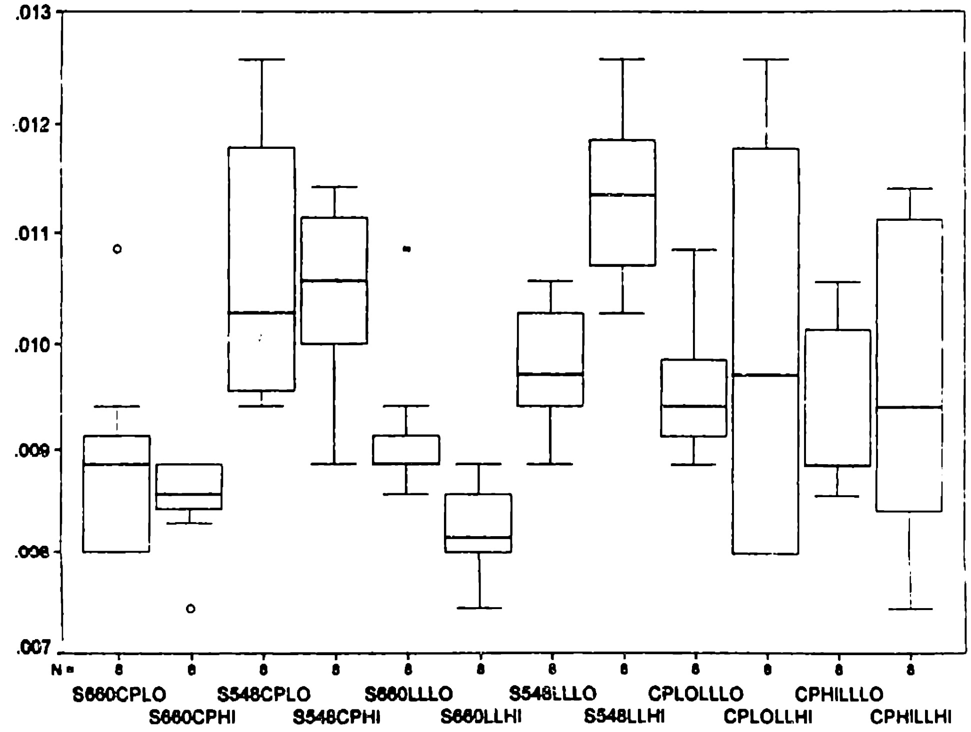
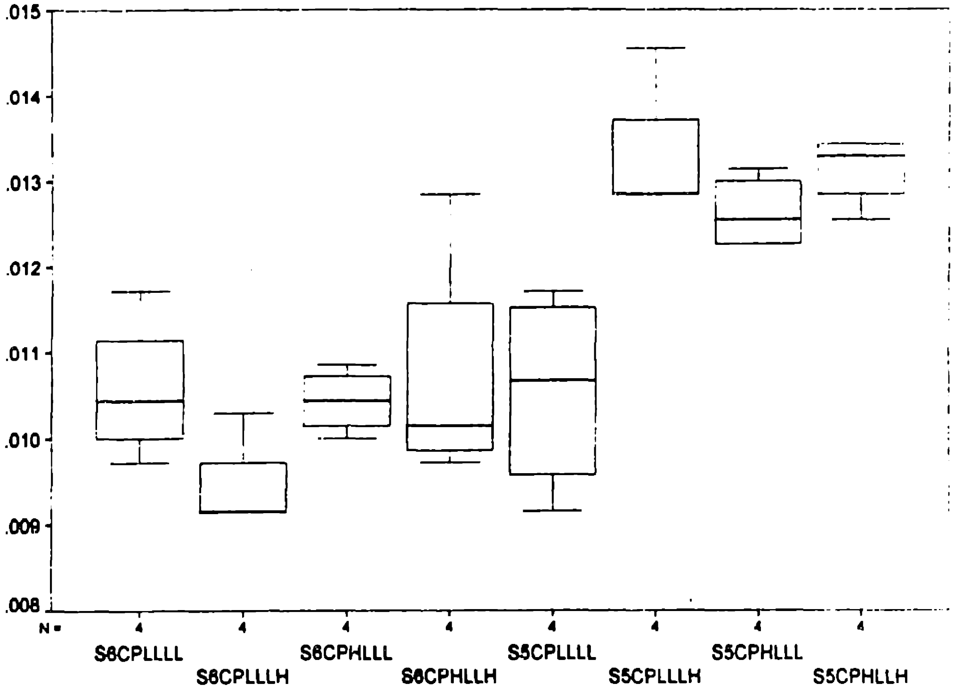


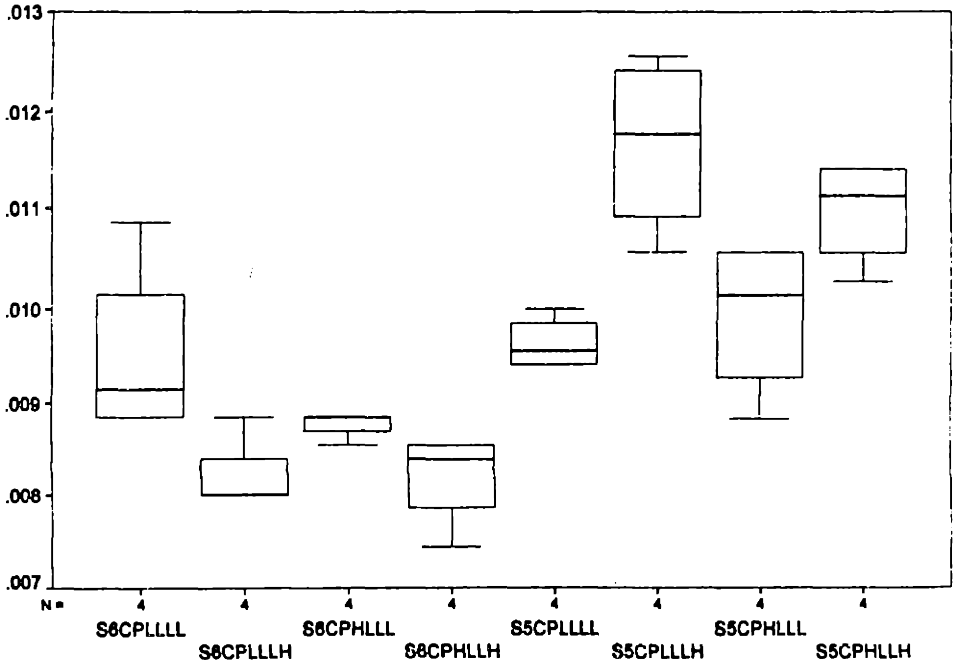
Left Hand Outers Minor Strains

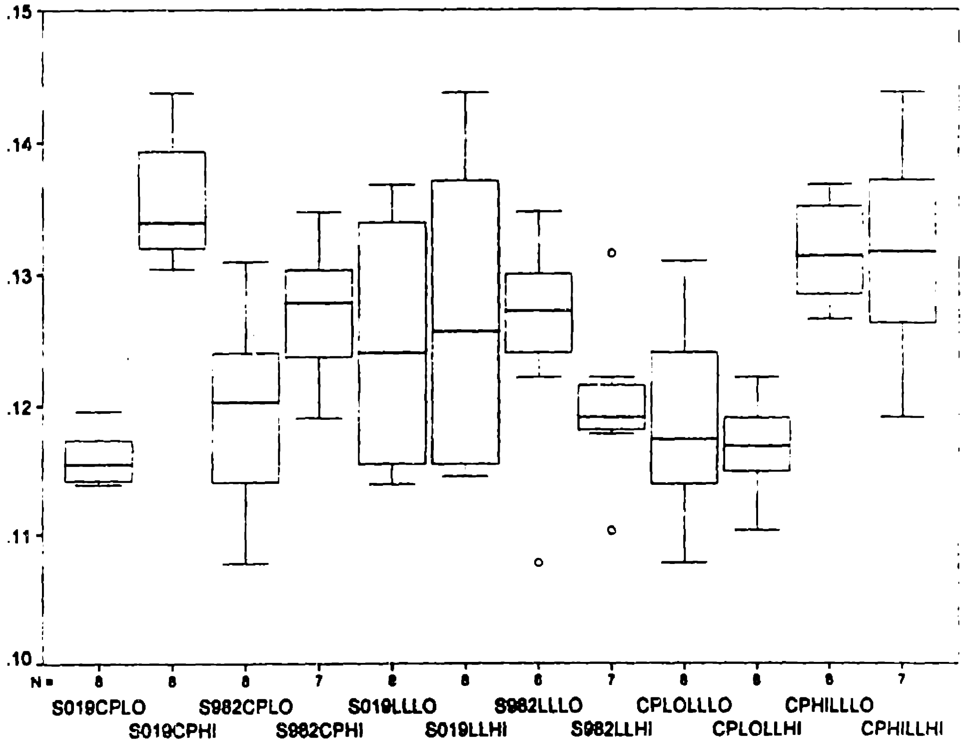
3-Way Interactions

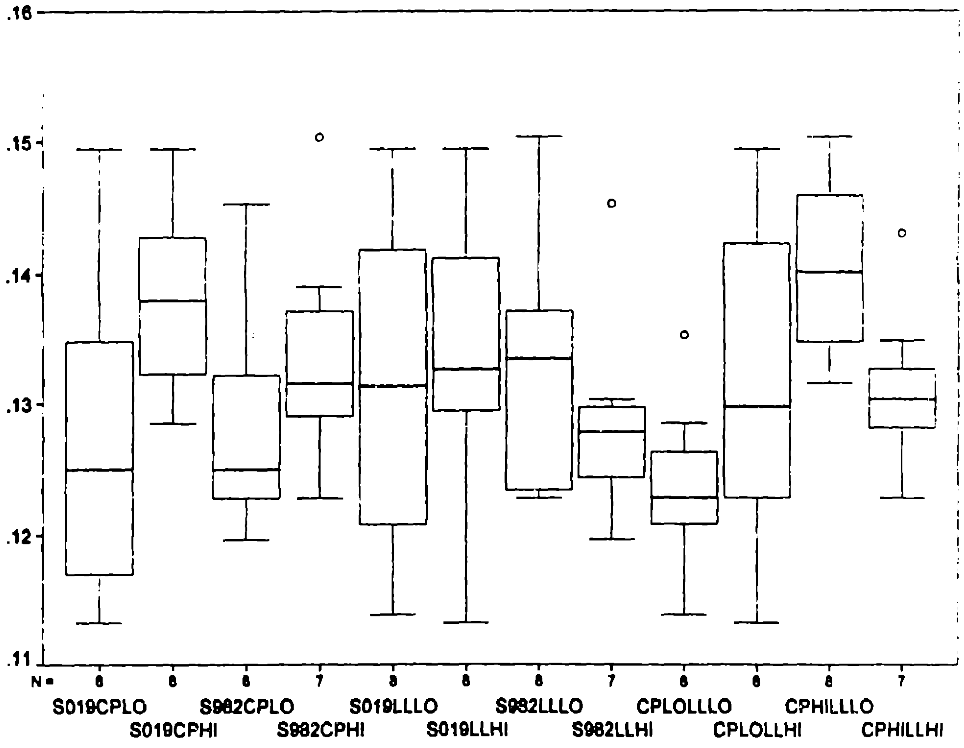


Right Hand Outers Minor Strains

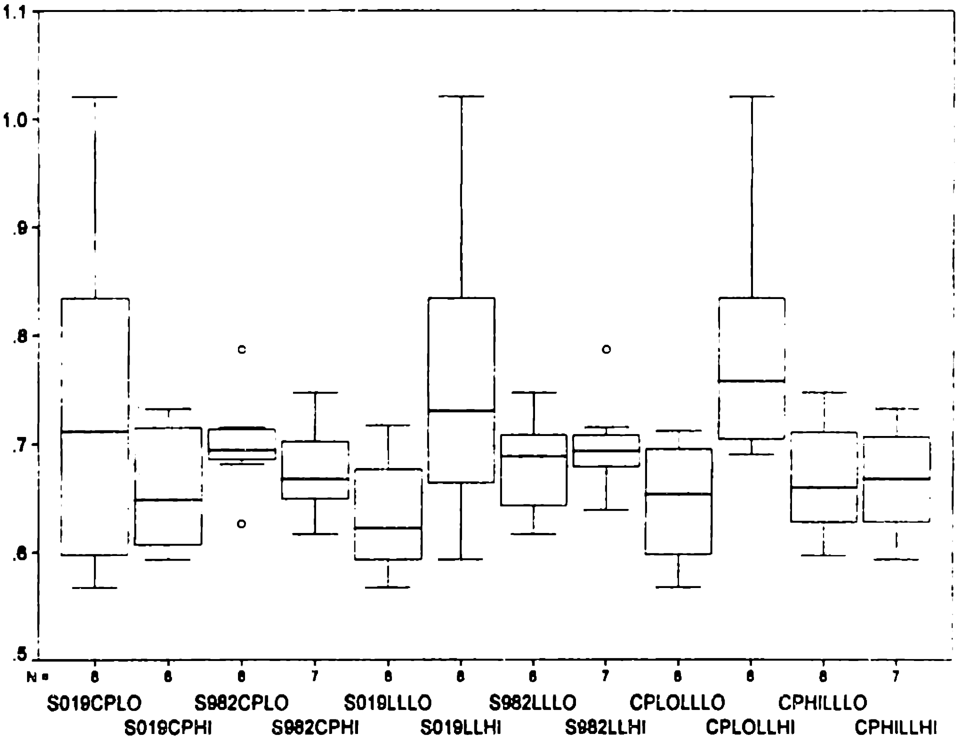
3-Way Interactions



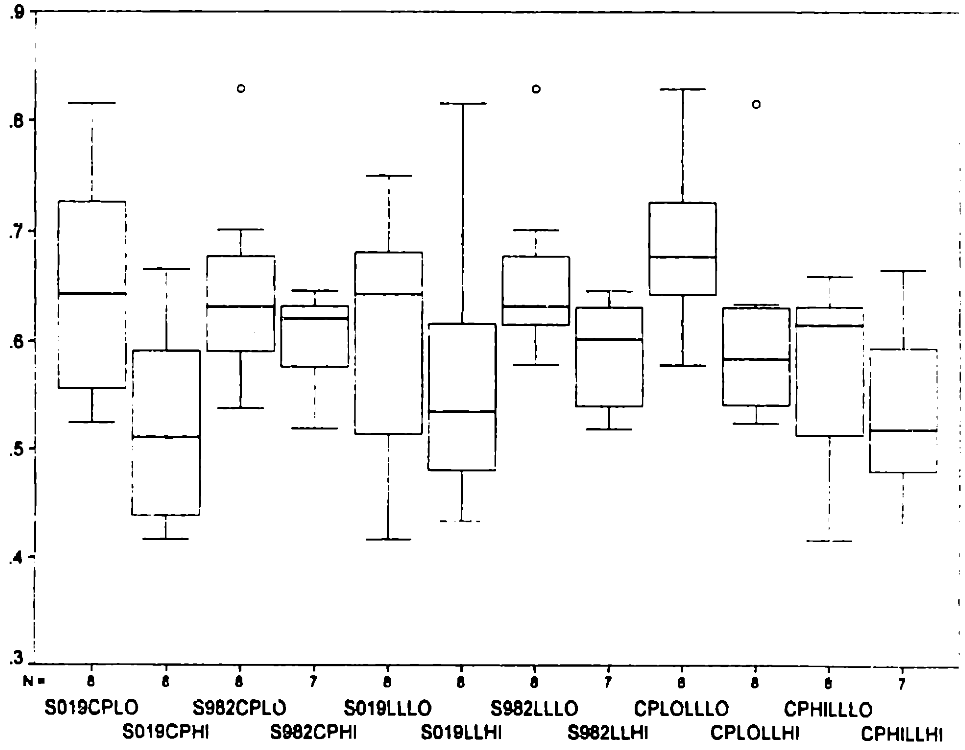

Left Inners Thickness Strains


Right Inners Thickness Strains

Left Hand Inners Distortions

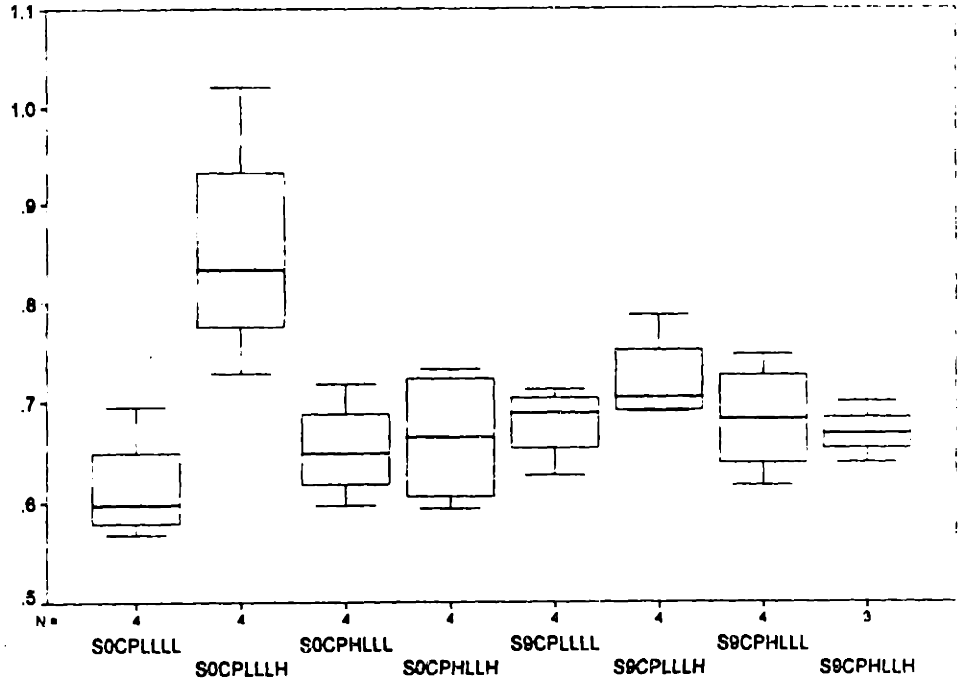


Right Hand Inners Distortions



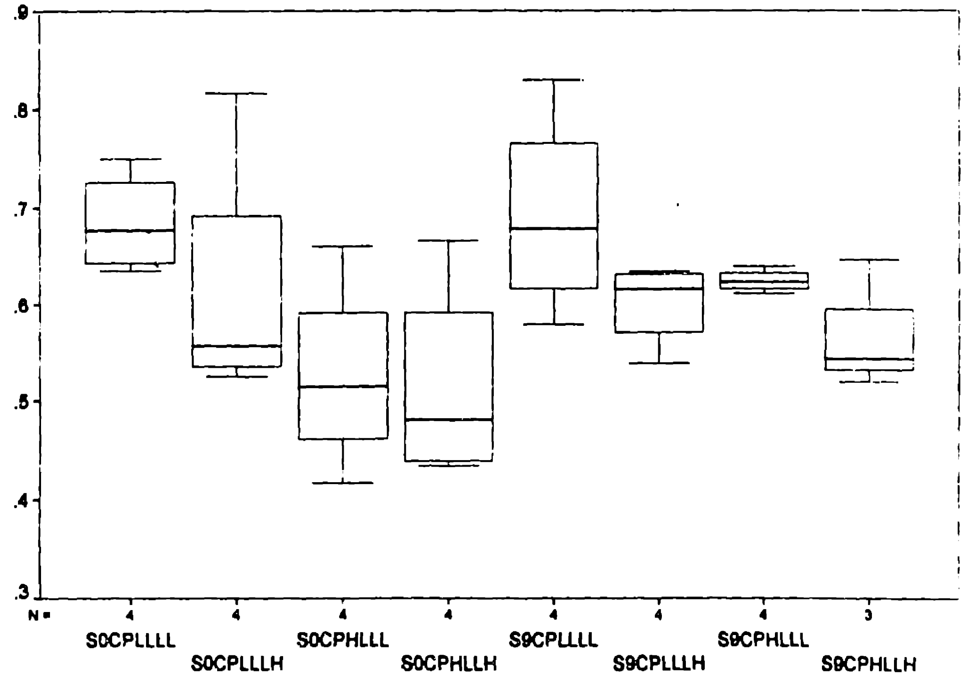
Left Hand Inners Distortions

3-Way Interactions



Right Hand Inners Distortions

3-Way Interactions



APPENDIX C. DOOR ASSEMBLY EXPERIMENT STATISTICAL TESTS.

This appendix details the statistical tests for the means and variances of the factors considered in the door assembly experiment. T-tests are used to compare the means of each of the four output measures by level of each of the eight experimental factors for both the left and right-hand sides. Similarly, F-tests compare the variances. The form of the T-test used assumed equal variances if the F-test was not significant at the 90% confidence level.

The left-hand tests are shown first, followed by the right-hand tests. For each, the analysis is organized by experimental factor. In addition to the mean and variance comparisons, the distribution of the data for each output measure by each level of each factor is indicated by a quartile table.

Left Door Output Measures

RMS Flush by Inner Panel Steel Grade

t-Test: Two-Sample Assuming Equal Variances

	019	*982*
Mean	0.51173	0.49289
Variance	0.00445	0.00546
Observations	33	30
Pooled Variance	0.00493	
Hypothesized Mean	0	
df	61	
t	1.06325	
P(T<=t) one-tail	0.14593	
t Critical one-tail	1.67022	
P(T<=t) two-tail	0.29186	
t Critical two-tail	1.99962	

F-Test: Two-Sample for Variances

	019	*982*
Mean	0.51173	0.49289
Variance	0.00445	0.00546
Observations	33	30
df	32	29
F	1.22698	
P(F<=f) one-tail	0.28571	
F Critical one-tail	1.5946	
Maximum	0.6808	0.6346
3rd Quartile	0.5461	0.5385
Median	0.5110	0.5060
1st Quartile	0.4766	0.4516
Minimum	0.3736	0.2885

RMS x-Gap by Inner Panel Steel Grade

t-Test: Two-Sample Assuming Equal Variances

	019	*982*
Mean	0.30219	0.27932
Variance	0.0049	0.00725
Observations	33	30
Pooled Variance	0.00601	
Hypothesized Mean	0	
df	61	
t	1.16891	
P(T<=t) one-tail	0.12349	
t Critical one-tail	1.67022	
P(T<=t) two-tail	0.24699	
t Critical two-tail	1.99962	

F-Test: Two-Sample for Variances

	019	*982*
Mean	0.30219	0.27932
Variance	0.0049	0.00725
Observations	33	30
df	32	29
F	1.47973	
P(F<=f) one-tail	0.14053	
F Critical one-tail	1.5946	
Maximum	0.4434	0.4473
3rd Quartile	0.3399	0.3493
Median	0.2962	0.2537
1st Quartile	0.2456	0.2123
Minimum	0.1960	0.1671

RMS z-Gap by Inner Panel Steel Grade

t-Test: Two-Sample Assuming Unequal Variances

	019	*982*
Mean	0.41241	0.43944
Variance	0.00781	0.01518
Observations	33	30
Pearson Correlatior	#N/A	
Pooled Variance	0.00601	
df	52.1462	
t	-0.992	
P(T<=t) one-tail	0.1629	
t Critical one-tail	1.67469	
P(T<=t) two-tail	0.3258	
t Critical two-tail	2.00665	

F-Test: Two-Sample for Variances

	019	*982*
Mean	0.41241	0.43944
Variance	0.00781	0.01518
Observations	33	30
df	32	29
F	1.9424	
P(F<=f) one-tail	0.03472	
F Critical one-tail	1.5946	
Maximum	0.7097	0.6757
3rd Quartile	0.4584	0.5077
Median	0.3989	0.4130
1st Quartile	0.3619	0.3550
Minimum	0.2558	0.2302

Left Door Output Measures

Avg. Hem Gap by Inner Panel Steel Grade

t-Test: Two-Sample Assuming Equal Variances

	019	*982*
Mean	2.51862	2.52315
Variance	0.00222	0.00166
Observations	33	30
Pooled Variance	0.00195	
Hypothesized Mean	0	
df	61	
t	-0.4062	
P(T<=t) one-tail	0.34301	
t Critical one-tail	1.67022	
P(T<=t) two-tail	0.68603	
t Critical two-tail	1.99962	

F-Test: Two-Sample for Variances

	019	*982*
Mean	2.51862	2.52315
Variance	0.00222	0.00166
Observations	33	30
df	32	29
F	1.34072	
P(F<=f) one-tail	0.21396	
F Critical one-tail	1.84236	
Maximum	2.6433	2.6344
3rd Quartile	2.5378	2.5558
Median	2.5111	2.5094
1st Quartile	2.4911	2.4964
Minimum	2.4200	2.4656

RMS Flush by Inner Panel Cushion Pressure

t-Test: Two-Sample Assuming Unequal Variances

	Low	*High*
Mean	0.46934	0.5183
Variance	0.00769	0.00304
Observations	20	43
Pearson Correlatior	#N/A	
Pooled Variance	0.00195	
df	26.2309	
t	-2.2948	
P(T<=t) one-tail	0.01503	
t Critical one-tail	1.70562	
P(T<=t) two-tail	0.03007	
t Critical two-tail	2.05553	

F-Test: Two-Sample for Variances

	Low	*High*
Mean	0.46934	0.5183
Variance	0.00769	0.00304
Observations	20	43
df	19	42
F	2.5287	
P(F<=f) one-tail	0.00615	
F Critical one-tail	1.83987	
Maximum	0.6808	0.6346
3rd Quartile	0.5214	0.5501
Median	0.4881	0.5331
1st Quartile	0.4088	0.4913
Minimum	0.2885	0.3785

RMS x-Gap by Inner Panel Cushion Pressure

t-Test: Two-Sample Assuming Equal Variances

	Low	*High*
Mean	0.26691	0.30264
Variance	0.00631	0.00566
Observations	20	43
Pooled Variance	0.00586	
Hypothesized Mean	0	
df	61	
t	-1.7244	
P(T<=t) one-tail	0.04485	
t Critical one-tail	1.67022	
P(T<=t) two-tail	0.0897	
t Critical two-tail	1.99962	

F-Test: Two-Sample for Variances

	Low	*High*
Mean	0.26691	0.30264
Variance	0.00631	0.00566
Observations	20	43
df	19	42
F	1.11535	
P(F<=f) one-tail	0.37145	
F Critical one-tail	1.83987	
Maximum	0.4298	0.4473
3rd Quartile	0.3173	0.3519
Median	0.2468	0.2959
1st Quartile	0.2075	0.2442
Minimum	0.1753	0.1671

Left Door Output Measures

RMS z-Gap by Inner Panel Cushion Pressure

t-Test: Two-Sample Assuming Unequal Variances

	Low	High
Mean	0.41267	0.43115
Variance	0.01903	0.00798
Observations	20	43
Pearson Correlatior	#N/A	
Pooled Variance	3.5	
df	26.6768	
t	-0.5481	
P(T<=t) one-tail	0.29413	
t Critical one-tail	1.70562	
P(T<=t) two-tail	0.58827	
t Critical two-tail	2.05553	

F-Test: Two-Sample for Variances

	Low	High
Mean	0.41267	0.43115
Variance	0.01903	0.00798
Observations	20	43
df	19	42
F	2.38426	
P(F<=f) one-tail	0.00954	
F Critical one-tail	1.83987	
Maximum	0.6645	0.7097
3rd Quartile	0.4795	0.4774
Median	0.3941	0.4085
1st Quartile	0.3249	0.3691
Minimum	0.2302	0.2973

Avg. Hem Gap by Inner Panel Cushion Pressure

t-Test: Two-Sample Assuming Equal Variances

	Low	High
Mean	2.52983	2.51656
Variance	0.00235	0.00172
Observations	20	43
Pooled Variance	0.00192	
Hypothesized Mean	0	
df	61	
t	1.11915	
P(T<=t) one-tail	0.13373	
t Critical one-tail	1.67022	
P(T<=t) two-tail	0.26746	
t Critical two-tail	1.99962	

F-Test: Two-Sample for Variances

	Low	High
Mean	2.52983	2.51656
Variance	0.00235	0.00172
Observations	20	43
df	19	42
F	1.36407	
P(F<=f) one-tail	0.19748	
F Critical one-tail	1.83987	
Maximum	2.6433	2.6344
3rd Quartile	2.5681	2.5300
Median	2.5161	2.5078
1st Quartile	2.4942	2.4922
Minimum	2.4656	2.4200

RMS Flush by Inner Panel Lube Level

t-Test: Two-Sample Assuming Unequal Variances

	Low	High
Mean	0.51387	0.4672
Variance	0.00311	0.00969
Observations	48	15
Pearson Correlatior	#N/A	
Pooled Variance	0.00192	
df	16.893	
t	1.75042	
P(T<=t) one-tail	0.0496	
t Critical one-tail	1.74588	
P(T<=t) two-tail	0.09919	
t Critical two-tail	2.1199	

F-Test: Two-Sample for Variances

	Low	High
Mean	0.51387	0.4672
Variance	0.00311	0.00969
Observations	48	15
df	47	14
F	3.12155	
P(F<=f) one-tail	0.00173	
F Critical one-tail	1.65156	
Maximum	0.6346	0.6808
3rd Quartile	0.5445	0.5200
Median	0.5162	0.4583
1st Quartile	0.4917	0.4085
Minimum	0.3736	0.2885

Left Door Output Measures

RMS x-Gap by Inner Panel Lube Level

t-Test: Two-Sample Assuming Unequal Variances

	Low	*High*
Mean	0.30937	0.23345
Variance	0.00629	0.00098
Observations	48	15
Pearson Correlatior	#N/A	
Pooled Variance	0.00192	
df	57.5714	
t	5.42179	
P(T<=t) one-tail	6.2E-07	
t Critical one-tail	1.67203	
P(T<=t) two-tail	1.2E-06	
t Critical two-tail	2.00247	

F-Test: Two-Sample for Variances

	Low	*High*
Mean	0.30937	0.23345
Variance	0.00629	0.00098
Observations	48	15
df	47	14
F	6.43478	
P(F<=f) one-tail	0.00025	
F Critical one-tail	2.24716	
Maximum	0.4473	0.3181
3rd Quartile	0.3714	0.2456
Median	0.3128	0.2359
1st Quartile	0.2543	0.2093
Minimum	0.1671	0.1941

RMS z-Gap by Inner Panel Lube Level

t-Test: Two-Sample Assuming Unequal Variances

	Low	*High*
Mean	0.42814	0.41616
Variance	0.00897	0.01988
Observations	48	15
Pearson Correlatior	#N/A	
Pooled Variance	0.00192	
df	18.1208	
t	0.30797	
P(T<=t) one-tail	0.38082	
t Critical one-tail	1.73406	
P(T<=t) two-tail	0.76164	
t Critical two-tail	2.10092	

F-Test: Two-Sample for Variances

	Low	*High*
Mean	0.42814	0.41616
Variance	0.00897	0.01988
Observations	48	15
df	47	14
F	2.21541	
P(F<=f) one-tail	0.02135	
F Critical one-tail	1.65156	
Maximum	0.6757	0.7097
3rd Quartile	0.4834	0.4262
Median	0.4228	0.3696
1st Quartile	0.3631	0.3428
Minimum	0.2348	0.2302

Avg. Hem Gap by Inner Panel Lube Level

t-Test: Two-Sample Assuming Unequal Variances

	Low	*High*
Mean	2.51773	2.53052
Variance	0.00165	0.00288
Observations	48	15
Pearson Correlatior	#N/A	
Pooled Variance	0.00192	
df	19.2671	
t	-0.8504	
P(T<=t) one-tail	0.20284	
t Critical one-tail	1.72913	
P(T<=t) two-tail	0.40569	
t Critical two-tail	2.09302	

F-Test: Two-Sample for Variances

	Low	*High*
Mean	2.51773	2.53052
Variance	0.00165	0.00288
Observations	48	15
df	47	14
F	1.74883	
P(F<=f) one-tail	0.07713	
F Critical one-tail	1.65156	
Maximum	2.6178	2.6433
3rd Quartile	2.5400	2.5628
Median	2.5094	2.5122
1st Quartile	2.4928	2.4928
Minimum	2.4200	2.4767

Left Door Output Measures

RMS Flush by Outer Panel Steel Grade

t-Test: Two-Sample Assuming Unequal Variances

	660	*548*
Mean	0.51308	0.49276
Variance	0.00346	0.00633
Observations	31	32
Pearson Correlatior	#N/A	
Pooled Variance	0.00192	
df	57.0751	
t	1.155	
P(T<=t) one-tail	0.12645	
t Critical one-tail	1.67203	
P(T<=t) two-tail	0.25291	
t Critical two-tail	2.00247	

F-Test: Two-Sample for Variances

	660	*548*
Mean	0.51308	0.49276
Variance	0.00346	0.00633
Observations	31	32
df	30	31
F	1.82953	
P(F<=f) one-tail	0.05078	
F Critical one-tail	1.60231	
Maximum	0.6346	0.6808
3rd Quartile	0.5450	0.5417
Median	0.5098	0.5055
1st Quartile	0.4836	0.4480
Minimum	0.3736	0.2885

RMS x-Gap by Outer Panel Steel Grade

t-Test: Two-Sample Assuming Equal Variances

	660	*548*
Mean	0.31155	0.27168
Variance	0.00639	0.00511
Observations	31	32
Pooled Variance	0.00574	
Hypothesized Mean	0	
df	61	
t	2.08897	
P(T<=t) one-tail	0.02044	
t Critical one-tail	1.67022	
P(T<=t) two-tail	0.04089	
t Critical two-tail	1.99962	

F-Test: Two-Sample for Variances

	660	*548*
Mean	0.31155	0.27168
Variance	0.00639	0.00511
Observations	31	32
df	30	31
F	1.25137	
P(F<=f) one-tail	0.26902	
F Critical one-tail	1.82834	
Maximum	0.4473	0.4243
3rd Quartile	0.3970	0.3246
Median	0.2839	0.2515
1st Quartile	0.2523	0.2082
Minimum	0.1671	0.1753

RMS z-Gap by Outer Panel Steel Grade

t-Test: Two-Sample Assuming Equal Variances

	660	*548*
Mean	0.44552	0.40568
Variance	0.01017	0.01199
Observations	31	32
Pooled Variance	0.01109	
Hypothesized Mean	0	
df	61	
t	1.50124	
P(T<=t) one-tail	0.06923	
t Critical one-tail	1.67022	
P(T<=t) two-tail	0.13845	
t Critical two-tail	1.99962	

F-Test: Two-Sample for Variances

	660	*548*
Mean	0.44552	0.40568
Variance	0.01017	0.01199
Observations	31	32
df	30	31
F	1.17927	
P(F<=f) one-tail	0.32668	
F Critical one-tail	1.60231	
Maximum	0.7097	0.6645
3rd Quartile	0.5022	0.4488
Median	0.4248	0.4015
1st Quartile	0.3711	0.3387
Minimum	0.2973	0.2302

Left Door Output Measures

Avg. Hem Gap by Outer Panel Steel Grade

t-Test: Two-Sample Assuming Equal Variances

	660	*548*
Mean	2.51441	2.52694
Variance	0.00167	0.00215
Observations	31	32
Pooled Variance	0.00192	
Hypothesized Mean	0	
df	61	
t	-1.1358	
P(T<=t) one-tail	0.13024	
t Critical one-tail	1.67022	
P(T<=t) two-tail	0.26048	
t Critical two-tail	1.99962	

F-Test: Two-Sample for Variances

	660	*548*
Mean	2.51441	2.52694
Variance	0.00167	0.00215
Observations	31	32
df	30	31
F	1.28661	
P(F<=f) one-tail	0.24612	
F Critical one-tail	1.60231	
Maximum	2.6344	2.6433
3rd Quartile	2.5339	2.5658
Median	2.5100	2.5106
1st Quartile	2.4928	2.4928
Minimum	2.4200	2.4656

RMS Flush by Outer Panel Cushion Pressure

t-Test: Two-Sample Assuming Equal Variances

	Low	*High*
Mean	0.52968	0.49234
Variance	0.00398	0.00511
Observations	20	39
Pooled Variance	0.00474	
Hypothesized Mean	0	
df	57	
t	1.97312	
P(T<=t) one-tail	0.02667	
t Critical one-tail	1.67203	
P(T<=t) two-tail	0.05334	
t Critical two-tail	2.00247	

F-Test: Two-Sample for Variances

	Low	*High*
Mean	0.52968	0.49234
Variance	0.00398	0.00511
Observations	20	39
df	19	38
F	1.28416	
P(F<=f) one-tail	0.28433	
F Critical one-tail	1.73454	
Maximum	0.6808	0.6346
3rd Quartile	0.5548	0.5428
Median	0.5357	0.5043
1st Quartile	0.4984	0.4527
Minimum	0.3905	0.2885

RMS x-Gap by Outer Panel Cushion Pressure

t-Test: Two-Sample Assuming Equal Variances

	Low	*High*
Mean	0.2968	0.28036
Variance	0.00686	0.00524
Observations	20	39
Pooled Variance	0.00578	
Hypothesized Mean	0	
df	57	
t	0.78623	
P(T<=t) one-tail	0.21749	
t Critical one-tail	1.67203	
P(T<=t) two-tail	0.43499	
t Critical two-tail	2.00247	

F-Test: Two-Sample for Variances

	Low	*High*
Mean	0.2968	0.28036
Variance	0.00686	0.00524
Observations	20	39
df	19	38
F	1.30823	
P(F<=f) one-tail	0.23469	
F Critical one-tail	1.86733	
Maximum	0.4261	0.4473
3rd Quartile	0.3714	0.3235
Median	0.2821	0.2589
1st Quartile	0.2144	0.2366
Minimum	0.1855	0.1671

Left Door Output Measures

RMS z-Gap by Outer Panel Cushion Pressure

t-Test: Two-Sample Assuming Unequal Variances

	Low	*High*
Mean	0.40696	0.43212
Variance	0.00689	0.014
Observations	20	39
Pearson Correlatior	#N/A	
Pooled Variance	0.00578	
df	51.3537	
t	-0.9487	
P(T<=t) one-tail	0.17362	
t Critical one-tail	1.67528	
P(T<=t) two-tail	0.34723	
t Critical two-tail	2.00758	

F-Test: Two-Sample for Variances

	Low	*High*
Mean	0.40696	0.43212
Variance	0.00689	0.014
Observations	20	39
df	19	38
F	2.03248	
P(F<=f) one-tail	0.05013	
F Critical one-tail	1.73454	
Maximum	0.5269	0.7097
3rd Quartile	0.4761	0.4725
Median	0.4130	0.3989
1st Quartile	0.3557	0.3585
Minimum	0.2558	0.2302

Avg. Hem Gap by Outer Panel Cushion Pressure

t-Test: Two-Sample Assuming Equal Variances

	Low	*High*
Mean	2.51356	2.52353
Variance	0.00202	0.00204
Observations	20	39
Pooled Variance	0.00203	
Hypothesized Mean	0	
df	57	
t	-0.8047	
P(T<=t) one-tail	0.21216	
t Critical one-tail	1.67203	
P(T<=t) two-tail	0.42432	
t Critical two-tail	2.00247	

F-Test: Two-Sample for Variances

	Low	*High*
Mean	2.51356	2.52353
Variance	0.00202	0.00204
Observations	20	39
df	19	38
F	1.00702	
P(F<=f) one-tail	0.51075	
F Critical one-tail	1.73454	
Maximum	2.6433	2.6344
3rd Quartile	2.5200	2.5606
Median	2.5061	2.5111
1st Quartile	2.4972	2.4900
Minimum	2.4200	2.4344

RMS Flush by Outer Panel Lube Level

t-Test: Two-Sample Assuming Unequal Variances

	Low	*High*
Mean	0.49685	0.52012
Variance	0.00579	0.00225
Observations	47	16
Pearson Correlatior	#N/A	
Pooled Variance	0.00203	
df	42.194	
t	-1.4326	
P(T<=t) one-tail	0.07968	
t Critical one-tail	1.68195	
P(T<=t) two-tail	0.15936	
t Critical two-tail	2.01808	

F-Test: Two-Sample for Variances

	Low	*High*
Mean	0.49685	0.52012
Variance	0.00579	0.00225
Observations	47	16
df	46	15
F	2.56974	
P(F<=f) one-tail	0.02463	
F Critical one-tail	2.1872	
Maximum	0.6808	0.5712
3rd Quartile	0.5390	0.5445
Median	0.5038	0.5389
1st Quartile	0.4527	0.5059
Minimum	0.2885	0.3785

Left Door Output Measures

RMS x-Gap by Outer Panel Lube Level

t-Test: Two-Sample Assuming Equal Variances

	Low	*High*
Mean	0.27841	0.32915
Variance	0.00593	0.00475
Observations	47	16
Pooled Variance	0.00564	
Hypothesized Mean	0	
df	61	
t	-2.3335	
P(T<=t) one-tail	0.01147	
t Critical one-tail	1.67022	
P(T<=t) two-tail	0.02293	
t Critical two-tail	1.99962	

F-Test: Two-Sample for Variances

	Low	*High*
Mean	0.27841	0.32915
Variance	0.00593	0.00475
Observations	47	16
df	46	15
F	1.24875	
P(F<=f) one-tail	0.32935	
F Critical one-tail	2.1872	
Maximum	0.4473	0.4434
3rd Quartile	0.3324	0.3927
Median	0.2549	0.3233
1st Quartile	0.2160	0.2879
Minimum	0.1671	0.1960

RMS z-Gap by Outer Panel Lube Level

t-Test: Two-Sample Assuming Unequal Variances

	Low	*High*
Mean	0.41943	0.44247
Variance	0.0137	0.00433
Observations	47	16
Pearson Correlatior	#N/A	
Pooled Variance	0.00564	
df	46.929	
t	-0.9716	
P(T<=t) one-tail	0.16818	
t Critical one-tail	1.67866	
P(T<=t) two-tail	0.33635	
t Critical two-tail	2.01289	

F-Test: Two-Sample for Variances

	Low	*High*
Mean	0.41943	0.44247
Variance	0.0137	0.00433
Observations	47	16
df	46	15
F	3.16073	
P(F<=f) one-tail	0.00905	
F Critical one-tail	2.1872	
Maximum	0.7097	0.5269
3rd Quartile	0.4590	0.4834
Median	0.3855	0.4487
1st Quartile	0.3[illegible]	0.4205
Minimum	0.2[illegible]	0.2558

Avg. Hem Gap by Outer Panel Lube Level

t-Test: Two-Sample Assuming Equal Variances

	Low	*High*
Mean	2.5227	2.51514
Variance	0.00201	0.00176
Observations	47	16
Pooled Variance	0.00195	
Hypothesized Mean	0	
df	61	
t	0.59157	
P(T<=t) one-tail	0.27816	
t Critical one-tail	1.67022	
P(T<=t) two-tail	0.55632	
t Critical two-tail	1.99962	

F-Test: Two-Sample for Variances

	Low	*High*
Mean	2.5227	2.51514
Variance	0.00201	0.00176
Observations	47	16
df	46	15
F	1.14359	
P(F<=f) one-tail	0.40484	
F Critical one-tail	2.1872	
Maximum	2.6433	2.5878
3rd Quartile	2.5528	2.5289
Median	2.5089	2.5128
1st Quartile	2.4944	2.4892
Minimum	2.4200	2.4344

Left Door Output Measures

RMS Flush by Hemmer Set Point

t-Test: Two-Sample Assuming Equal Variances

	-15.0	*-14.9*
Mean	0.4833	0.52161
Variance	0.00505	0.00426
Observations	31	32
Pooled Variance	0.00465	
Hypothesized Mean	0	
df	61	
t	-2.2304	
P(T<=t) one-tail	0.0147	
t Critical one-tail	1.67022	
P(T<=t) two-tail	0.02941	
t Critical two-tail	1.99962	

F-Test: Two-Sample for Variances

	-15.0	*-14.9*
Mean	0.4833	0.52161
Variance	0.00505	0.00426
Observations	31	32
df	30	31
F	1.18489	
P(F<=f) one-tail	0.32043	
F Critical one-tail	1.82834	
Maximum	0.5976	0.6808
3rd Quartile	0.5390	0.5498
Median	0.4958	0.5214
1st Quartile	0.4452	0.5002
Minimum	0.2885	0.3785

RMS x-Gap by Hemmer Set Point

t-Test: Two-Sample Assuming Equal Variances

	-15.0	*-14.9*
Mean	0.29708	0.2857
Variance	0.00636	0.00587
Observations	31	32
Pooled Variance	0.00611	
Hypothesized Mean	0	
df	61	
t	0.5773	
P(T<=t) one-tail	0.28293	
t Critical one-tail	1.67022	
P(T<=t) two-tail	0.56586	
t Critical two-tail	1.99962	

F-Test: Two-Sample for Variances

	-15.0	*-14.9*
Mean	0.29708	0.2857
Variance	0.00636	0.00587
Observations	31	32
df	30	31
F	1.0838	
P(F<=f) one-tail	0.41201	
F Critical one-tail	1.82834	
Maximum	0.4473	0.4298
3rd Quartile	0.3574	0.3286
Median	0.2693	0.2718
1st Quartile	0.2374	0.2308
Minimum	0.1753	0.1671

RMS z-Gap by Hemmer Set Point

t-Test: Two-Sample Assuming Unequal Variances

	-15.0	*-14.9*
Mean	0.40149	0.44833
Variance	0.00819	0.01359
Observations	31	32
Pearson Correlatior	#N/A	
Pooled Variance	0.00611	
df	58.264	
t	-1.7845	
P(T<=t) one-tail	0.03979	
t Critical one-tail	1.67155	
P(T<=t) two-tail	0.07958	
t Critical two-tail	2.00172	

F-Test: Two-Sample for Variances

	-15.0	*-14.9*
Mean	0.40149	0.44833
Variance	0.00819	0.01359
Observations	31	32
df	30	31
F	1.65964	
P(F<=f) one-tail	0.08438	
F Critical one-tail	1.60231	
Maximum	0.6544	0.7097
3rd Quartile	0.4738	0.4987
Median	0.3855	0.4311
1st Quartile	0.3449	0.3674
Minimum	0.2302	0.2558

Left Door Output Measures

Avg. Hem Gap by Hemmer Set Point

t-Test: Two-Sample Assuming Equal Variances

	-15.0	*-14.9*
Mean	2.50265	2.53833
Variance	0.00127	0.00198
Observations	31	32
Pooled Variance	0.00163	
Hypothesized Mean	0	
df	61	
t	-3.507	
P(T<=t) one-tail	0.00043	
t Critical one-tail	1.67022	
P(T<=t) two-tail	0.00086	
t Critical two-tail	1.99962	

F-Test: Two-Sample for Variances

	-15.0	*-14.9*
Mean	2.50265	2.53833
Variance	0.00127	0.00198
Observations	31	32
df	30	31
F	1.56577	
P(F<=f) one-tail	0.11136	
F Critical one-tail	1.60231	
Maximum	2.5878	2.6433
3rd Quartile	2.5156	2.5669
Median	2.5011	2.5250
1st Quartile	2.4856	2.5033
Minimum	2.4200	2.4767

RMS Flush by Induction Cure Cycle

t-Test: Two-Sample Assuming Equal Variances

	On	*Off*
Mean	0.50598	0.49943
Variance	0.00569	0.00432
Observations	32	31
Pooled Variance	0.00501	
Hypothesized Mean	0	
df	61	
t	0.36693	
P(T<=t) one-tail	0.35747	
t Critical one-tail	1.67022	
P(T<=t) two-tail	0.71494	
t Critical two-tail	1.99962	

F-Test: Two-Sample for Variances

	On	*Off*
Mean	0.50598	0.49943
Variance	0.00569	0.00432
Observations	32	31
df	31	30
F	1.31715	
P(F<=f) one-tail	0.22644	
F Critical one-tail	1.83469	
Maximum	0.6808	0.6346
3rd Quartile	0.5460	0.5399
Median	0.5094	0.5076
1st Quartile	0.4708	0.4597
Minimum	0.2885	0.3496

RMS x-Gap by Induction Cure Cycle

t-Test: Two-Sample Assuming Equal Variances

	On	*Off*
Mean	0.30296	0.27926
Variance	0.00534	0.00668
Observations	32	31
Pooled Variance	0.006	
Hypothesized Mean	0	
df	61	
t	1.21423	
P(T<=t) one-tail	0.11467	
t Critical one-tail	1.67022	
P(T<=t) two-tail	0.22934	
t Critical two-tail	1.99962	

F-Test: Two-Sample for Variances

	On	*Off*
Mean	0.30296	0.27926
Variance	0.00534	0.00668
Observations	32	31
df	31	30
F	1.25088	
P(F<=f) one-tail	0.26937	
F Critical one-tail	1.59803	
Maximum	0.4473	0.4434
3rd Quartile	0.3461	0.3436
Median	0.2961	0.2508
1st Quartile	0.2487	0.2134
Minimum	0.1941	0.1671

Left Door Output Measures

RMS z-Gap by Induction Cure Cycle

t-Test: Two-Sample Assuming Unequal Variances

	On	*Off*
Mean	0.462	0.38739
Variance	0.01442	0.00556
Observations	32	31
Pearson Correlatior	#N/A	
Pooled Variance	0.006	
df	52.0577	
t	2.97247	
P(T<=t) one-tail	0.00223	
t Critical one-tail	1.67469	
P(T<=t) two-tail	0.00447	
t Critical two-tail	2.00665	

F-Test: Two-Sample for Variances

	On	*Off*
Mean	0.462	0.38739
Variance	0.01442	0.00556
Observations	32	31
df	31	30
F	2.59477	
P(F<=f) one-tail	0.00529	
F Critical one-tail	1.83469	

Maximum	0.7097	0.5203
3rd Quartile	0.5139	0.4251
Median	0.4426	0.3878
1st Quartile	0.3631	0.3354
Minimum	0.2302	0.2348

Avg. Hem Gap by Induction Cure Cycle

t-Test: Two-Sample Assuming Unequal Variances

	On	*Off*
Mean	2.52781	2.51351
Variance	0.00253	0.00126
Observations	32	31
Pearson Correlatior	#N/A	
Pooled Variance	0.006	
df	55.7726	
t	1.30688	
P(T<=t) one-tail	0.09835	
t Critical one-tail	1.67303	
P(T<=t) two-tail	0.19669	
t Critical two-tail	2.00404	

F-Test: Two-Sample for Variances

	On	*Off*
Mean	2.52781	2.51351
Variance	0.00253	0.00126
Observations	32	31
df	31	30
F	2.01501	
P(F<=f) one-tail	0.0291	
F Critical one-tail	1.83469	

Maximum	2.6433	2.5922
3rd Quartile	2.5669	2.5300
Median	2.5094	2.5122
1st Quartile	2.4986	2.4900
Minimum	2.4344	2.4200

Right Door Output Measures

RMS Flush by Inner Panel Steel Grade

t-Test: Two-Sample Assuming Equal Variances

	019	*982*
Mean	0.57719	0.58937
Variance	0.00677	0.0043
Observations	33	30
Pooled Variance	0.0056	
Hypothesized Mean	0	
df	61	
t	-0.6455	
P(T<=t) one-tail	0.26051	
t Critical one-tail	1.67022	
P(T<=t) two-tail	0.52101	
t Critical two-tail	1.99962	

F-Test: Two-Sample for Variances

	019	*982*
Mean	0.57719	0.58937
Variance	0.00677	0.0043
Observations	33	30
df	32	29
F	1.57348	
P(F<=f) one-tail	0.11042	
F Critical one-tail	1.84236	
Maximum	0.7049	0.7090
3rd Quartile	0.6339	0.6433
Median	0.5923	0.5888
1st Quartile	0.5308	0.5414
Minimum	0.3216	0.4301

RMS x-Gap by Inner Panel Steel Grade

t-Test: Two-Sample Assuming Unequal Variances

	019	*982*
Mean	0.2324	0.20715
Variance	0.005	0.00092
Observations	33	30
Pearson Correlatior	#N/A	
Pooled Variance	0.0056	
df	44.2445	
t	1.87122	
P(T<=t) one-tail	0.03399	
t Critical one-tail	1.68023	
P(T<=t) two-tail	0.06797	
t Critical two-tail	2.01537	

F-Test: Two-Sample for Variances

	019	*982*
Mean	0.2324	0.20715
Variance	0.005	0.00092
Observations	33	30
df	32	29
F	5.4442	
P(F<=f) one-tail	7.1E-06	
F Critical one-tail	1.84236	
Maximum	0.4652	0.2779
3rd Quartile	0.2435	0.2251
Median	0.2140	0.2054
1st Quartile	0.1821	0.1812
Minimum	0.1611	0.1682

RMS z-Gap by Inner Panel Steel Grade

t-Test: Two-Sample Assuming Equal Variances

	019	*982*
Mean	0.26196	0.27713
Variance	0.00204	0.00233
Observations	33	30
Pooled Variance	0.00218	
Hypothesized Mean	0	
df	61	
t	-1.2886	
P(T<=t) one-tail	0.10121	
t Critical one-tail	1.67022	
P(T<=t) two-tail	0.20242	
t Critical two-tail	1.99962	

F-Test: Two-Sample for Variances

	019	*982*
Mean	0.26196	0.27713
Variance	0.00204	0.00233
Observations	33	30
df	32	29
F	1.14472	
P(F<=f) one-tail	0.35347	
F Critical one-tail	1.5946	
Maximum	0.3884	0.3661
3rd Quartile	0.2897	0.3122
Median	0.2587	0.2677
1st Quartile	0.2369	0.2390
Minimum	0.1475	0.1934

Right Door Output Measures

Avg. Hem Gap by Inner Panel Steel Grade

t-Test: Two-Sample Assuming Equal Variances

	019	*982*
Mean	2.60139	2.59047
Variance	0.00433	0.0048
Observations	33	30
Pooled Variance	0.00455	
Hypothesized Mean	0	
df	61	
t	0.64134	
P(T<=t) one-tail	0.26185	
t Critical one-tail	1.67022	
P(T<=t) two-tail	0.5237	
t Critical two-tail	1.99962	

F-Test: Two-Sample for Variances

	019	*982*
Mean	2.60139	2.59047
Variance	0.00433	0.0048
Observations	33	30
df	32	29
F	1.11003	
P(F<=f) one-tail	0.38526	
F Critical one-tail	1.5946	
Maximum	2.7250	2.7963
3rd Quartile	2.6433	2.6292
Median	2.6067	2.5956
1st Quartile	2.5422	2.5333
Minimum	2.4822	2.4933

RMS Flush by Inner Panel Cushion Pressure

t-Test: Two-Sample Assuming Equal Variances

	Low	*High*
Mean	0.56781	0.59005
Variance	0.0046	0.00594
Observations	20	43
Pooled Variance	0.00552	
Hypothesized Mean	0	
df	61	
t	-1.1057	
P(T<=t) one-tail	0.13661	
t Critical one-tail	1.67022	
P(T<=t) two-tail	0.27321	
t Critical two-tail	1.99962	

F-Test: Two-Sample for Variances

	Low	*High*
Mean	0.56781	0.59005
Variance	0.0046	0.00594
Observations	20	43
df	19	42
F	1.29118	
P(F<=f) one-tail	0.27841	
F Critical one-tail	1.72546	
Maximum	0.7049	0.7090
3rd Quartile	0.5960	0.6459
Median	0.5709	0.6103
1st Quartile	0.5381	0.5420
Minimum	0.4301	0.3216

RMS x-Gap by Inner Panel Cushion Pressure

t-Test: Two-Sample Assuming Unequal Variances

	Low	*High*
Mean	0.21691	0.22199
Variance	0.00172	0.00389
Observations	20	43
Pearson Correlatior	#N/A	
Pooled Variance	0.00552	
df	53.3334	
t	-0.3823	
P(T<=t) one-tail	0.35189	
t Critical one-tail	1.67412	
P(T<=t) two-tail	0.70378	
t Critical two-tail	2.00575	

F-Test: Two-Sample for Variances

	Low	*High*
Mean	0.21691	0.22199
Variance	0.00172	0.00389
Observations	20	43
df	19	42
F	2.26428	
P(F<=f) one-tail	0.02858	
F Critical one-tail	1.72546	
Maximum	0.3209	0.4652
3rd Quartile	0.2326	0.2326
Median	0.2083	0.2120
1st Quartile	0.1856	0.1808
Minimum	0.1611	0.1655

Right Door Output Measures

RMS z-Gap by Inner Panel Cushion Pressure

t-Test: Two-Sample Assuming Equal Variances

	Low	*High*
Mean	0.27022	0.2687
Variance	0.00242	0.00215
Observations	20	43
Pooled Variance	0.00224	
Hypothesized Mean	0	
df	61	
t	0.11885	
P(T<=t) one-tail	0.45289	
t Critical one-tail	1.67022	
P(T<=t) two-tail	0.90579	
t Critical two-tail	1.99962	

F-Test: Two-Sample for Variances

	Low	*High*
Mean	0.27022	0.2687
Variance	0.00242	0.00215
Observations	20	43
df	19	42
F	1.12275	
P(F<=f) one-tail	0.36505	
F Critical one-tail	1.83987	
Maximum	0.3661	0.3884
3rd Quartile	0.3030	0.2966
Median	0.2686	0.2587
1st Quartile	0.2317	0.2391
Minimum	0.1797	0.1475

Avg. Hem Gap by Inner Panel Cushion Pressure

t-Test: Two-Sample Assuming Equal Variances

	Low	*High*
Mean	2.58223	2.60268
Variance	0.00463	0.00443
Observations	20	43
Pooled Variance	0.00449	
Hypothesized Mean	0	
df	61	
t	-1.1279	
P(T<=t) one-tail	0.13188	
t Critical one-tail	1.67022	
P(T<=t) two-tail	0.26377	
t Critical two-tail	1.99962	

F-Test: Two-Sample for Variances

	Low	*High*
Mean	2.58223	2.60268
Variance	0.00463	0.00443
Observations	20	43
df	19	42
F	1.04583	
P(F<=f) one-tail	0.43513	
F Critical one-tail	1.83987	
Maximum	2.7250	2.7963
3rd Quartile	2.6206	2.6389
Median	2.5933	2.6067
1st Quartile	2.5228	2.5472
Minimum	2.4933	2.4822

RMS Flush by Inner Panel Lube Level

t-Test: Two-Sample Assuming Unequal Variances

	Low	*High*
Mean	0.58282	0.58351
Variance	0.0066	0.00239
Observations	48	15
Pearson Correlatior	#N/A	
Pooled Variance	0.00449	
df	39.7397	
t	-0.0401	
P(T<=t) one-tail	0.48412	
t Critical one-tail	1.68488	
P(T<=t) two-tail	0.96825	
t Critical two-tail	2.02269	

F-Test: Two-Sample for Variances

	Low	*High*
Mean	0.58282	0.58351
Variance	0.0066	0.00239
Observations	48	15
df	47	14
F	2.75808	
P(F<=f) one-tail	0.02084	
F Critical one-tail	2.24716	
Maximum	0.7090	0.6856
3rd Quartile	0.6444	0.6082
Median	0.6069	0.5681
1st Quartile	0.5287	0.5524
Minimum	0.3216	0.5069

Right Door Output Measures

RMS x-Gap by Inner Panel Lube Level

t-Test: Two-Sample Assuming Unequal Variances

	Low	*High*
Mean	0.21906	0.22457
Variance	0.0027	0.00494
Observations	48	15
Pearson Correlatior	#N/A	
Pooled Variance	0.00449	
df	19.0393	
t	-0.2807	
P(T<=t) one-tail	0.39099	
t Critical one-tail	1.72913	
P(T<=t) two-tail	0.78198	
t Critical two-tail	2.09302	

F-Test: Two-Sample for Variances

	Low	*High*
Mean	0.21906	0.22457
Variance	0.0027	0.00494
Observations	48	15
df	47	14
F	1.82482	
P(F<=f) one-tail	0.0628	
F Critical one-tail	1.65156	

Maximum	0.4652	0.4413
3rd Quartile	0.2331	0.2260
Median	0.2131	0.2029
1st Quartile	0.1807	0.1850
Minimum	0.1611	0.1700

RMS z-Gap by Inner Panel Lube Level

t-Test: Two-Sample Assuming Equal Variances

	Low	*High*
Mean	0.27157	0.26155
Variance	0.00238	0.00168
Observations	48	15
Pooled Variance	0.00222	
Hypothesized Mean	0	
df	61	
t	0.71863	
P(T<=t) one-tail	0.23755	
t Critical one-tail	1.67022	
P(T<=t) two-tail	0.47511	
t Critical two-tail	1.99962	

F-Test: Two-Sample for Variances

	Low	*High*
Mean	0.27157	0.26155
Variance	0.00238	0.00168
Observations	48	15
df	47	14
F	1.41837	
P(F<=f) one-tail	0.24194	
F Critical one-tail	2.24716	

Maximum	0.3884	0.3124
3rd Quartile	0.3043	0.2945
Median	0.2641	0.2669
1st Quartile	0.2373	0.2432
Minimum	0.1475	0.1797

Avg. Hem Gap by Inner Panel Lube Level

t-Test: Two-Sample Assuming Equal Variances

	Low	*High*
Mean	2.60904	2.55508
Variance	0.00423	0.00341
Observations	48	15
Pooled Variance	0.00404	
Hypothesized Mean	0	
df	61	
t	2.87052	
P(T<=t) one-tail	0.00281	
t Critical one-tail	1.67022	
P(T<=t) two-tail	0.00563	
t Critical two-tail	1.99962	

F-Test: Two-Sample for Variances

	Low	*High*
Mean	2.60904	2.55508
Variance	0.00423	0.00341
Observations	48	15
df	47	14
F	1.24021	
P(F<=f) one-tail	0.34187	
F Critical one-tail	2.24716	

Maximum	2.7963	2.6667
3rd Quartile	2.6408	2.6017
Median	2.6117	2.5344
1st Quartile	2.5578	2.5056
Minimum	2.4933	2.4822

Right Door Output Measures

RMS Flush by Outer Panel Steel Grade

t-Test: Two-Sample Assuming Equal Variances

	660	548
Mean	0.60023	0.56628
Variance	0.00623	0.00448
Observations	31	32
Pooled Variance	0.00534	
Hypothesized Mean	0	
df	61	
t	1.8441	
P(T<=t) one-tail	0.03501	
t Critical one-tail	1.67022	
P(T<=t) two-tail	0.07003	
t Critical two-tail	1.99962	

F-Test: Two-Sample for Variances

	660	548
Mean	0.60023	0.56628
Variance	0.00623	0.00448
Observations	31	32
df	30	31
F	1.39053	
P(F<=f) one-tail	0.18311	
F Critical one-tail	1.82834	
Maximum	0.7090	0.6856
3rd Quartile	0.6499	0.6142
Median	0.6280	0.5743
1st Quartile	0.5619	0.5287
Minimum	0.3216	0.4301

RMS x-Gap by Outer Panel Steel Grade

t-Test: Two-Sample Assuming Unequal Variances

	660	548
Mean	0.22796	0.21302
Variance	0.0044	0.00197
Observations	31	32
Pearson Correlatior	#N/A	
Pooled Variance	0.00534	
df	52.1474	
t	1.0472	
P(T<=t) one-tail	0.14993	
t Critical one-tail	1.67469	
P(T<=t) two-tail	0.29985	
t Critical two-tail	2.00665	

F-Test: Two-Sample for Variances

	660	548
Mean	0.22796	0.21302
Variance	0.0044	0.00197
Observations	31	32
df	30	31
F	2.23676	
P(F<=f) one-tail	0.01453	
F Critical one-tail	1.82834	
Maximum	0.4652	0.3237
3rd Quartile	0.2326	0.2327
Median	0.2197	0.2025
1st Quartile	0.1855	0.1796
Minimum	0.1682	0.1611

RMS z-Gap by Outer Panel Steel Grade

t-Test: Two-Sample Assuming Unequal Variances

	660	548
Mean	0.26234	0.27581
Variance	0.00151	0.00285
Observations	31	32
Pearson Correlatior	#N/A	
Pooled Variance	0.00534	
df	56.6183	
t	-1.1475	
P(T<=t) one-tail	0.12804	
t Critical one-tail	1.67252	
P(T<=t) two-tail	0.25607	
t Critical two-tail	2.00324	

F-Test: Two-Sample for Variances

	660	548
Mean	0.26234	0.27581
Variance	0.00151	0.00285
Observations	31	32
df	30	31
F	1.89425	
P(F<=f) one-tail	0.04181	
F Critical one-tail	1.60231	
Maximum	0.3429	0.3884
3rd Quartile	0.2898	0.3120
Median	0.2587	0.2724
1st Quartile	0.2399	0.2333
Minimum	0.1475	0.1797

Right Door Output Measures

Avg. Hem Gap by Outer Panel Steel Grade

t-Test: Two-Sample Assuming Equal Variances

	660	548
Mean	2.58477	2.60725
Variance	0.00379	0.00509
Observations	31	32
Pooled Variance	0.00445	
Hypothesized Mean	0	
df	61	
t	-1.3365	
P(T<=t) one-tail	0.09318	
t Critical one-tail	1.67022	
P(T<=t) two-tail	0.18635	
t Critical two-tail	1.99962	

F-Test: Two-Sample for Variances

	660	548
Mean	2.58477	2.60725
Variance	0.00379	0.00509
Observations	31	32
df	30	31
F	1.34403	
P(F<=f) one-tail	0.21024	
F Critical one-tail	1.60231	
Maximum	2.7186	2.7963
3rd Quartile	2.6278	2.6464
Median	2.5989	2.6070
1st Quartile	2.5372	2.5456
Minimum	2.4822	2.4933

RMS Flush by Outer Panel Cushion Pressure

t-Test: Two-Sample Assuming Unequal Variances

	Low	High
Mean	0.59901	0.57066
Variance	0.0076	0.00445
Observations	20	39
Pearson Correlatior	#N/A	
Pooled Variance	0.00445	
df	30.7463	
t	1.27525	
P(T<=t) one-tail	0.106	
t Critical one-tail	1.69726	
P(T<=t) two-tail	0.21201	
t Critical two-tail	2.04227	

F-Test: Two-Sample for Variances

	Low	High
Mean	0.59901	0.57066
Variance	0.0076	0.00445
Observations	20	39
df	19	38
F	1.70659	
P(F<=f) one-tail	0.07926	
F Critical one-tail	1.86733	
Maximum	0.7090	0.6872
3rd Quartile	0.6520	0.6281
Median	0.6157	0.5737
1st Quartile	0.5854	0.5167
Minimum	0.3216	0.4301

RMS x-Gap by Outer Panel Cushion Pressure

t-Test: Two-Sample Assuming Unequal Variances

	Low	High
Mean	0.23234	0.21309
Variance	0.00501	0.00252
Observations	20	39
Pearson Correlatior	#N/A	
Pooled Variance	0.00445	
df	29.1087	
t	1.08482	
P(T<=t) one-tail	0.14347	
t Critical one-tail	1.69913	
P(T<=t) two-tail	0.28694	
t Critical two-tail	2.04523	

F-Test: Two-Sample for Variances

	Low	High
Mean	0.23234	0.21309
Variance	0.00501	0.00252
Observations	20	39
df	19	38
F	1.986	
P(F<=f) one-tail	0.03546	
F Critical one-tail	1.86733	
Maximum	0.4652	0.4413
3rd Quartile	0.2622	0.2272
Median	0.2139	0.2029
1st Quartile	0.1818	0.1806
Minimum	0.1611	0.1655

Right Door Output Measures

RMS z-Gap by Outer Panel Cushion Pressure

t-Test: Two-Sample Assuming Unequal Variances

	Low	*High*
Mean	0.25959	0.27326
Variance	0.00138	0.00273
Observations	20	39
Pearson Correlatior	#N/A	
Pooled Variance	0.00445	
df	50.8833	
t	-1.1583	
P(T<=t) one-tail	0.12612	
t Critical one-tail	1.67591	
P(T<=t) two-tail	0.25224	
t Critical two-tail	2.00856	

F-Test: Two-Sample for Variances

	Low	*High*
Mean	0.25959	0.27326
Variance	0.00138	0.00273
Observations	20	39
df	19	38
F	1.97531	
P(F<=f) one-tail	0.05715	
F Critical one-tail	1.73454	
Maximum	0.3458	0.3884
3rd Quartile	0.2830	0.3106
Median	0.2553	0.2669
1st Quartile	0.2388	0.2379
Minimum	0.1797	0.1475

Avg. Hem Gap by Outer Panel Cushion Pressure

t-Test: Two-Sample Assuming Equal Variances

	Low	*High*
Mean	2.61855	2.58704
Variance	0.00343	0.00494
Observations	20	39
Pooled Variance	0.00444	
Hypothesized Mean	0	
df	57	
t	1.72007	
P(T<=t) one-tail	0.04542	
t Critical one-tail	1.67203	
P(T<=t) two-tail	0.09085	
t Critical two-tail	2.00247	

F-Test: Two-Sample for Variances

	Low	*High*
Mean	2.61855	2.58704
Variance	0.00343	0.00494
Observations	20	39
df	19	38
F	1.4424	
P(F<=f) one-tail	0.198	
F Critical one-tail	1.73454	
Maximum	2.7250	2.7963
3rd Quartile	2.6408	2.6328
Median	2.6211	2.5878
1st Quartile	2.5947	2.5353
Minimum	2.5256	2.4822

RMS Flush by Outer Panel Lube Level

t-Test: Two-Sample Assuming Equal Variances

	Low	*High*
Mean	0.58466	0.57807
Variance	0.00563	0.00562
Observations	47	16
Pooled Variance	0.00563	
Hypothesized Mean	0	
df	61	
t	0.30363	
P(T<=t) one-tail	0.38122	
t Critical one-tail	1.67022	
P(T<=t) two-tail	0.76245	
t Critical two-tail	1.99962	

F-Test: Two-Sample for Variances

	Low	*High*
Mean	0.58466	0.57807
Variance	0.00563	0.00562
Observations	47	16
df	46	15
F	1.0011	
P(F<=f) one-tail	0.52752	
F Critical one-tail	2.1872	
Maximum	0.7049	0.7090
3rd Quartile	0.6440	0.6294
Median	0.5894	0.6001
1st Quartile	0.5465	0.5194
Minimum	0.3216	0.4509

Right Door Output Measures

RMS x-Gap by Outer Panel Lube Level

t-Test: Two-Sample Assuming Equal Variances

	Low	*High*
Mean	0.2188	0.225
Variance	0.00346	0.00247
Observations	47	16
Pooled Variance	0.00321	
Hypothesized Mean	0	
df	61	
t	-0.3777	
P(T<=t) one-tail	0.35349	
t Critical one-tail	1.67022	
P(T<=t) two-tail	0.70698	
t Critical two-tail	1.99962	

F-Test: Two-Sample for Variances

	Low	*High*
Mean	0.2188	0.225
Variance	0.00346	0.00247
Observations	47	16
df	46	15
F	1.40112	
P(F<=f) one-tail	0.24205	
F Critical one-tail	2.1872	
Maximum	0.4652	0.3237
3rd Quartile	0.2290	0.2643
Median	0.2095	0.2132
1st Quartile	0.1823	0.1803
Minimum	0.1655	0.1611

RMS z-Gap by Outer Panel Lube Level

t-Test: Two-Sample Assuming Equal Variances

	Low	*High*
Mean	0.2743	0.25416
Variance	0.002	0.00264
Observations	47	16
Pooled Variance	0.00216	
Hypothesized Mean	0	
df	61	
t	1.49748	
P(T<=t) one-tail	0.06971	
t Critical one-tail	1.67022	
P(T<=t) two-tail	0.13943	
t Critical two-tail	1.99962	

F-Test: Two-Sample for Variances

	Low	*High*
Mean	0.2743	0.25416
Variance	0.002	0.00264
Observations	47	16
df	46	15
F	1.32222	
P(F<=f) one-tail	0.22823	
F Critical one-tail	1.63922	
Maximum	0.3661	0.3884
3rd Quartile	0.3067	0.2761
Median	0.2669	0.2449
1st Quartile	0.2381	0.2351
Minimum	0.1797	0.1475

Avg. Hem Gap by Outer Panel Lube Level

t-Test: Two-Sample Assuming Unequal Variances

	Low	*High*
Mean	2.58162	2.63898
Variance	0.00444	0.00239
Observations	47	16
Pearson Correlatior	#N/A	
Pooled Variance	0.00216	
df	35.3481	
t	-3.6716	
P(T<=t) one-tail	0.0004	
t Critical one-tail	1.68957	
P(T<=t) two-tail	0.0008	
t Critical two-tail	2.03011	

F-Test: Two-Sample for Variances

	Low	*High*
Mean	2.58162	2.63898
Variance	0.00444	0.00239
Observations	47	16
df	46	15
F	1.85656	
P(F<=f) one-tail	0.09564	
F Critical one-tail	2.1872	
Maximum	2.7963	2.7250
3rd Quartile	2.6206	2.6694
Median	2.5822	2.6411
1st Quartile	2.5344	2.6122
Minimum	2.4822	2.5300

Right Door Output Measures

RMS Flush by Hemmer Set Point

t-Test: Two-Sample Assuming Unequal Variances

	-15.0	-14.9
Mean	0.59255	0.57372
Variance	0.00368	0.00735
Observations	31	32
Pearson Correlatior	#N/A	
Pooled Variance	0.00216	
df	55.8922	
t	1.00886	
P(T<=t) one-tail	0.15873	
t Critical one-tail	1.67303	
P(T<=t) two-tail	0.31746	
t Critical two-tail	2.00404	

F-Test: Two-Sample for Variances

	-15.0	-14.9
Mean	0.59255	0.57372
Variance	0.00368	0.00735
Observations	31	32
df	30	31
F	1.9978	
P(F<=f) one-tail	0.03064	
F Critical one-tail	1.60231	

Maximum	0.6856	0.7090
3rd Quartile	0.6425	0.6282
Median	0.5920	0.5908
1st Quartile	0.5591	0.5196
Minimum	0.4616	0.3216

RMS x-Gap by Hemmer Set Point

t-Test: Two-Sample Assuming Unequal Variances

	-15.0	-14.9
Mean	0.21968	0.22105
Variance	0.00169	0.0047
Observations	31	32
Pearson Correlatior	#N/A	
Pooled Variance	0.00216	
df	50.9978	
t	-0.0964	
P(T<=t) one-tail	0.46179	
t Critical one-tail	1.67591	
P(T<=t) two-tail	0.92357	
t Critical two-tail	2.00856	

F-Test: Two-Sample for Variances

	-15.0	-14.9
Mean	0.21968	0.22105
Variance	0.00169	0.0047
Observations	31	32
df	30	31
F	2.78527	
P(F<=f) one-tail	0.00309	
F Critical one-tail	1.60231	

Maximum	0.3237	0.4652
3rd Quartile	0.2295	0.2383
Median	0.2138	0.2094
1st Quartile	0.1855	0.1803
Minimum	0.1700	0.1611

RMS z-Gap by Hemmer Set Point

t-Test: Two-Sample Assuming Equal Variances

	-15.0	-14.9
Mean	0.27783	0.26081
Variance	0.00212	0.0022
Observations	31	32
Pooled Variance	0.00216	
Hypothesized Mean	0	
df	61	
t	1.45261	
P(T<=t) one-tail	0.07573	
t Critical one-tail	1.67022	
P(T<=t) two-tail	0.15146	
t Critical two-tail	1.99962	

F-Test: Two-Sample for Variances

	-15.0	-14.9
Mean	0.27783	0.26081
Variance	0.00212	0.0022
Observations	31	32
df	30	31
F	1.03837	
P(F<=f) one-tail	0.45973	
F Critical one-tail	1.60231	

Maximum	0.3884	0.3661
3rd Quartile	0.3073	0.2895
Median	0.2809	0.2610
1st Quartile	0.2399	0.2369
Minimum	0.2096	0.1475

Right Door Output Measures

Avg. Hem Gap by Hemmer Set Point

t-Test: Two-Sample Assuming Equal Variances

	-15.0	*-14.9*
Mean	2.57254	2.6191
Variance	0.00444	0.00362
Observations	31	32
Pooled Variance	0.00402	
Hypothesized Mean	0	
df	61	
t	-2.9122	
P(T<=t) one-tail	0.0025	
t Critical one-tail	1.67022	
P(T<=t) two-tail	0.00501	
t Critical two-tail	1.99962	

F-Test: Two-Sample for Variances

	-15.0	*-14.9*
Mean	2.57254	2.6191
Variance	0.00444	0.00362
Observations	31	32
df	30	31
F	1.22659	
P(F<=f) one-tail	0.28736	
F Critical one-tail	1.82834	
Maximum	2.7250	2.7963
3rd Quartile	2.6133	2.6464
Median	2.5589	2.6211
1st Quartile	2.5200	2.5808
Minimum	2.4822	2.5067

RMS Flush by Induction Cure Cycle

t-Test: Two-Sample Assuming Equal Variances

	On	*Off*
Mean	0.578	0.58782
Variance	0.00673	0.00452
Observations	31	32
Pooled Variance	0.00561	
Hypothesized Mean	0	
df	61	
t	-0.5205	
P(T<=t) one-tail	0.30231	
t Critical one-tail	1.67022	
P(T<=t) two-tail	0.60463	
t Critical two-tail	1.99962	

F-Test: Two-Sample for Variances

	On	*Off*
Mean	0.578	0.58782
Variance	0.00673	0.00452
Observations	31	32
df	30	31
F	1.4886	
P(F<=f) one-tail	0.13806	
F Critical one-tail	1.82834	
Maximum	0.7049	0.7090
3rd Quartile	0.6335	0.6447
Median	0.6063	0.5840
1st Quartile	0.5258	0.5431
Minimum	0.3216	0.4301

RMS x-Gap by Induction Cure Cycle

t-Test: Two-Sample Assuming Equal Variances

	On	*Off*
Mean	0.21604	0.22457
Variance	0.00266	0.00373
Observations	31	32
Pooled Variance	0.0032	
Hypothesized Mean	0	
df	61	
t	-0.5981	
P(T<=t) one-tail	0.27599	
t Critical one-tail	1.67022	
P(T<=t) two-tail	0.55199	
t Critical two-tail	1.99962	

F-Test: Two-Sample for Variances

	On	*Off*
Mean	0.21604	0.22457
Variance	0.00266	0.00373
Observations	31	32
df	30	31
F	1.40471	
P(F<=f) one-tail	0.17734	
F Critical one-tail	1.60231	
Maximum	0.4413	0.4652
3rd Quartile	0.2206	0.2452
Median	0.2094	0.2226
1st Quartile	0.1838	0.1805
Minimum	0.1700	0.1611

Right Door Output Measures

RMS z-Gap by Induction Cure Cycle

t-Test: Two-Sample Assuming Equal Variances

	On	*Off*
Mean	0.27062	0.26779
Variance	0.00208	0.00239
Observations	31	32
Pooled Variance	0.00224	
Hypothesized Mean	0	
df	61	
t	0.23806	
P(T<=t) one-tail	0.40632	
t Critical one-tail	1.67022	
P(T<=t) two-tail	0.81264	
t Critical two-tail	1.99962	

F-Test: Two-Sample for Variances

	On	*Off*
Mean	0.27062	0.26779
Variance	0.00208	0.00239
Observations	31	32
df	30	31
F	1.15106	
P(F<=f) one-tail	0.35088	
F Critical one-tail	1.60231	
Maximum	0.3861	0.3884
3rd Quartile	0.3007	0.2994
Median	0.2685	0.2535
1st Quartile	0.2414	0.2362
Minimum	0.1475	0.1797

Avg. Hem Gap by Induction Cure Cycle

t-Test: Two-Sample Assuming Unequal Variances

	On	*Off*
Mean	2.59837	2.59408
Variance	0.00333	0.00579
Observations	31	32
Pearson Correlatior	#N/A	
Pooled Variance	0.00224	
df	57.7052	
t	0.25273	
P(T<=t) one-tail	0.40069	
t Critical one-tail	1.67203	
P(T<=t) two-tail	0.80139	
t Critical two-tail	2.00247	

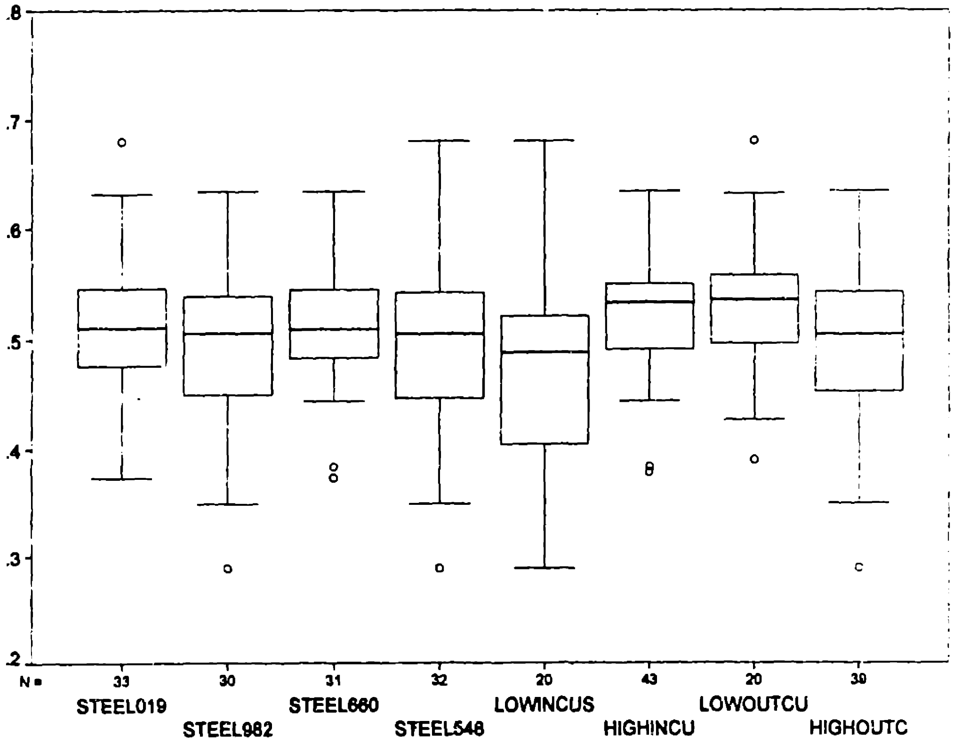
F-Test: Two-Sample for Variances

	On	*Off*
Mean	2.59837	2.59408
Variance	0.00333	0.00579
Observations	31	32
df	30	31
F	1.74007	
P(F<=f) one-tail	0.06639	
F Critical one-tail	1.60231	
Maximum	2.6978	2.7963
3rd Quartile	2.6394	2.6331
Median	2.6063	2.5961
1st Quartile	2.5533	2.5344
Minimum	2.4878	2.4822

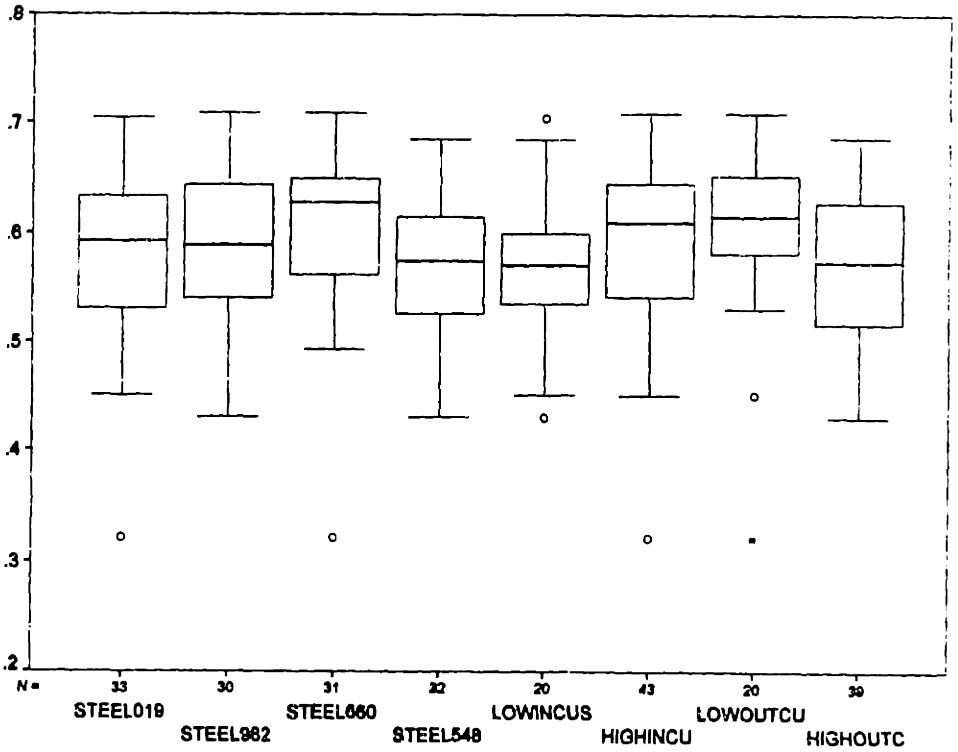
APPENDIX D. DOOR ASSEMBLY EXPERIMENT MAIN EFFECTS.

This appendix presents the door assembly experiment main effects in graphical form. Boxplots are used to compare the levels of each factor for each output measure, as described in Appendix B.

Each box in the charts has an eight character code name to signify the level of the factor that the box represents. For the steel grades, the codes are STEEL019, STEEL982, STEEL660 and STEEL548 for the 019, 982, 660 and 548 steel grades, respectively. For the cushion pressures, the codes are LOWINCUS, HIGHINCU, LOWOUTCU and HIGHOUTC to represent the low inner cushion pressure, high inner cushion pressure, low outer cushion pressure and high outer cushion pressure. For the lubricant levels, the codes are LOWINLUB, HIGHINLU, LOWOUTLU and HIGHOUTL to represent the low inner lubricant level, high inner lubricant level, low outer lubricant level and high outer lubricant level, respectively. For the hemmer set points, the codes are HEMSET15 and HEMSET14 to represent the hemmer set points -15.0 and -14.9. Finally, for the induction cure cycles, the codes are INDUCTON and INDUCOFF to represent the induction cure cycle on and off.

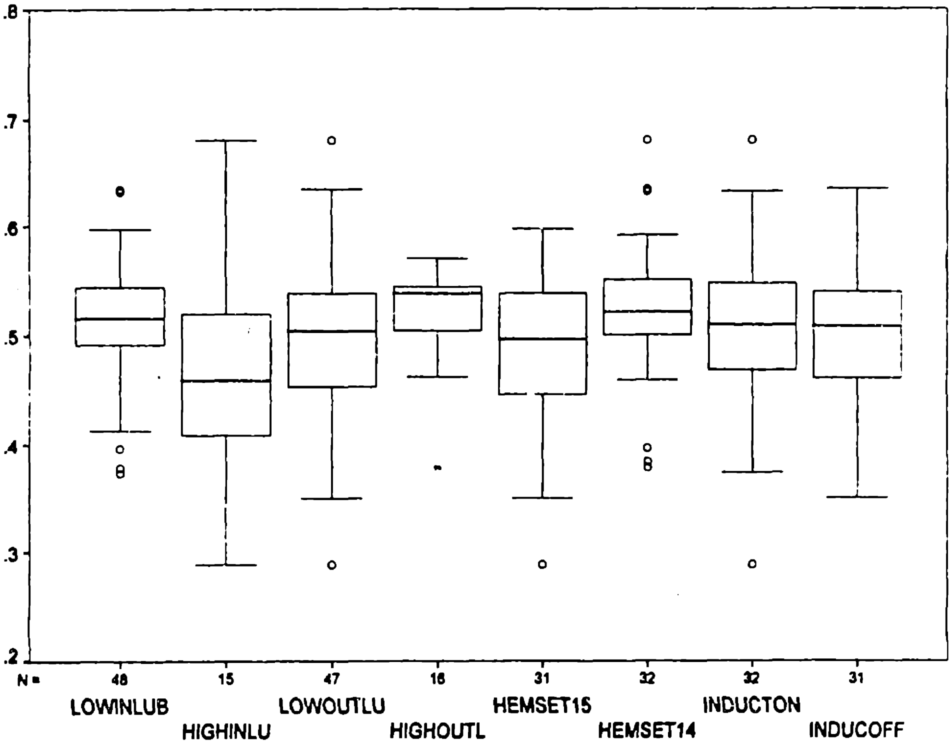


Left Door RMS Flushness 1

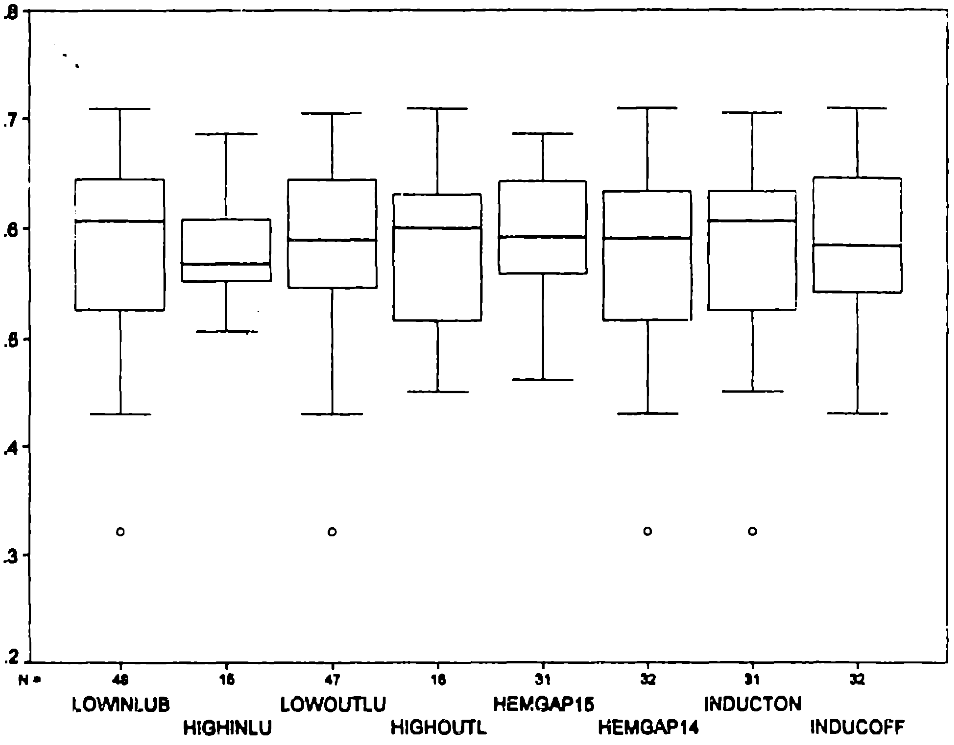


Right Door RMS Flushness 1

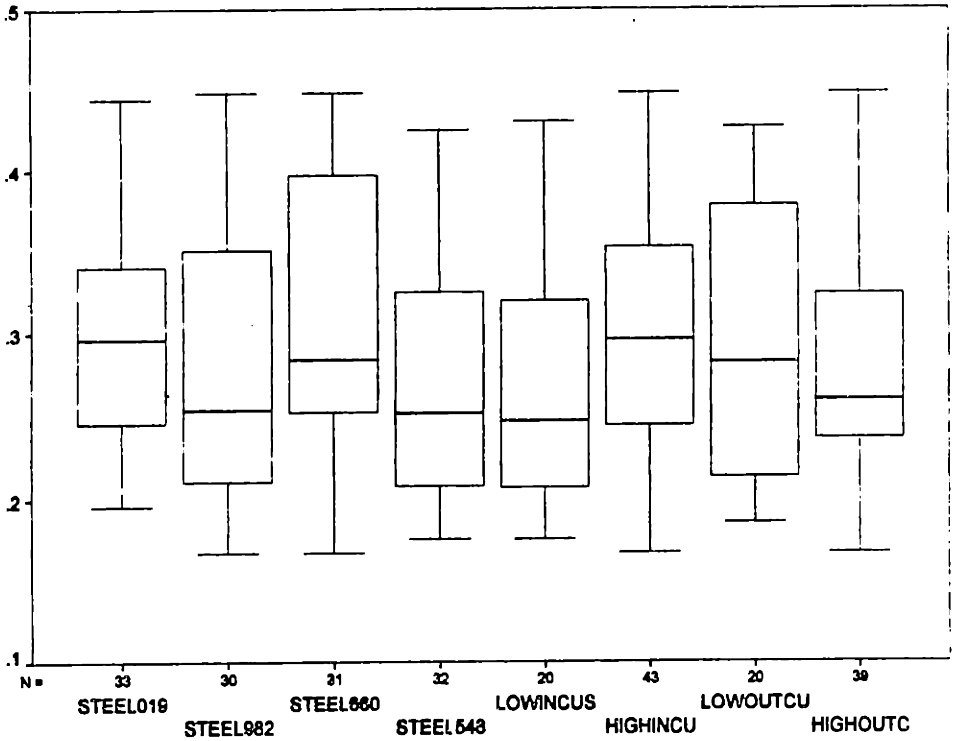
Left Door RMS Flushness 2



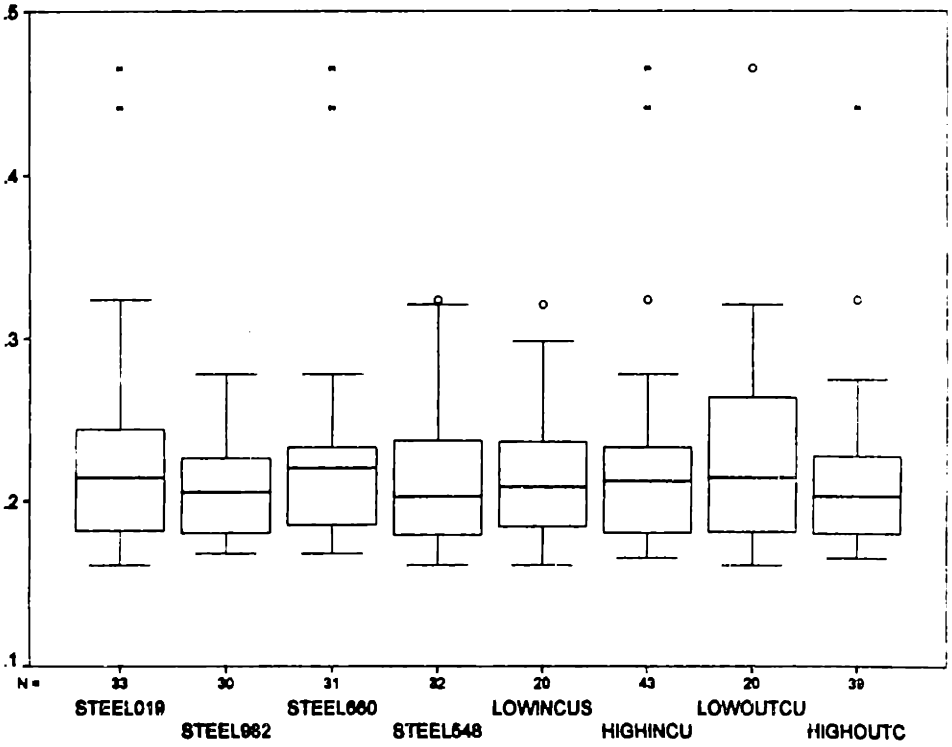
Right Door RMS Flushness 2

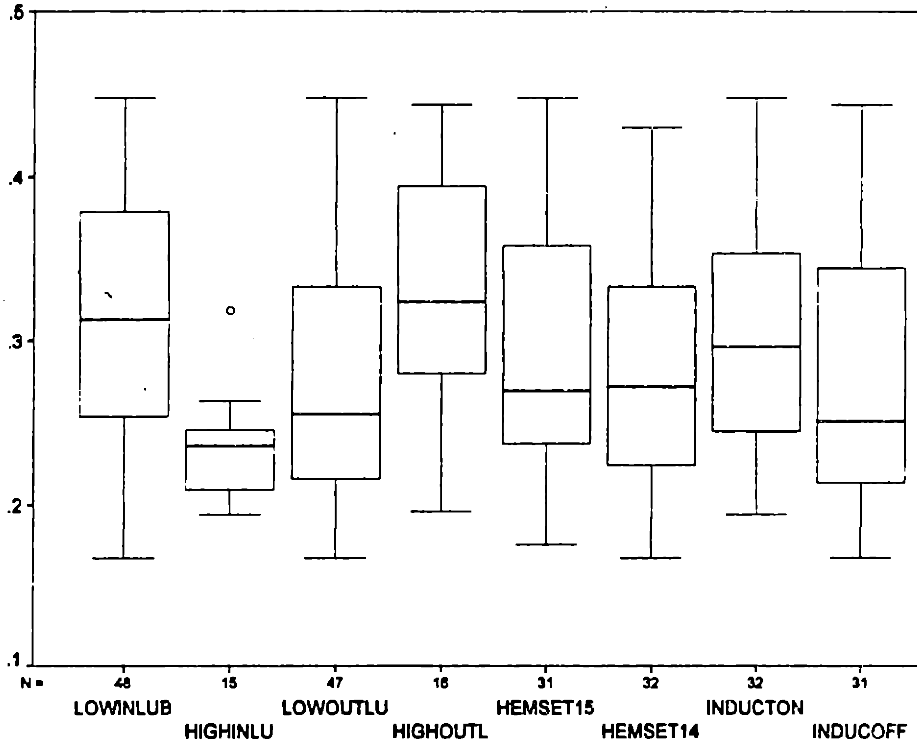


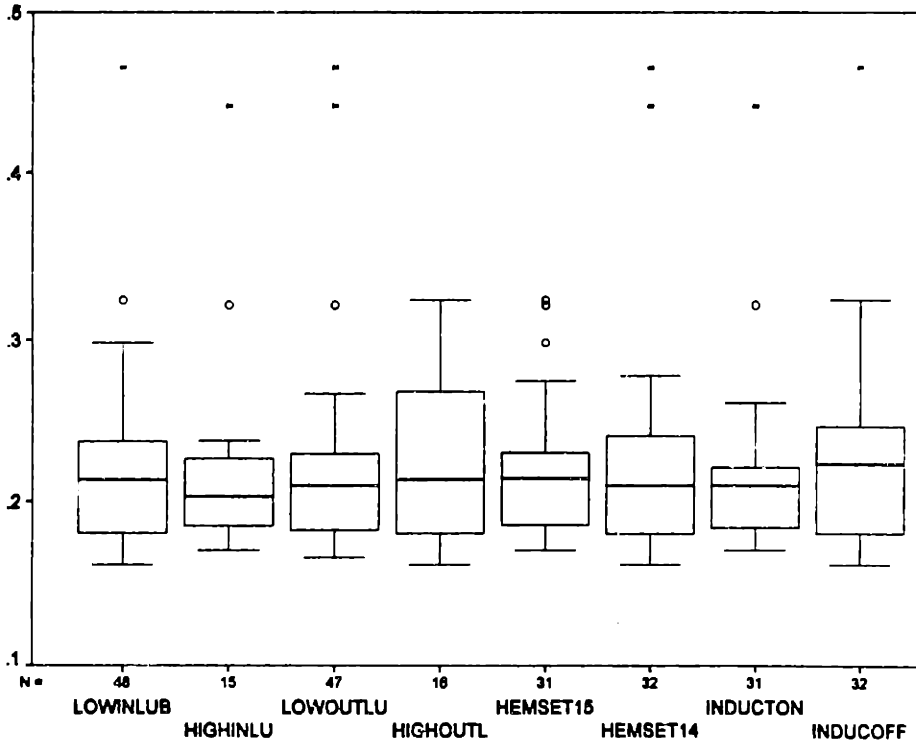
Left Door RMS x-Gap 1



Right Door RMS x-Gap 1




Left Door RMS x-Gap 2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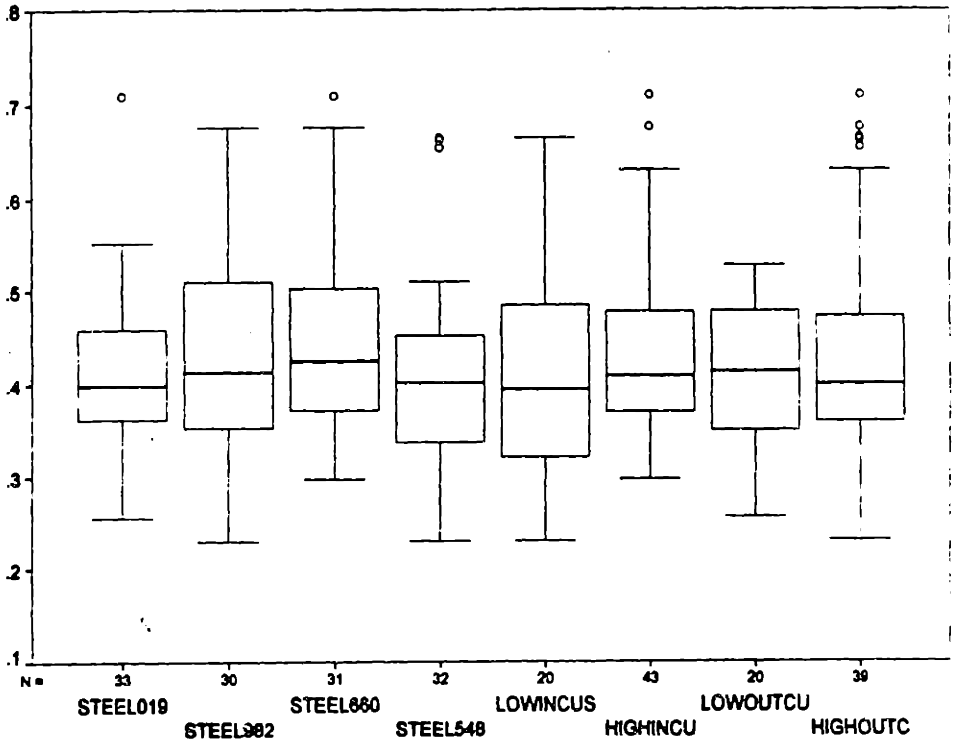
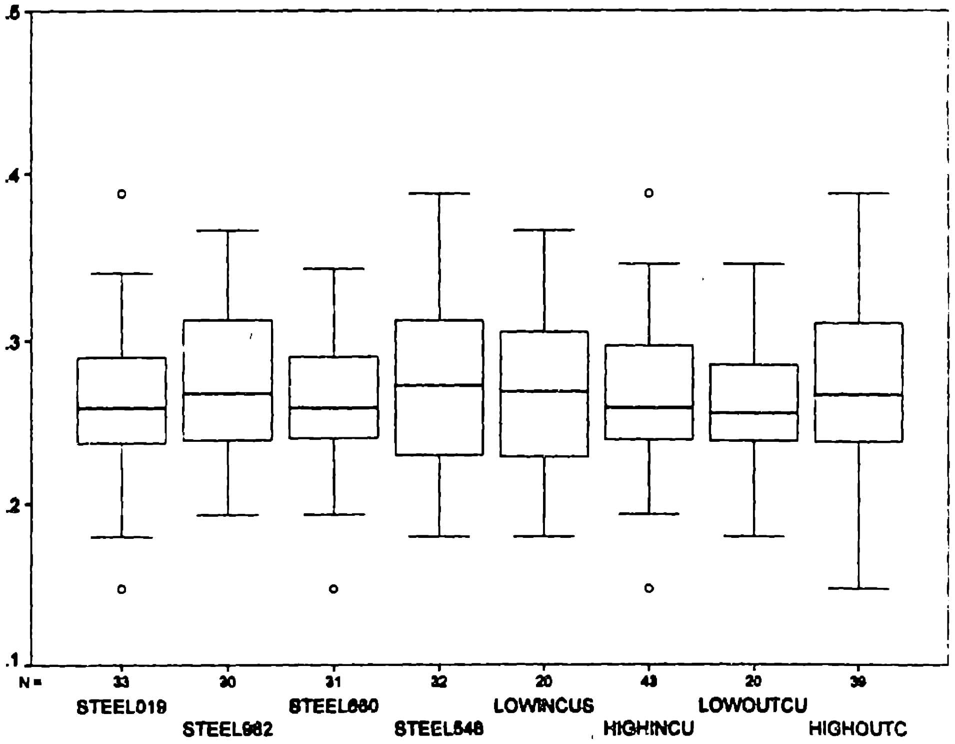


Left Door RMS z-Gap 1



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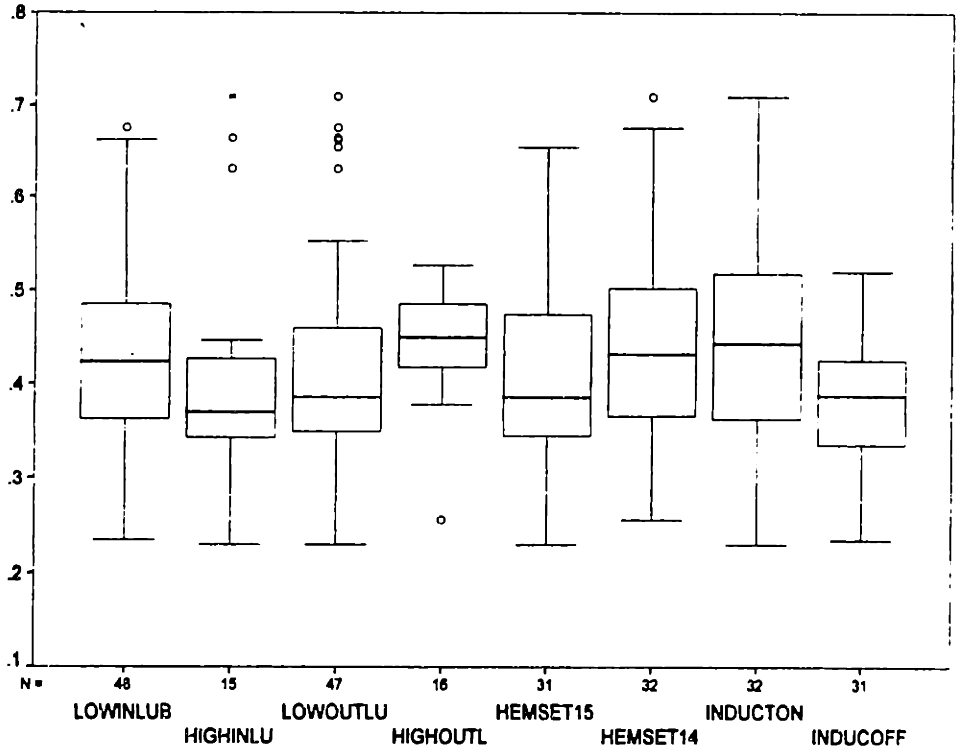
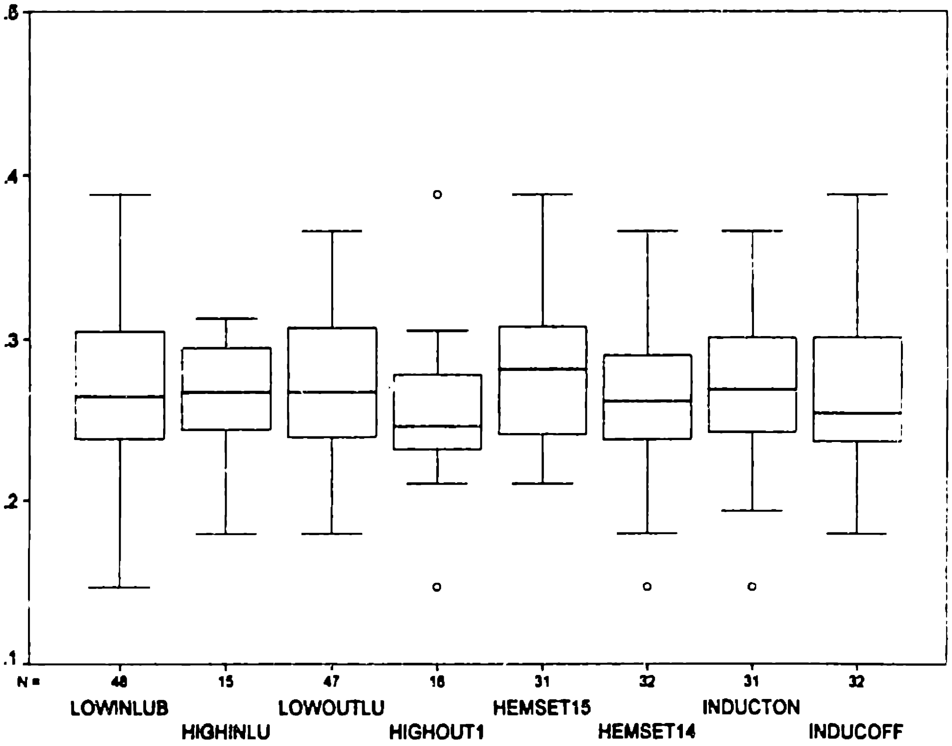
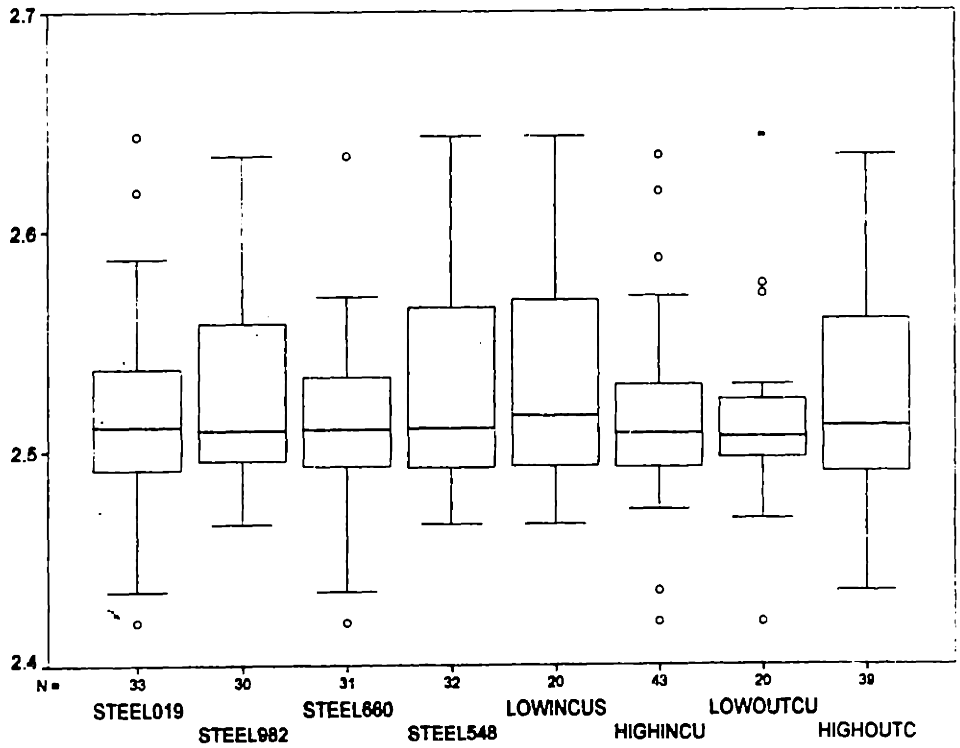
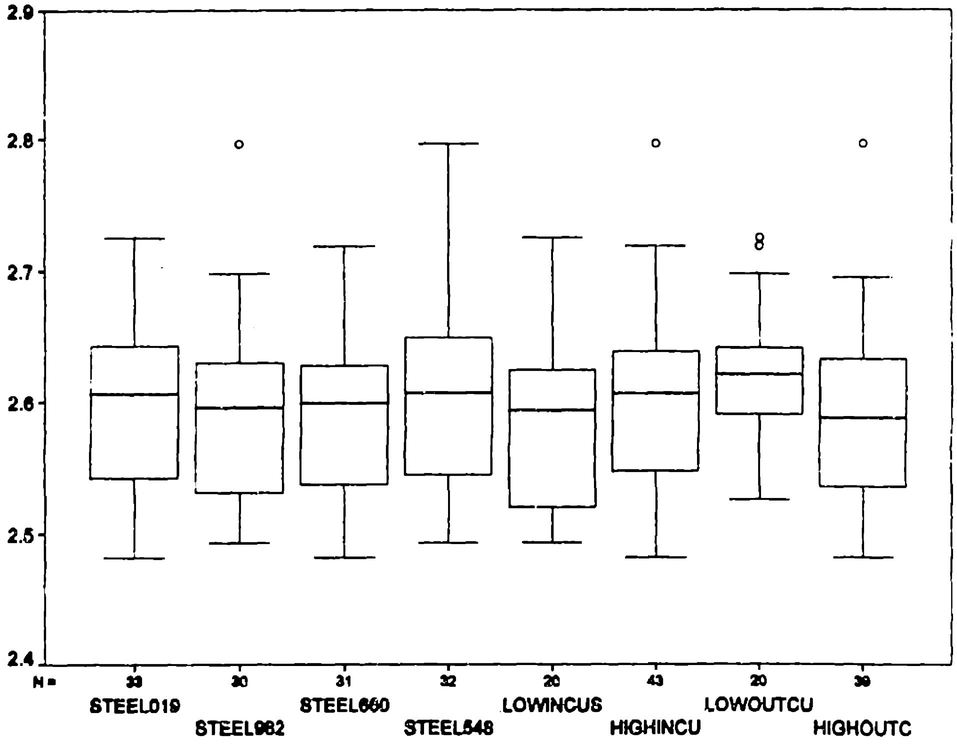

Left Door RMS z-Gap 2


Right Door RMS z-Gap 2

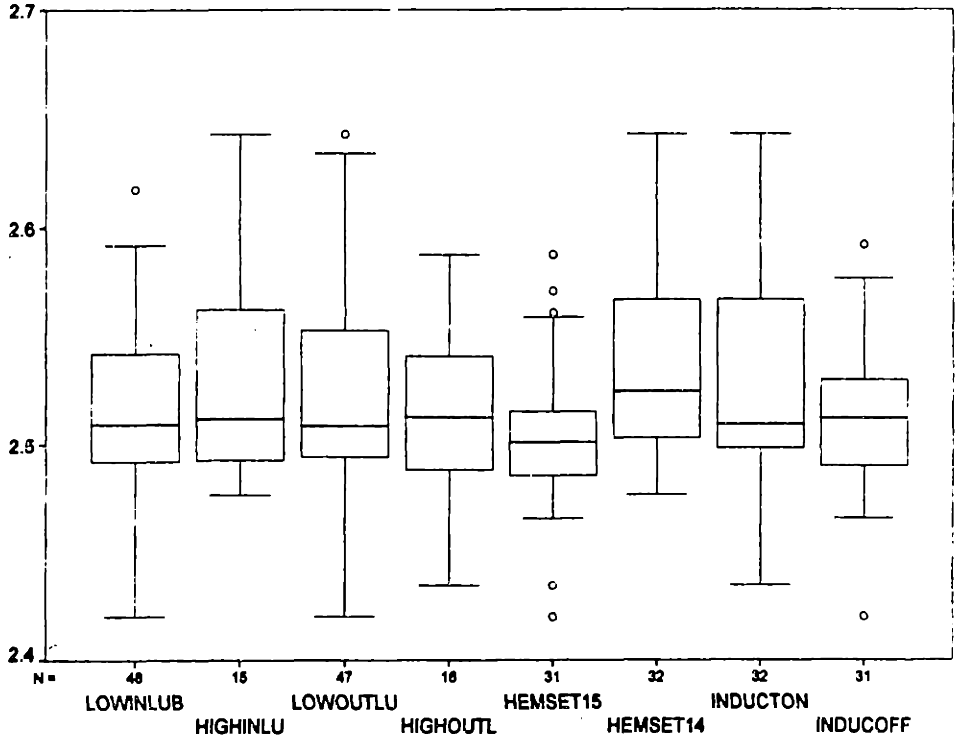
Left Door Average Hem Gap 1



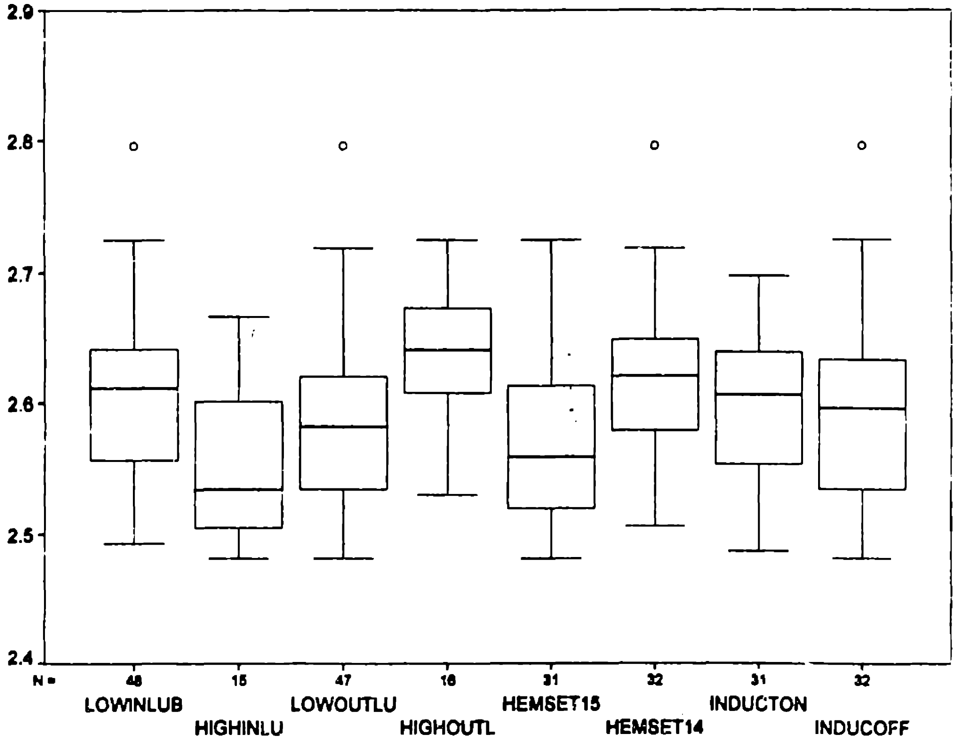
Right Door Average Hem Gap 1



Left Door Average Hem Gap 2



Right Door Average Hem Gap 2



APPENDIX E. DOOR ASSEMBLY EXPERIMENT INTERACTIONS.

This appendix presents the significant door assembly experiment two-way interactions in graphical form. Boxplots are used to compare the levels of each factor for each output measure, as described in Appendix B.

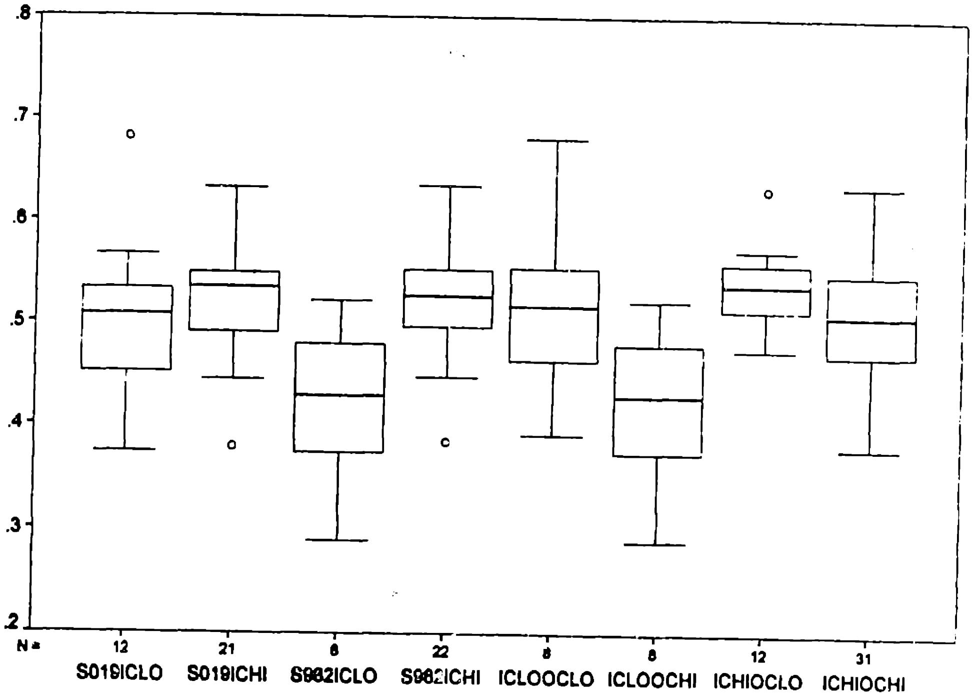
Each box in the charts has an eight character code name to signify the level of the two interacting factors that the box represents. The first four characters represent the level of the first factor, while the second four characters represent the level of the second factor.

The codes for the steel grades are S019, S982, S660 and S548 for the 019, 982, 660 and 548 steel grades, respectively. For the cushion pressures, the codes are ICLO, ICHI, OCLO and OCHI for the low inner cushion pressure, high inner cushion pressure, low outer cushion pressure and high outer cushion pressure. For the lubricant levels, the codes are ILLO, ILHI, OLLO, and OLHI for the low inner lubricant level, high inner lubricant level, low outer lubricant level and high outer lubricant level, respectively. For the hemmer set points, the codes are HS15 and HS14 to represent the hemmer set points -15.0 and -14.9. Finally, for the induction cure cycles, the codes are ICON and ICOF to represent the induction cure cycle on and off.

For example, the code S982ICLO represents the interaction among the 982 steel grade and low inner cushion pressure. Similarly, the code HS14ICOF represents the values of the data when the hemmer set point was at -14.9 and the induction cure cycle was turned off.

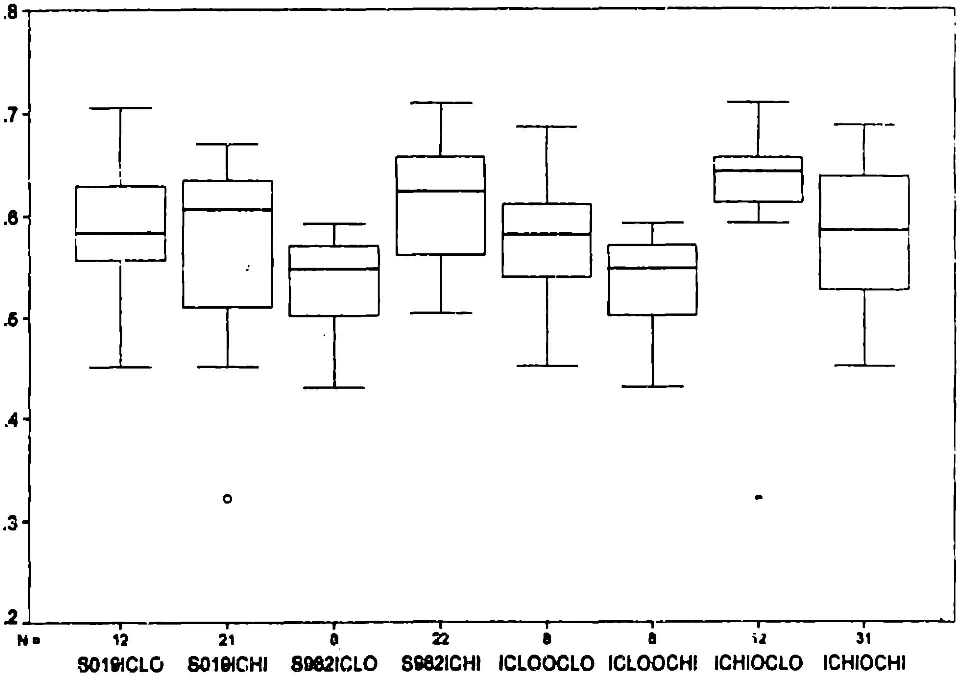
Left Door RMS Flushness 3

2-Way Interactions



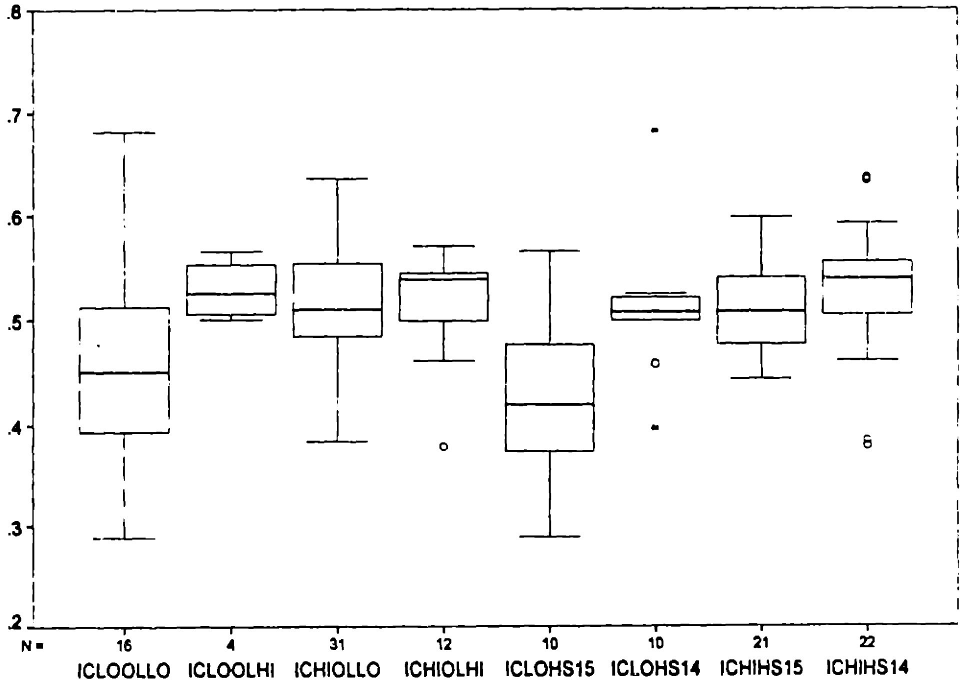
Right Door RMS Flushness 3

2-Way Interactions



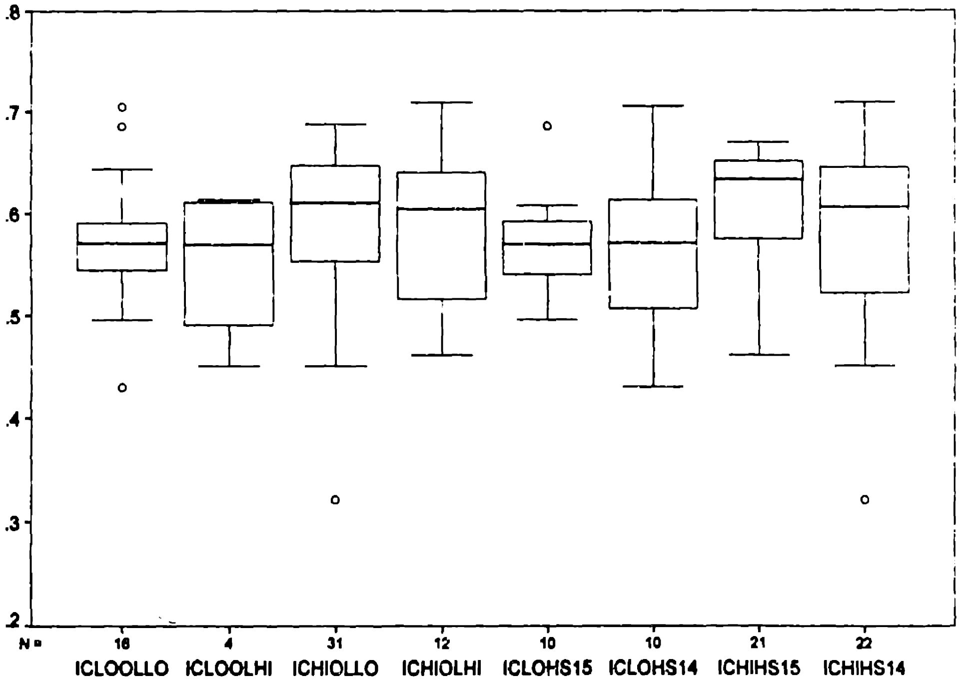
Left Door RMS Flushness 4

2-Way Interactions



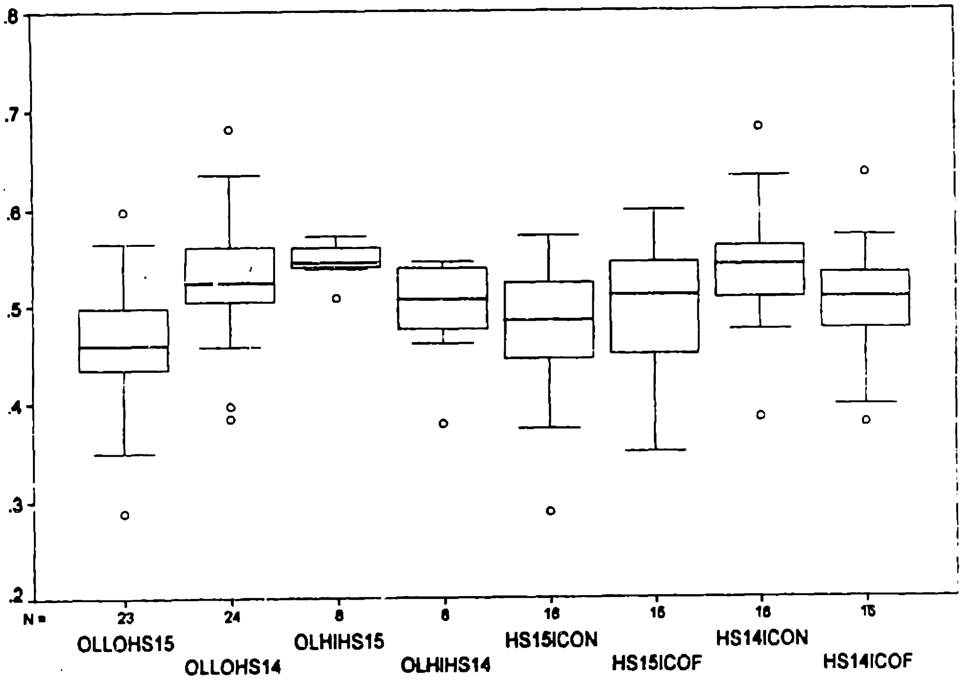
Right Door RMS Flushness 4

2-Way Interactions



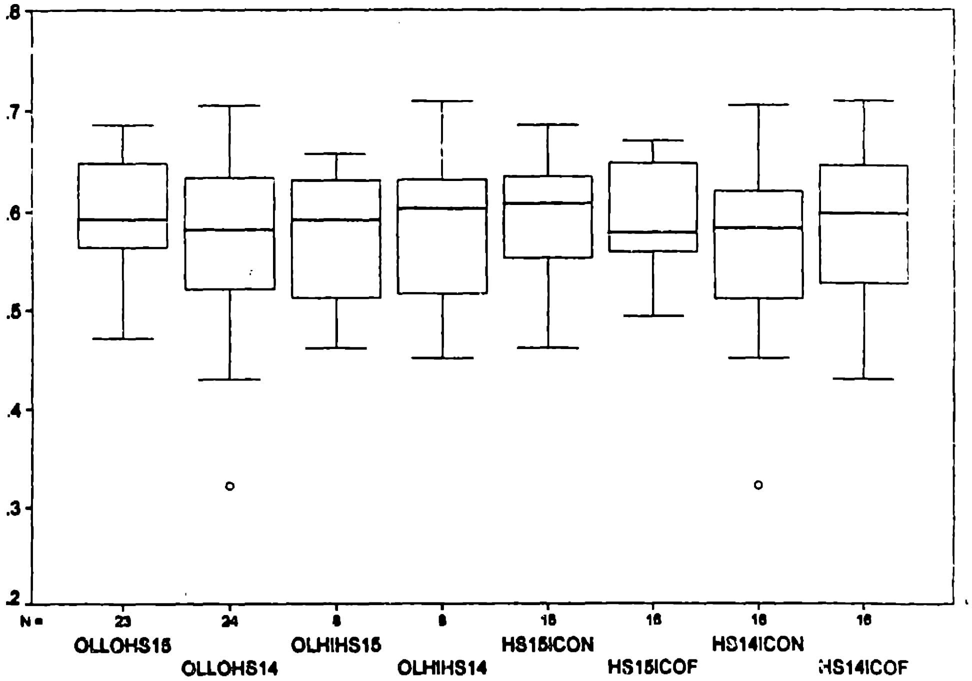
Left Door RMS Flushness 5

2-Way Interactions



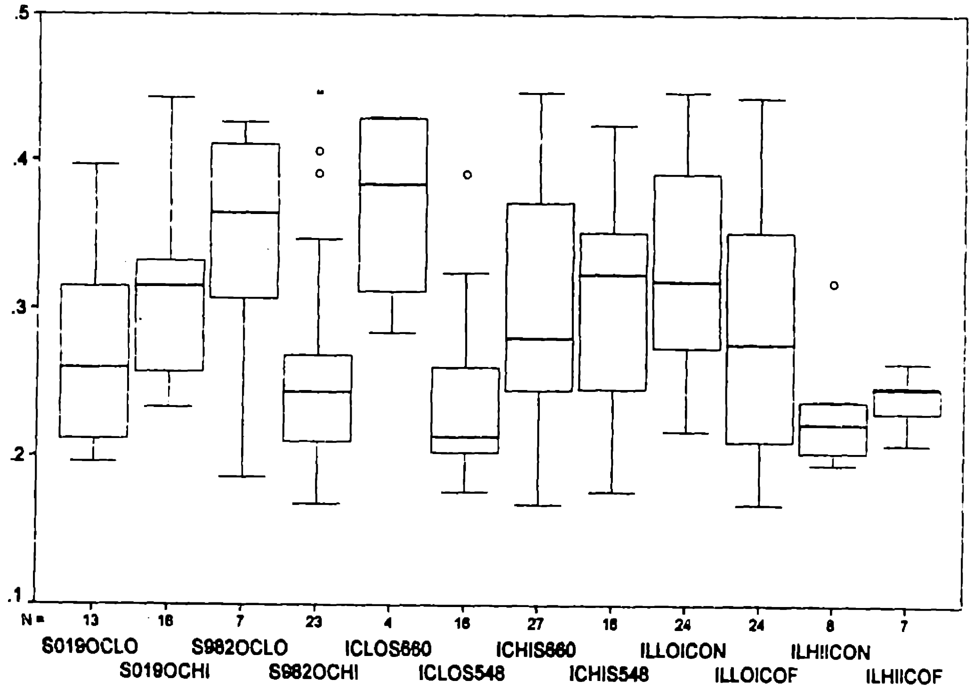
Right Door RMS Flushness 5

2-Way Interactions



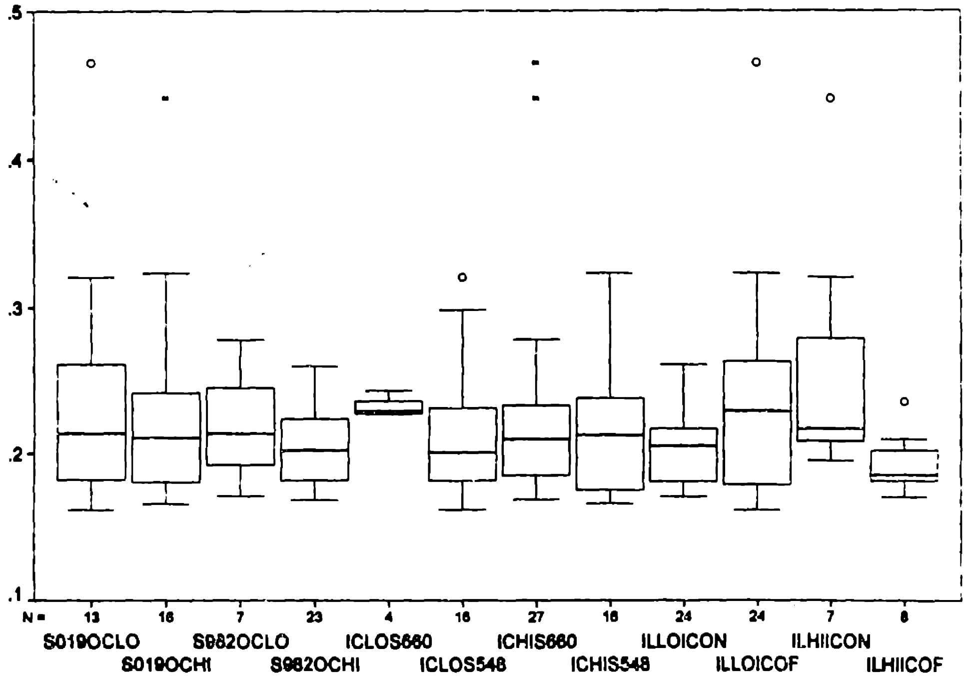
Left Door RMS x-Gap 3

2-Way Interactions



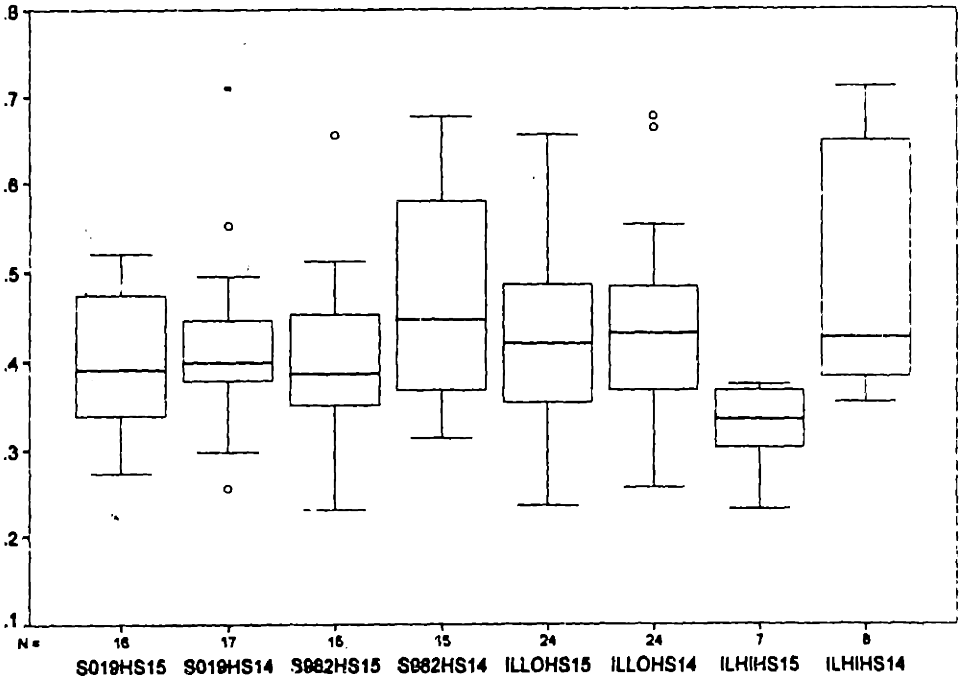
Right Door RMS x-Gap 3

2-Way Interactions



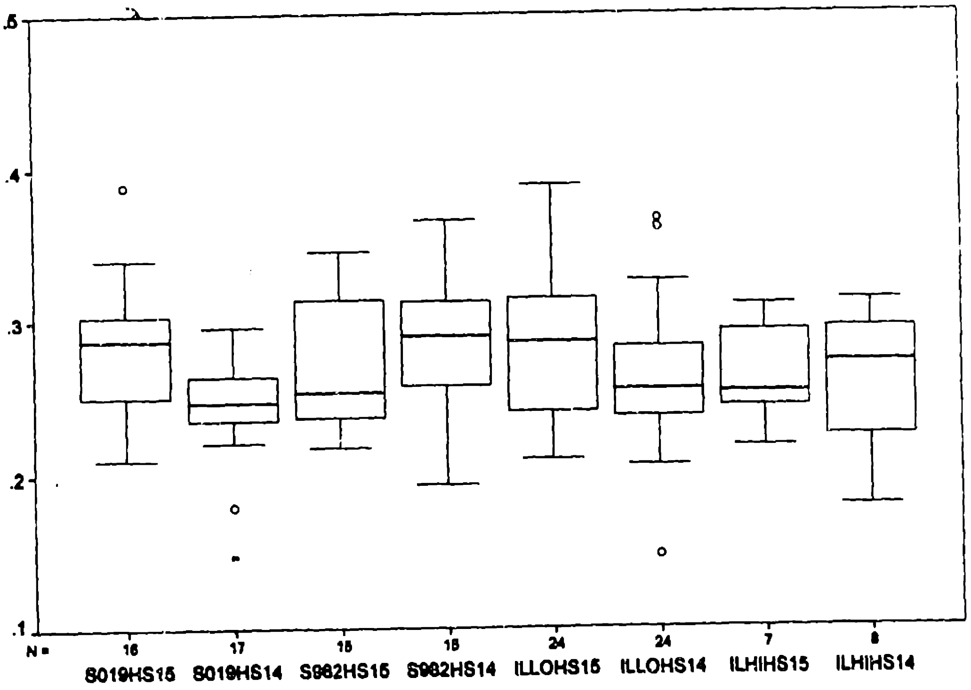
Left Door RMS z-Gap 3

2-Way Interactions



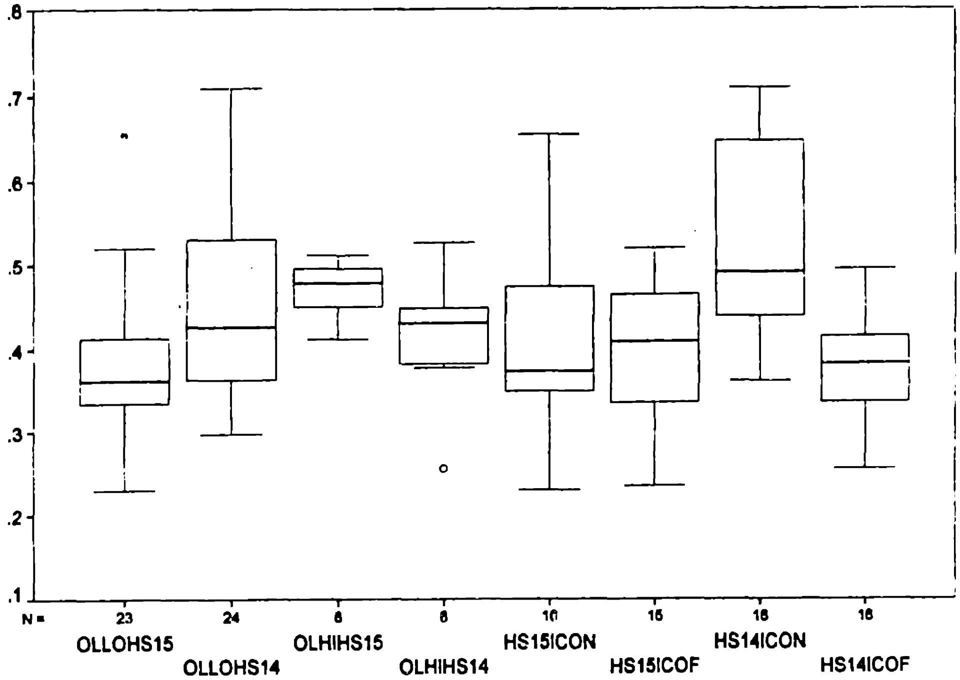
Right Door RMS z-Gap 3

2-Way Interactions



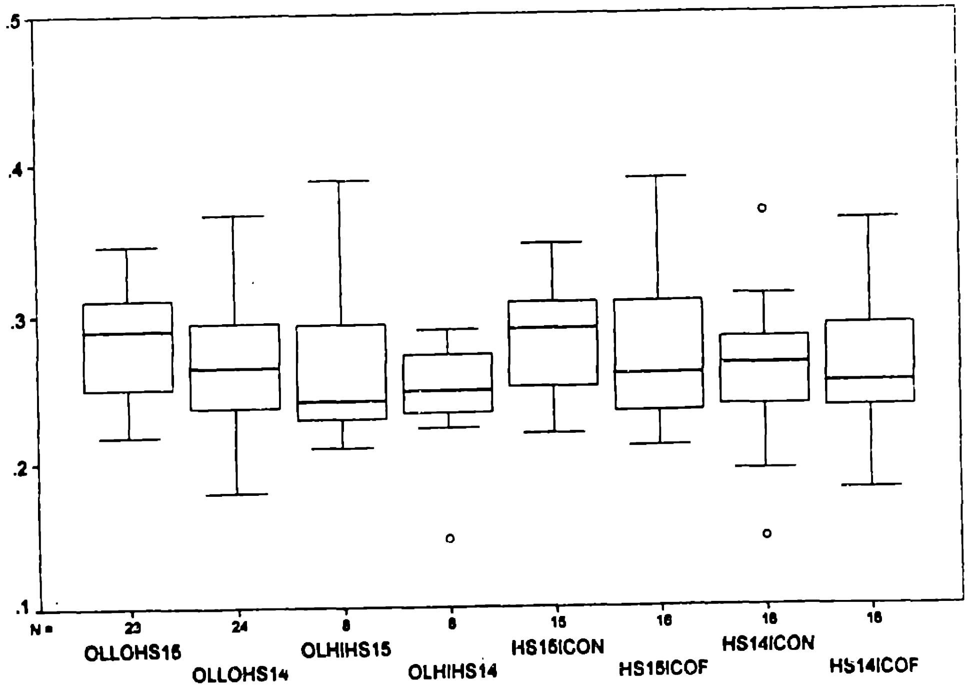
Left Door RMS z-Gap 4

2-Way Interactions



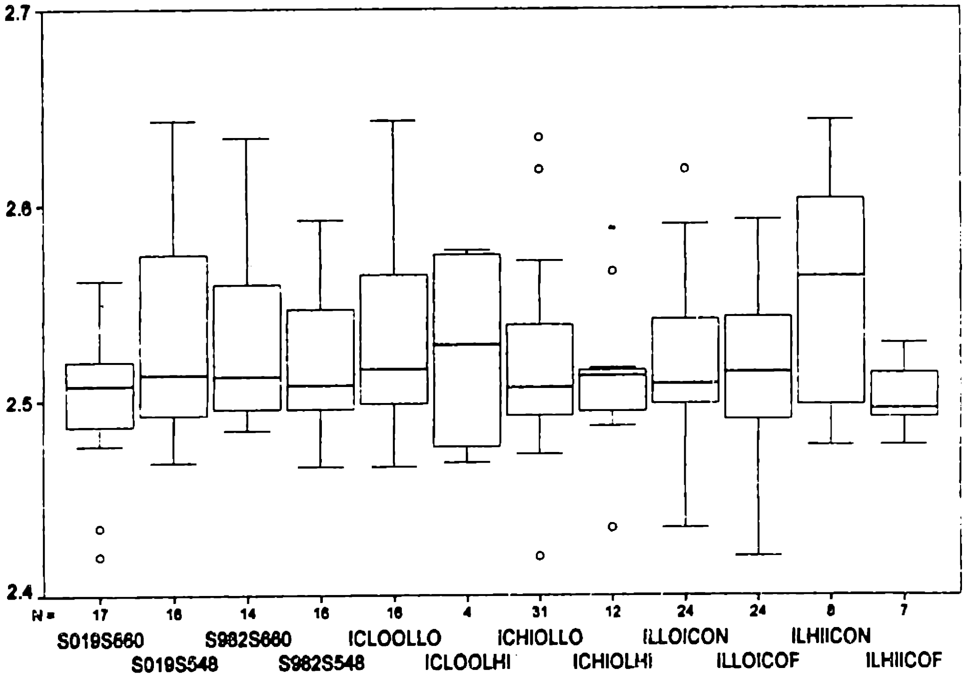
Right Door RMS z-Gap 4

2-Way Interactions



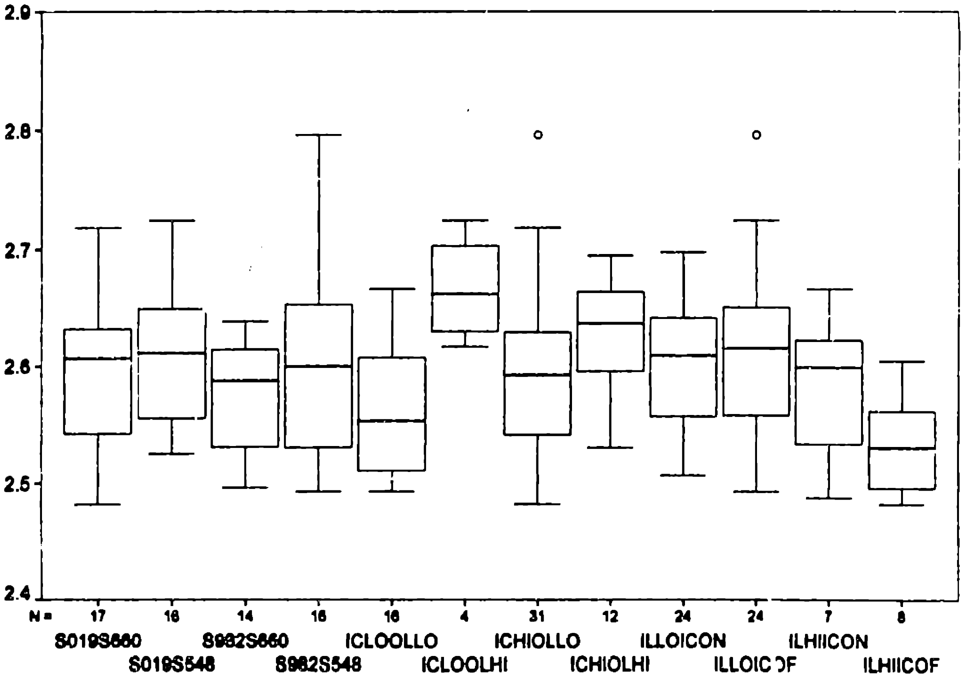
Left Door Average Hem Gap 3

2-Way Interactions



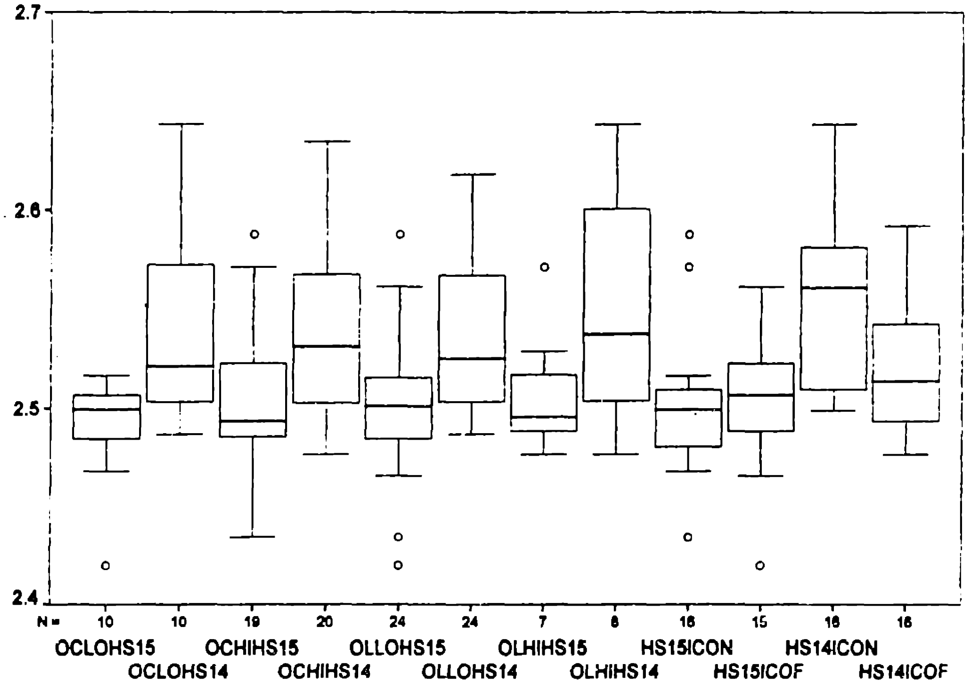
Right Door Average Hem Gap 3

2-Way Interactions



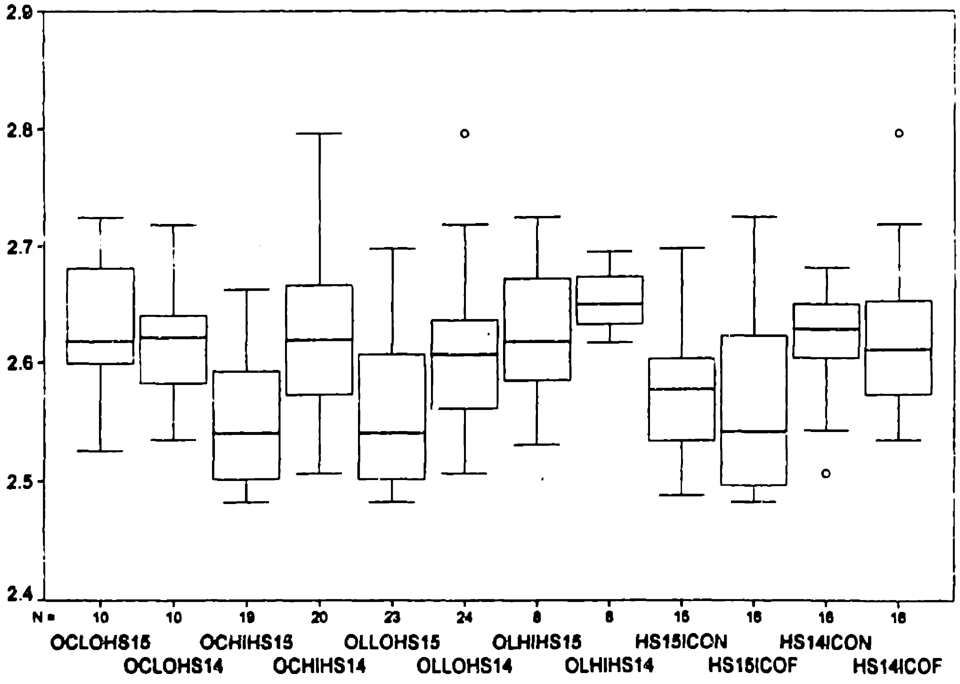
Left Door Average Hem Gap 4

2-Way Interactions



Right Door Average Hem Gap 4

2-Way Interactions



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