An Economic Analysis of Aluminum Sheet Production and Prospects of Aluminum for the Automotive Unibody

by

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Abstract

In order to lower fuel consumption and reduce emissions, aluminum is being considered as an alternative to steel in large scale production of autobodies. This study evaluates the prospects of aluminum sheets as a cost efficient alternative to steel in autobodies with the unibody design. The study focuses on the processing technologies and alloy selection for aluminum automotive sheets and looks at the impact of these on the total part forming cost of the unibody. Technical cost modeling was used to analyze the costs of traditional direct chill casting and subsequent rolling of aluminum alloy sheet and compared the technology to the alternative continuous casting fabrication method. A change to continuous casting displayed large potential cost savings and was believed to be crucial in order for aluminum to be competitive with steel. A large cost penalty is associated with the alloying and heat treatment of 6xxx series sheet for outer body panels as opposed to 5xxx series sheet for interior panels. Changes in production method for 6xxx series sheet or a replacement by 5xxx series sheet will have large impact on the cost of the autobody. The volatility in the price of aluminum ingot has a critical influence on the price of sheet. Changes in the price level have been shown to be equally critical for the final sheet cost as substantial technical improvements. Recent developments of high strength steel have shown promise for substantial weight reduction in steel automobiles and make the challenge even greater for aluminum as its possible successor.

Thesis Supervisor: Joel P. Clark
Title: Professor of Materials Engineering

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1 Introduction

1.1 Background

Reduction in fuel consumption and the use of recyclable materials have prompted extensive use of aluminum in automobiles. In many areas of vehicle construction, such as container and van bodies, aluminum alloy is the rule rather than the exception. In luxury and high performance cars, aluminum was used historically, was next replaced by steel and currently competes for varying shares of the market with steels and composites. Small sized large volume cars were first produced in aluminum alloy, but are currently entirely dominated by steel structures.

The virtues of fuel economy are that the cars are less expensive to operate and that there is a reduction in CO_2 and other emissions. Aluminum vehicles are easy to recycle and generate little waste. Despite some increases in fuel prices in 1999 and 2000, fuel economy is not much of an issue for most American car owners. The government, however, recognizes the value of public goods like clean air and little waste. In the United States, $240 million have been spent annually from 1994 to 2000 on the Partnership for a New Generation Vehicles (PNGV). This is a collaboration with the country's automobile companies to develop vehicles so efficient that even the greenest of environmentalists will have difficulty complaining about the amount of fossil fuel they consume. Improvements of the engine by introduction of fuel cells and diesel/electric hybrids are being developed. However, the first and easiest step on the way towards better fuel economy is to make the cars lighter.

Currently, the least complex way to reduce weight is to replace steel by aluminum. Aluminum intensive vehicles weigh roughly half as much as similar vehicles made of steel. This increases the fuel economy by around 40%, which again is estimated to reduce CO_2 emissions over a vehicle's lifetime by 20%. The major draw-back of aluminum is its cost. The delivered cost of aluminum sheet is three to four times that of automotive steel, though some of this is gained back because a lower weight is needed to provide the necessary structural strength. Automakers state that the price of automotive aluminum sheet needs to decrease to about 1 $/lb in order to be competitive with steel.

1.2 The Aluminum and Automotive Industries

In August 1999 three aluminum producers decided to merge: Canada's Alcan, France's Pechiney and Switzerland's Algroup. Alcoa, then the world's largest producer of aluminum, responded by acquiring the smaller American rival Reynolds Metals. These deals boosted Alcoa's share of the North American market to 35% while the merger of the three competitors gave them a market share of 20%. The EU has later attempted to restrict the market power of these groups by ruling that Pechiney could not participate in the merger. The industry consolidation was driven by low prices in aluminum over the last few years. Metal markets have gotten more efficient and competition has been increasing as manufacturers have gone global. Firms reckon that size yields economy of scale and to a certain extent more opportunities for exercise of market power.

The volatility in aluminum prices on the open market has deterred many of the auto manufacturers from undertaking the large investments necessary for aluminum vehicle production. General Motors and Alcan agreed in 1998 on a ten year deal to guarantee General Motors a stable price and fixed supply of aluminum. The aluminum industry is realizing the importance of the high value automotive products and is eager to concentrate a lot more resources towards these. Instead of being commodity suppliers, the aluminum manufacturers begin to see themselves as automotive producers. Aluminum and auto manufacturers make large investments in cooperative research efforts. Aluminum producers are increasingly being involved in post-production processes such as design, forming and joining of auto parts.

The design of autobodies can be radically changed with the introduction of aluminum. The space frame design was developed uniquely for aluminum autobodies and has been used in cars such as the Audi A8 and Acura NSX. The load bearing frame consists of extruded and cast parts, while thin stamped panels cover the exterior of the vehicle. The space frame construction has proved economical in low volume production. If aluminum is to replace steel however, cars made from aluminum will have to be produced in large volumes where the unibody design can reap far more benefits from economies of scale. The unibody construction is the design utilized by the auto industry for today's steel auto bodies. The unibody structure is manufactured from wrought metal sheets using stamping and spot welding. Ford Motor Company is developing the P2000 that is a family sized car made using the unibody design for the aluminum body. The car weighs 2000 pounds, which is 40% lighter than the comparably sized Taurus, and achieves 63 miles per gallon.

Aluminum sheet production is currently very expensive and large reductions in production costs need to be attained in order to make the aluminum unibody competitive with steel. Continuous casting is a relatively cheap production technology that has penetrated the aluminum foil market. Most aluminum sheet for automotive applications is rolled from ingots or extruded in batch operations. It is believed that substantial cost savings can be attained by replacing these manufacturing methods by continuous casting also for automotive sheet.

2 Problem Statement

The purpose of this study is to evaluate the prospects of rolled aluminum sheets as a cost efficient alternative to steel in automotive bodies with the unibody design. The study focuses on the processing technologies and alloy selection for aluminum automotive sheets.

In general, the aluminum designs have been disclaimed because the cost of manufacturing these designs appears to be higher. The price of aluminum sheet has to decrease to significantly lower levels in order to be competitive with steel. A primary reason for the high price of aluminum sheet is that the raw material cost of aluminum ingot is significantly higher than the material cost for steel. However, despite the materials cost penalty, aluminum space frame designs have reached the market in the luxury car segment and aluminum unibody designs such as the Ford P2000 are in the early stages of commercialization. This study attempts to identify and discuss factors that can reduce the cost of aluminum sheet and ultimately make aluminum autobodies a competitive alternative. Technical cost modeling is the primary tool used to asses the impact of these factors on the cost of the product.

Substantial decreases in production costs are believed to be viable as a result of advances in the sheet production technology. This study addresses to which extent these cost savings can be attained using continuous casting as a substitute for the traditional DC casting technology of aluminum sheets. Different aluminum alloys have different material and production costs. The requirements of the alloys in different parts and alternative alloy selections are investigated.

The sheet production process and alloy selection also has implications on the forming and assembly of the autobody. The effect on the cost of the autobody as a result of varying sheet costs and properties is assessed. The objective is to point out the overall potential cost savings as a result of the advances proposed in this study and to evaluate whether and to what extent further advances have to be made. Other performance issues, environmental issues and challenges from the advancement in steel technology are also discussed.

3 Methodology

3.1 Technical Cost Modelling

Technical cost modeling (TCM) is the analysis of manufacturing processes using computer spreadsheet based tools with elements from engineering process analysis, operations research simulation, and financial accounting. The TCM models simulate production processes such as sheet casting, rolling and stamping in order to obtain the inclusive cost of manufacturing a specific component or set of components. The main benefits of TCM include its ability to highlight the major cost drivers in industrial processes, to compare alternative technologies systematically, and to provide flexibility in simulating market conditions and government regulations. This study applies TCM to the analysis of sheet casting and rolling as well as well as stamping, casting and autobody assembly processes.

Four basic categories of inputs are required for a TCM model [1]:

1. Product specifications (e.g. product dimensions, alloy designation)
2. Material properties (e.g. density, specific heat, Young's modulus)
3. Cost specifications (e. g. material prices, wages, energy prices, equipment cost)
4. Management specifications (e. g. production volume, production method, equipment dedication, scrap rate)

These four categories of inputs are integrated in a spreadsheet in order to simulate the production process by executing a series of calculations based on engineering and economic principles. The output displays the production costs broken down into variable and fixed cost categories as well as the required investments. This enables the user to identify which aspects of the operations have the greatest impact on cost. The effect of varying input parameters and alternative decisions can readily be evaluated. The tool can also easily be modified to account for changes in the production process and technological advances.

The concept of technical cost modeling is to break down the cost of manufacturing into small elements. Variable costs do not change significantly with the production volume on a per unit basis. Material cost is dependent on the final product weight, the scrap weight generated as well as the price of raw material and scrap. Labor costs include only the cost of workers directly involved in the manufacturing process. The final variable cost element is energy, which accounts for the power requirements from the production machinery.

Fixed costs do not vary with the level of output (within the limits of the facilities). They mainly arise from capital investments and overhead costs. The costs of investments are calculated as equal periodical interest bearing payments over the lifetime of the equipment. Machine costs consist of the cost of the machinery including the necessary installation costs. Building costs account for the space requirement of the manufacturing line. Auxiliary equipment is necessary equipment that can not be directly identified with a certain stage in the production process. Examples of auxiliary equipment are transportation and storage equipment. Maintenance costs and auxiliary equipment costs are difficult to estimate and are generally calculated as a percentage of machine costs. Overhead costs account for those workers who are not classified as direct laborers as well as office facilities for these. These costs are very specific to the company and are usually best quantified as a percentage of the other fixed costs.

For each operation in the manufacturing process, the processing conditions and necessary equipment are specified. These include among others labor requirement, energy requirement, scrap rates and required production equipment. TCM models generally include the option to scale the capacity and cost of the equipment with the output or to dedicate the equipment by specifying the maximum level of output and letting the product bear the entire cost regardless of the amount of production. For simplicity, and because of the nature of the data used in this analysis, the aluminum rolling TCM cost model will always use the assumption of non-dedicated equipment unless otherwise specified.

TCM models are flexible and adapt easily to cost allocation decisions. However, because of uncertain data for some of the cost variables such as overhead and maintenance, TCM is better used for estimations of cost trends and comparisons than as an absolute pricing tool. Nevertheless, it does single out limiting process parameters and emphasizes the relative importance of factor inputs.

3.2 The Scenario Approach

Estimates and several uncertain inputs in the TCM models used in this analysis imply that there may be substantial variation in the outputs. As discussed, the TCM models are better used for estimations and trends. Nevertheless, absolute values for the price of aluminum sheet are being used in this study. Instead of blindly using the outputs of the TCM models, linear estimates and reasonable approximations were used to analyze different cost scenarios. The outputs of the TCM models generally served as the "Reasonable" scenario. In addition "Worst Case" and "Best Case" scenarios were constructed using sensible estimations.

In order to compare the different technologies and to evaluate the competitiveness of the technology of discussion, the TCM models can be used iteratively. Instead of estimating cost for a certain set of inputs, the models can be used to identify the necessary input values in order to achieve a specific output. When manufacturing conditions are uncertain, an examination of which conditions are necessary to achieve a cost competitive output can be extremely useful for strategic management decisions. This approach is used in the analysis to determine how inputs such as aluminum ingot price would have to change in order to be competitive with steel for automotive bodies.

4 Aluminum Alloys for Automotive Unibodies

4.1 General Properties

Commercially pure aluminum is a face-centerd cubic metal with density of 0.098 lb/in^3, a melting point of approximately 1215°F and specific heat of 0.215 Btu/lb°F. Additions of alloying elements usually decrease the melting point, increase the strength and can either increase or decrease corrosion resistance. Some alloying elements, alone or in combinations, produce alloys that respond to heat treatment. The commonly used alloying elements are silver, silicon, magnesium, manganese and zinc.

Aluminum and its commercial alloys are relatively ductile materials and can be hot or cold worked into most of the common manufactured forms [6]. The commercially pure metals and some of the alloys are of non-heat treatable compositions and attain their strength either by virtue of their alloy content or because of strain hardening resulting from cold work. However, the strength of many of the alloys can be further increased by suitable heat treatments at temperatures around 900 - 1000°F. The heat treatment serves to substantially dissolve the alloying elements which are subsequently retained in supersaturated solid solution upon rapid cooling. Certain of the heat treatable aluminum alloys (Cu, Mg, Si) age harden considerably at room temperature while others must be heated to about 300°F for a few hours to attain their maximum strength. Most alloys which age harden at room temperature will develop even greater strength by a precipitation treatment at 300 - 400°F.

The effects of either cold work or heat treatment on the strength and workability of the materials can be removed by annealing them at temperatures of about 600 - 800°F depending on the alloy. The strength of the non-heat treatable alloy can then be regained only by the introduction of additional cold work.

4.2 Alloy Designation - The 5xxx and 6xxx Series for Automotive Sheets

Automotive bodies with the unibody design are constructed almost exclusively from stamped metal sheets. In the case of aluminum, these are wrought sheets where the alloys are specified by a four digit designation. The first digit indicates the major alloy constituent while the last three digits fully designate the alloy.

As a result of performance and cost issues, only 5xxx and 6xxx alloys have been found suitable for automotive sheets. The 5xxx series alloys contain magnesium as the major alloying element and are moderate to high strength non-heat treatable alloys. Alloys in this series possess good welding and low temperature characteristics and good resistance to corrosion [6]. Certain limitations have to be placed on the amount of cold work and service temperatures.

The 6xxx series alloys are heat treatable and contain silicon and magnesium as the major alloying elements. They possess good formability and corrosion resistance, with medium strength. The 6xxx series alloys are normally formed in the solution heat-treated condition and then artificially aged to attain optimum properties. The aging is normally achieved during the painting process of the autobody. Significant synergies are achieved since the paint has to be cured at elevated temperatures similar to those needed for precipitation heat treatment. The automotive industry therefore often refers to the precipitation hardening as paint-bake hardening.

4.3 Aluminum Forming

Sheets for automotive bodies are press formed using metal stamping. The aluminum sheet is placed in a press and hit to obtain a desired shape. The part might be hit multiple times in different dies to reach its final appearance. Aluminum alloys are generally less formable than steel. This implies that smaller levels of strain can be tolerated when the sheet is formed [8]. They also incur larger problems with springback, in which the metal reverts its shape slightly towards the pre-stamping shape upon removal from the die.

The service demands for automotive forming are often in conflict with the demands of the stamping operations. Dent resistance is a critical service requirement and is proportional to the yield strength of the alloy [7]. Higher yield strength in the final component is therefore seen as beneficial. However, in stamping higher yield strength alloys generally suffer from increased springback as well as inferior formability. Although the yield strength differs between the 5xxx and 6xxx series, their stiffness determined by the Young's modulus is for all practical purposes the same. Structures made with alloys from the two different series therefore have identical dimensional requirements.

In the 6xxx series these conflicting demands are partially overcome by achieving the final hardness in the paint bake cycle which occurs after forming. The 6xxx series alloys achieve a significantly better dent resistance and are therefore used for outer panels. The 6xxx series alloys also do not have the same problems with luttering, wrinkles forming on the surface, as the 5xxx series alloys. This is another reason for using 6xxx alloys for panels requiring aesthetic appeal.

The main advantage of the 5xxx series is that it is less expensive. These alloys are used for interior panels without the same requirements for appearance. The 5xxx alloys are also slightly more formable than the 6xxx alloys. However, since they have to be formed in their hardened state there are larger problems with springback. This is especially problematic for complex parts that have to undergo numerous forming operations and thereby obtain substantial work hardening.

5 Aluminum Sheet Production Technical Cost Modeling

5.1 Background

A TCM model developed at the MIT Materials Systems Laboratory for the production of beverage can aluminum sheet was used as the base for the analysis. The model included a direct-chill (DC) casting process and several rolling and heat treatment steps. It was substantially modified in order to facilitate the option of using continuous casting instead of DC casting. Automotive sheets have a substantially larger gauge than can stock and require fewer rolling steps. The model was modified in order to reflect both can and automotive sheet production. Figure 5.1 depicts the production sequence for aluminum automotive sheets. Further description of the model will only be concerned with the production of automotive sheet. Refer to Appendix A for a display of the main elements of the aluminum rolling model.

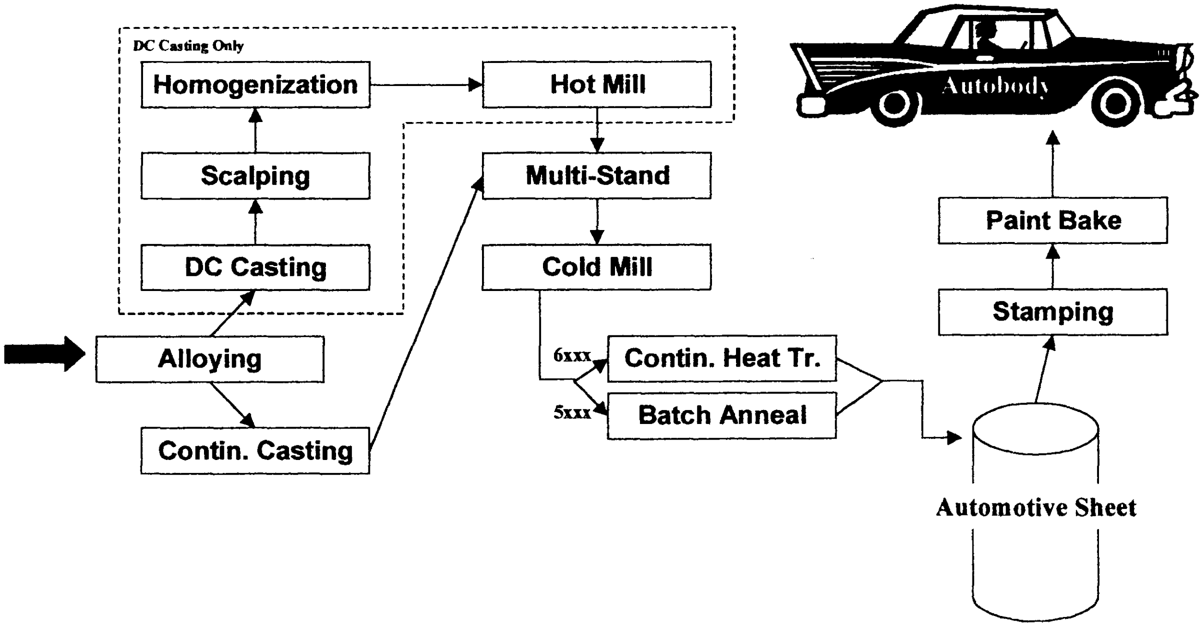


Figure 5.1: Production sequence for aluminum automotive sheets. If continuous casting is used instead of DC casting several processing steps can be eliminated.

5.2 Material Choice and Alloying

The aluminum is alloyed by melting aluminum ingot in an alloying furnace and adding the required amounts of alloying metals in order to reach the specified alloy composition. In the TCM model, the material price of the alloy is iteratively calculated by specifying the amount of different input materials such that the desired alloy composition range is reached. The melting temperature and specific heat are assumed to be those of pure aluminum throughout the analysis. The two alloys used in this analysis are 5754 and 6111 of which the compositions are displayed in Table 5.1. In the American automotive industry these are the most widely used alloys for inner and outer parts respectively.

	Si	Mg	Fe	Cu	Mn	Cr	Zn	Ti	Other
5754	0.90%	0.75%	0.40%	0.75%	0.30%	0.10%	0.15%	0.10%	0.15%
6111	0.08%	3.20%	0.20%	0.06%	0.30%	0.08%	-	-	0.15%

Table 5.1: Target compositions of the 5754 and 6111 aluminum alloys.

5.3 Direct-Chill Casting and Subsequent Hot Rolling

The principal casting process for light metals is the direct-chill (DC) process [2]. This is also the predominant casting technology for aluminum, but is now being challenged by continuous casting. The alloy melt is transferred from the alloying furnace to a holding furnace before casting. Most of today's DC casting capacity is of the vertical type for semicontinuous casting and is used to produce rectangular slabs. The DC cast ingot thickness is set to 25 inches this analysis. The subsequent scalping step is necessary to produce a flat surface to be presented to the rolling mills and involves milling resulting in some material loss. Following scalping, the ingots are annealed at approximately 800°F in order to homogenize the alloy, to develop specific microstructures and to obtain desired temperatures for hot rolling.

The cast ingot subsequently passes several times through a hot rolling mill which reduces the gauge thickness on the order of 60% per pass. The temperature during hot rolling should be at least above 500°F depending on the alloy [3]. Three passes through the hot mill have been assumed to be required in order to reduce the gauge to 1.5 inch. This first hot rolling step requires relatively expensive equipment. Further gauge reduction by hot rolling is achieved in the less expensive multi stand hot mill.

5.4 Continuous Casting

During the last few years continuous casting of wide aluminum sheet has emerged from a promising technology to a highly cost competitive alternative to the DC production process. During continuous casting, liquid metal is solidified directly into the sheet form. A substantial number of the gauge reducing steps required in the DC process can be eliminated. Further production savings can be attained because the aluminum sheet can be directly fed into rolling mills. Lower investment costs, higher yields and shorter in-process times result in lower manufacturing costs. To date, continuous cast aluminum has been limited to less demanding applications because of quality issues such as gauge control, microstructural segregation and crystallographical texture formation [4]. However, automotive sheets for experimental purposes have successfully been produced by continuous casting, and large scale commercial operations can be expected in the near future.

Continuous casting can be done using twin-roll, belt or electromagnetic casting. Twin-roll casting is the predominant technology and the only one which will be analyzed in this study. Twin-roll casters consist of two rollers rotating in opposite directions forcing molten aluminum through a thin gap as it is being cooled. The casting rate is limited by the requirement to have a sufficiently strong solidified shell around a liquid core when the sheet leaves the caster. Casting rates as high as 218 lb/in/hr (casting rate per unit width) have been reported for gauges as low as 0.025 inches [5]. However, high quality sheet for automotive applications can only be produced at gauges larger than 0.118 inches where casting rates of 84 lb/in/hr can be achieved. Most continuous casters are designed to cast over a large range of gauges. This provides advantageous flexibility for production facilities which thereby can produce several different products and easily adjust to changes in demand. The cast sheet can potentially be subsequently fed directly into the cold rolling mills. Manufacturers currently recommend to hot roll the sheet before cold rolling, and this practice is followed in the TCM model for this analysis.

5.5 Rolling

As described in section 5.2, the DC cast ingots pass several times through a hot mill step in order to vastly reduce the gauge. The less expensive multi-stand hot rolling mill can be used to further reduce the gauge of both DC and continuously cast (CC) sheet. The DC cast sheet passes through several hot mill stands to reduce the thickness of the sheet to desired gauges. Since the initial gauge of CC sheet is lower, fewer of these hot mills is required. A gauge reduction slightly less than 50% per mill is to be expected in the multi-stand hot mill. In this analysis the CC sheet was estimated to only need one hot mill while the DC cast sheet required 3 stands in order to achieve the necessary gauge reduction.

Cold milling is the gauge reducing step following hot milling. This step is also necessary for work hardening of the 5xxx series alloys. The sheet may be passed several times through the mill and a gauge reduction of approximately 40% can be achieved per pass. In this analysis it was only necessary to use one pass through the cold mill for the continuous cast aluminum while the DC cast sheet required 4 passes.

5.6 Heat Treatment

Aluminum sheet in the 6xxx series require a high temperature solution heat treatment at temperatures in the range of 1050°F. This has to be done in a continuous heat treatment furnace. The TCM model for this analysis is based on a technology using electric fans to support the sheet as it passes through the furnace. Such fans consume large amounts of energy and are a significant contribution to the operating cost of the furnace.

Aluminum sheet in the 5xxx series is less sensitive to the heat treatment process. These alloys may instead be heat treated in much less expensive furnaces containing large batches of multiple coils. The heat treatment temperatures are in the range of 650 - 800°F depending on the alloy.

5.7 Exogenous Cost Factors and Management Decisions

The price of aluminum ingot is the single most important cost driver in the TCM model. Several other prices determined in the marketplace such as the price of scrap, energy and wages have large influence on the final cost. The interest rate, for example, is an important determinant for equipment and building costs since these are calculated as present values of equal annual payments over the lifetime of the investments . Management decisions such as the operating time of the factory are also of importance. Table 5.2 displays the most significant exogenous and managerial cost determinants used in this analysis.

Aluminum ingot price	0.76	$/lb
Scrap price	0.45	$/lb
Wage (including benefits)	35	$/hr
Electricity Cost	0.10	$/hr
Gas Cost	2.25	$/MBtu
Interest Rate	12%	
Equipment Life	20	yr
Building Life	25	yr
Maintenance Costs (fraction of equipment cost)	20%	
Fixed Overhead (fraction of fixed costs)	35%	
Daily operating time	24	hr/day
Annual operating time	365	days/year
Downtime	10%	

Table 5.2: The most significant exogenous and managerial cost determinants used in this analysis.

6 Economic Analysis of Aluminum Sheet Production Methods

6.1 Direct-Chill Cast Sheet

A breakdown of the cost elements resulting from the various stages of production is necessary in order to understand which factors drive the cost of aluminum sheet. Figure 6.1a displays the breakdown of the cost of DC cast sheet, please refer to Appendix A for a complete breakdown of the cost. A cost summary of the production costs for DC cast sheets are shown in Table 6.1a-b. Using the approach of non-dedicated equipment the cost of 0.039in (1mm) automotive 5754 sheet is 1.32 $/lb and the cost of 6111 sheet is 1.60 $/lb.

The alloy cost, which is incorporated into the alloying step, is close to 50% of the overall cost for both 5754 and 6111 sheet. Clearly this is the main cost driver, and changes in the cost of aluminum ingot, and to a lesser extent the alloying materials and scrap, have substantial impact on the price of aluminum sheet. Refer to Section 6.2 for a further discussion of these issues. The remaining variable costs due to labor and energy add up to approximately 10% of the total cost. These costs are relatively evenly distributed across all the production stages and generally range from one to three cents. An exception is the 5 cent energy cost of continuous heat treatment of the 6xxx series alloys. This is due to a large energy requirement for air cooling fans. For process steps with low machine costs, energy and labor are the main contributors to cost. However, the variable costs are dominated by fixed costs for the most expensive and thereby most significant production steps.

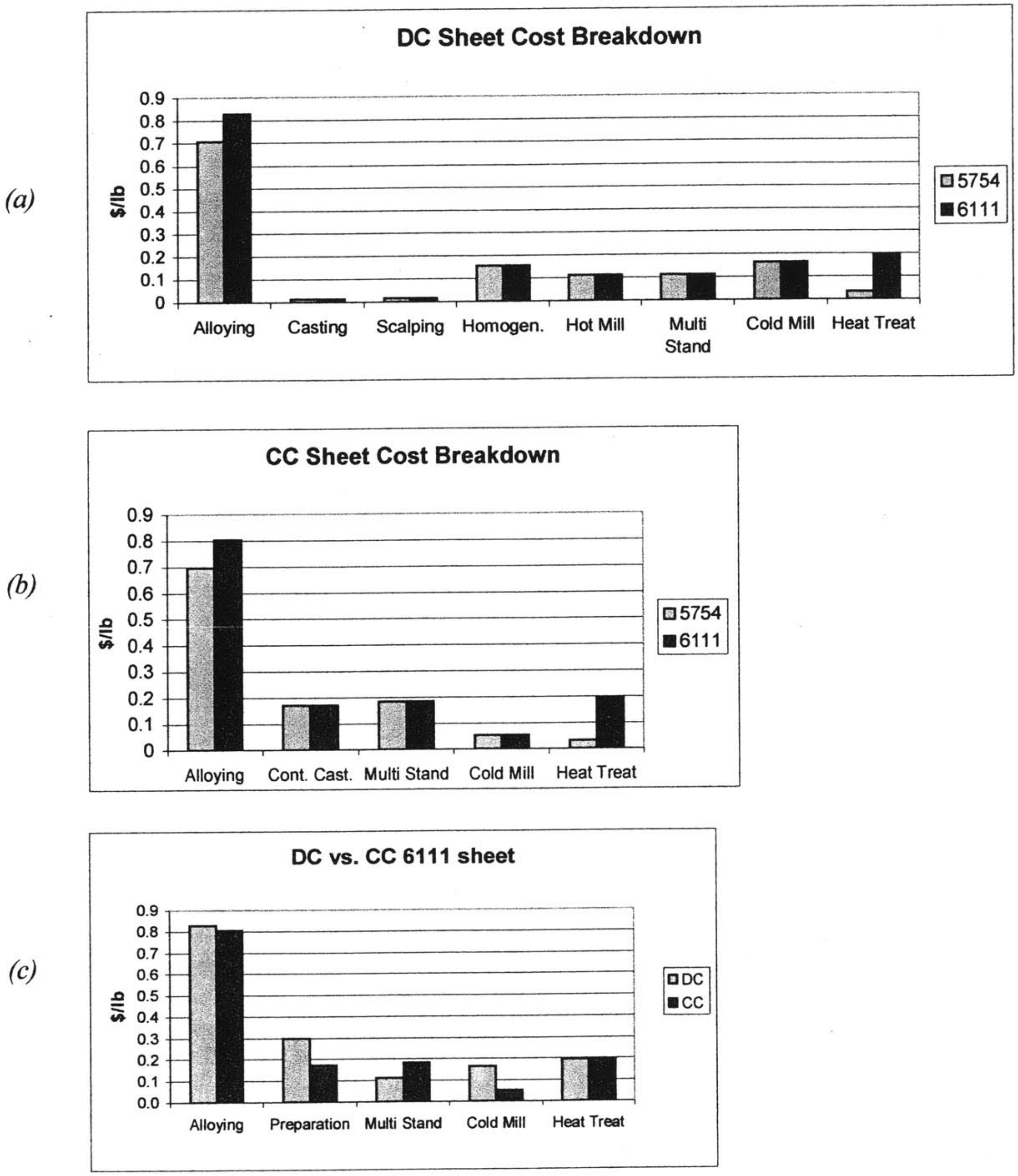
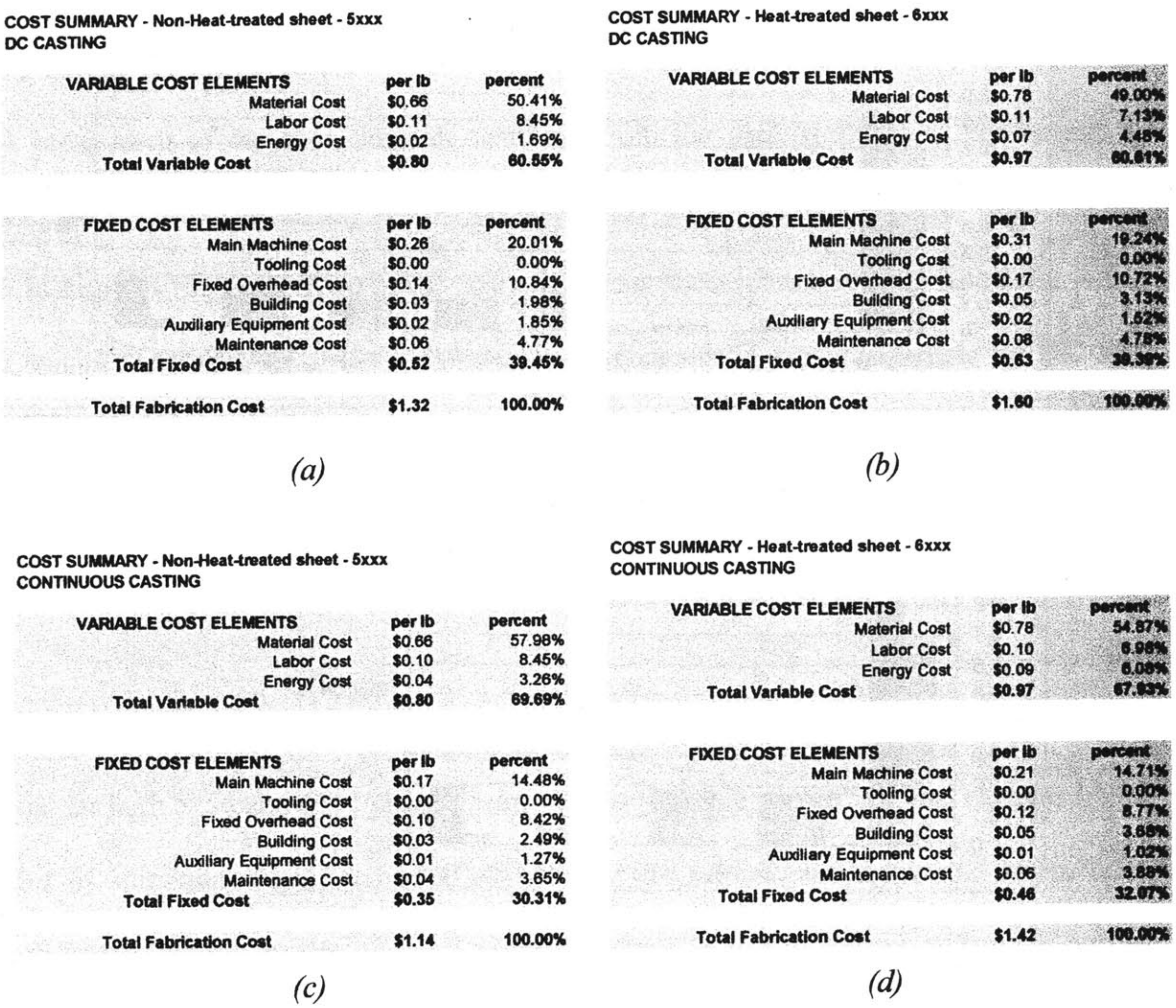


Figure 6.1: Breakdown of processing costs of DC and CC sheets.



COST SUMMARY - Non-Heat-treated sheet - 5xxx
DC CASTING

VARIABLE COST ELEMENTS	**per lb**	**percent**
Material Cost	$0.66	50.41%
Labor Cost	$0.11	8.45%
Energy Cost	$0.02	1.69%
Total Variable Cost	**$0.80**	**60.55%**

FIXED COST ELEMENTS	**per lb**	**percent**
Main Machine Cost	$0.26	20.01%
Tooling Cost	$0.00	0.00%
Fixed Overhead Cost	$0.14	10.84%
Building Cost	$0.03	1.98%
Auxiliary Equipment Cost	$0.02	1.85%
Maintenance Cost	$0.06	4.77%
Total Fixed Cost	**$0.52**	**39.45%**
Total Fabrication Cost	**$1.32**	**100.00%**

(a)

COST SUMMARY - Heat-treated sheet - 6xxx
DC CASTING

VARIABLE COST ELEMENTS	**per lb**	**percent**
Material Cost	$0.78	49.00%
Labor Cost	$0.11	7.13%
Energy Cost	$0.07	4.48%
Total Variable Cost	**$0.97**	**60.61%**

FIXED COST ELEMENTS	**per lb**	**percent**
Main Machine Cost	$0.31	19.24%
Tooling Cost	$0.00	0.00%
Fixed Overhead Cost	$0.17	10.72%
Building Cost	$0.05	3.13%
Auxiliary Equipment Cost	$0.02	1.62%
Maintenance Cost	$0.08	4.78%
Total Fixed Cost	**$0.63**	**39.39%**
Total Fabrication Cost	**$1.60**	**100.00%**

(b)

COST SUMMARY - Non-Heat-treated sheet - 5xxx
CONTINUOUS CASTING

VARIABLE COST ELEMENTS	**per lb**	**percent**
Material Cost	$0.66	57.98%
Labor Cost	$0.10	8.45%
Energy Cost	$0.04	3.26%
Total Variable Cost	**$0.80**	**69.69%**

FIXED COST ELEMENTS	**per lb**	**percent**
Main Machine Cost	$0.17	14.48%
Tooling Cost	$0.00	0.00%
Fixed Overhead Cost	$0.10	8.42%
Building Cost	$0.03	2.49%
Auxiliary Equipment Cost	$0.01	1.27%
Maintenance Cost	$0.04	3.65%
Total Fixed Cost	**$0.35**	**30.31%**
Total Fabrication Cost	**$1.14**	**100.00%**

(c)

COST SUMMARY - Heat-treated sheet - 6xxx
CONTINUOUS CASTING

VARIABLE COST ELEMENTS	**per lb**	**percent**
Material Cost	$0.78	54.87%
Labor Cost	$0.10	6.98%
Energy Cost	$0.09	6.08%
Total Variable Cost	**$0.97**	**67.93%**

FIXED COST ELEMENTS	**per lb**	**percent**
Main Machine Cost	$0.21	14.71%
Tooling Cost	$0.00	0.00%
Fixed Overhead Cost	$0.12	8.77%
Building Cost	$0.05	3.68%
Auxiliary Equipment Cost	$0.01	1.02%
Maintenance Cost	$0.06	3.88%
Total Fixed Cost	**$0.46**	**32.07%**
Total Fabrication Cost	**$1.42**	**100.00%**

(d)

Table 6.1: Cost summary for 5754 and 6111 sheets for the different production methods assuming non-dedicated equipment

Fixed cost elements roughly account for the remaining 40% of the costs. The investments in machinery result in the majority of these costs. The machine costs directly determine the maintenance costs and indirectly determine auxiliary equipment costs depending on the process step. These costs together with the relatively insignificant building costs drive the overhead costs. The maintenance, auxiliary equipment and overhead costs are simply determined as a percentage of the machine and building costs as a reasonable "rule of thumb" estimate. In reality, several other factors that are difficult to identify and that differ between plants determine these costs. The costs of machine investments thereby have a disproportionate influence on the fixed costs accounting for more than 90% of these. It is therefore crucial that the investments are accurately determined.

The difference in cost between 5xxx and 6xxx alloys only arise from two different sources. First, 6xxx series alloys consist of more expensive alloying materials and have a higher purity level which both contribute to a higher material cost. Second, processing costs differ due to the different heat treatment technologies. 6xxx series alloys require a relatively expensive solution heat treatment while an inexpensive batch anneal can be used for the 5xxx series alloys. The continuous heat treatment of 6xxx series requires large machine investments and high energy consumption and results in a cost difference of approximately 0.16 $/lb for this step only.

The costs of casting, scalping and batch anneal are relatively small. These processes have low machine investment requirements and their costs are mainly derived from labor and energy. Homogenization as well as the three rolling steps are relatively expensive because of the costly machines. There is a slight increase in the cost of each rolling step from the hot mill (3 passes) to the multi stand (3 stands) to the cold mill (4 passes). Keeping in mind that the unit investment cost of the machinery decreases for each rolling step, this might seem odd at first glance. However, the rolling speed is assumed to be constant for each processing step when measured in length per unit time and not volume processed. Since the length increases for each step as the thickness decreases, the time requirement for the mill goes up. The length and thereby time requirement increases exponentially with the number of passes. At thicker gauges, more expensive rolling mills with lower rolling speeds are required. Nevertheless, the rolling speeds of the lower gauge mills do not scale in proportion with the increased length. A larger number of parallel streams are generally required at lower gauges. A good metric for the cost of the rolling equipment is the required investment per rolling speed. For the equipment used in this analysis this metric is displayed in Table 6.2.

	Investment per Rolling Speed $M/(ft/min)
Hot Mill	6.5
Multi Stand (per stand)	1.4
Cold Mill	0.2
Continuous Casting	15

Table 6.2: The required investment per rolling speed for the rolling equipment used in this analysis.

6.2 Continuously Cast Sheet

The TCM model confirms that there is great potential for continuous casting of aluminum. Figure 6.1b displays the breakdown of the cost of CC sheet, please refer to Appendix A for a complete breakdown of the cost. A cost summary of the production costs and investment for CC sheets are shown in Table 6.1c-d. Using the approach of non-dedicated equipment the cost of 0.039in (1mm) automotive 5754 sheet is 1.14 $/lb and the cost of 6111 sheet is 1.42 $/lb.

The factors that distinguish between the cost of 5xxx and 6xxx series sheets are identical for both DC and CC sheet. Consequently, the cost difference between 5xxx and 6xxx of 0.28 $/lb seen for DC sheet is also observed for CC sheet. Once again the cost difference between 5xxx and 6xxx series alloy sheet arises from two sources, the use of different alloying materials and different heat treatment processing methods. An insignificantly lower material cost for CC sheet is due to the assumption that less scrap is being generated than in the production process for DC sheet.

Figure 6.1c shows a cost comparison between the production sequences of DC and CC 6111 sheets. Continuous casting replaces the casting, scalping, homogenization and hot mill steps used in conventional DC casting. The cost of continuous casting is 0.17 $/lb, while the cost of the similar preparation step for DC sheet is 0.30 $/lb. The costs of the processes challenged to be replaced by continuous casting are higher than the cost of continuous casting. The gauge of the continuously cast sheet is much less than the exiting gauge from the hot mill. This implies further cost savings downstream resulting from the fact that CC sheet only requires a single hot mill pass and a single cold mill pass, while the DC sheet is assumed to need three multi stand and four cold roll passes. The cost of these steps amounts to 0.19 $/lb for the CC sheet and 0.28 $/lb for the DC sheet. An interesting feature is that the cost of the multi stand hot mill is higher for the CC sheet which only requires one stand. Its low gauge results in a longer milling time which offsets the additional capital costs of having three stands for the DC sheet.

The possibility to skip the hot rolling step and go directly to cold rolling for continuously cast sheet was discussed in Section 5.4. Noting that the required investment per rolling speed is 0.2 $M/(ft/min) and 1.4 $M/(ft/min) for cold rolling and multi stand hot rolling respectively, there is a potential for further cost savings of CC sheet. However, a lower gauge reduction per pass is assumed for cold rolling than for hot rolling. One hot roll and one cold roll pass have to be replaced by three cold rolling passes. Substantial cost savings of 0.10 $/lb are still generated as a result of the elimination of the hot rolling step. This yields a final potential cost of 5754 sheet of 1.04 $/lb. This change in the production process might be especially advantageous for 5xxx series sheet. Since the hardness is achieved by work hardening in the cold state, multiple cold rolls might be a necessity in order to obtain the desired hardness.

Another cost saving potential of continuous casting is not captured by the TCM model. Handling costs and in-process time can be eliminated by having the sheet pass directly from the caster to the rolling mills. For practical reasons it might still be advantageous not to have one continuous line because it would be very vulnerable to breakdown of machinery.

6.3 Utilization of Equipment and Economies of Scale

Large scale industrial operations involve substantial fixed costs. At high levels of output these costs can be distributed over larger amounts of product and therefore the average production cost per unit material decreases. Processes that display decreasing average costs with increasing levels of output are referred to as having economies of scale [9]. Figure 6.2 shows the cost of CC 5754 sheet for varying production volumes under the assumption of dedicated production equipment. Although the trend is decreasing cost with increasing output, economies of scale are not observed over the whole range of production volumes. The aluminum sheet production plant employs many pieces of expensive equipment that each has a maximum capacity. When the production volume exceeds this maximum, it is assumed that a costly investment in another piece of the same equipment for parallel processing is necessary. Therefore, an increase in average cost is seen as the production volume exceeds the capacity for one or more pieces of equipment.

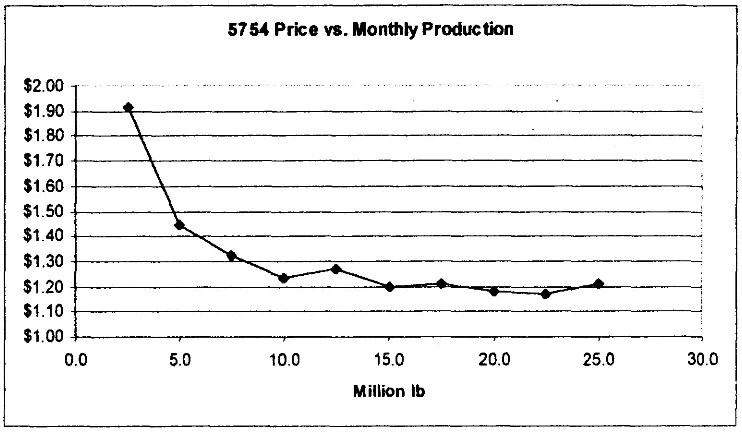
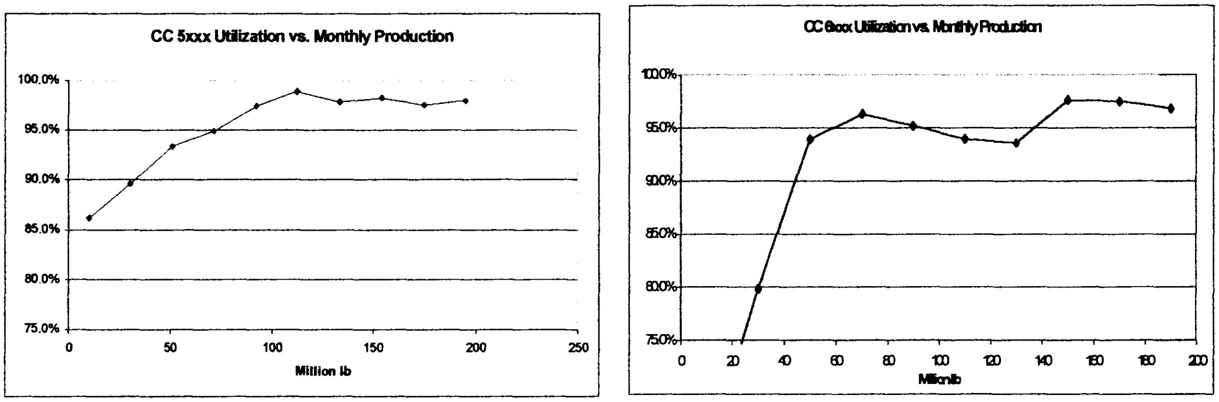


Figure 6.2: Price of CC 5754 sheet for varying production volumes under the assumption of dedicated production equipment.

The data for the TCM model has been collected from several different manufacturers. The price and capacity are quoted for machinery not necessarily designed for a plant with the same production volume. It is reasonable to believe that aluminum manufacturers would be able to scale most parts of the manufacturing process to the same capacity. Equipment with excess capacity could in many cases be employed in the production of other products during the available free time. For these reasons, a better cost estimate is achieved when the cost and capacity of the equipment is assumed to scale linearly with the amount of production. Nevertheless, this assumption implies that every single part of the plant is utilized at its maximum level. In reality there will always be a few bottlenecks and parts of the facilities will have excess capacity. For CC sheet that passes the cold rolling mill only once, an output of 24 million lb/month is necessary to reach full capacity of the mill. The degree of utilization for a piece of equipment can be measured as a percentage of maximum capacity. For example, if the TCM model predicts that 1.7 cold rolling parallel streams are needed at an output of 40 million lb/month, having 2 necessary rolling mills results in a utilization of 85%. An overall utilization factor can be calculated by taking a weighted average of the utilization of each piece of equipment weighted by the fixed cost elements associated with that equipment. Figure 6.3a-b show the utilization factor for 5xxx and 6xxx sheets for varying outputs. Necessary outputs to reach utilization levels over to 95% are 65M lb/month.



(a) *(b)*

Figure 6.3: Utilization factor for CC 6xxx and 5xxx sheet for varying levels of output

Even at high levels of output the utilization of the equipment varies with the production volume. If dedicated equipment is chosen and a production volume is specified, the price generated by the TCM model increases non-continuously when the number of necessary machines increases. The aluminum manufacturers are probably much better at maximizing utilization by adjusting their production volumes and facilities than what is reflected by the TCM model. A more consistent estimate of the price is therefore obtained by using the approach of non-dedicated equipment and adjusting fixed costs to reflect the expected level of utilization at the specific production volume. The price of aluminum alloy sheet can be calculated by dividing the fixed costs by the utilization factor while the variable costs remain constant. These values for different degrees of utilization are displayed in Table 6.3. The reader should keep in mind that alternative production equipment for alternative production volumes is likely to exist. For that reason it is reasonable to believe that aluminum manufacturers might be able to achieve a higher utilization at lower production volumes than what is reflected in the TCM cost model.

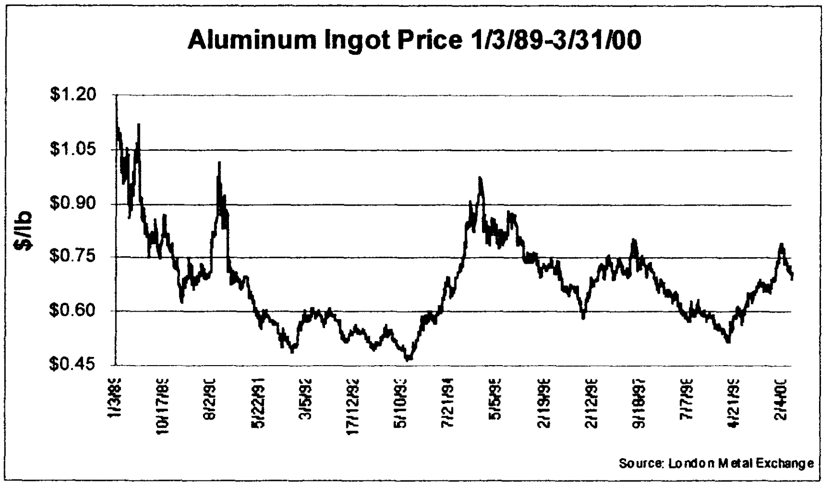
Factory Utilization	100%	97%	90%	80%
		Output (M lb/month)		
5xxx		> 95	~ 30	~ 14
6xxx		> 140	~ 40	~ 30
		Price ($/lb)		
DC 5754	1.32	1.34	1.38	1.45
DC 6111	1.60	1.62	1.67	1.76
CC 5754	1.14	1.16	1.19	1.24
CC 6111	1.42	1.44	1.48	1.55

Table 6.3: Aluminum sheet production cost for different factory utilizations.

6.4 Aluminum Price Fluctuations

There has historically been large volatility in the price of aluminum. Figure 6.4 displays the price of aluminum ingot in the period 1989 - 2000 [14]. Since 1989 the price of aluminum ingot has ranged between 0.46 $/lb and 1.18 $/lb. The average price for February and March 2000 was 0.76 $/lb and is the value used in this analysis. A significantly lower average price of 0.63 $/lb has been observed over the two years until March 2000. Nevertheless, prices can not be expected to decrease in the near future. In fact, estimates suggest that the price will go up, but it is very difficult to predict such a market [15].

The price of steel automotive sheet has traditionally been much more stable. The material cost of steel is much lower than the cost of aluminum alloy. Volatility in the price of iron and other alloying elements have a much lower impact on the volatility of the final sheet price because the fraction of material cost is lower for steel sheet than it is for aluminum sheet. Further, the world production of steel is significantly larger than the production of aluminum. The price of steel is thereby less susceptible to localized or company specific economic perturbations.



Aluminum Ingot Price 1/3/89-3/31/00

Source: London Metal Exchange

Figure 6.4: Historical price of aluminum ingot.

The price risk of aluminum has been an important argument for the auto industry not to undertake the substantial investments required to switch from steel to aluminum sheet in autobodies. It is truly difficult to guard oneself against the price risk over long periods of time. However, aluminum and auto manufacturers are known to reach price stability agreements [10]. For shorter time periods ranging up to a few years it is possible to use financial instruments at a relatively low cost to hedge against the price risk.

7 Impact of Sheet Cost on the Part Fabrication Cost

7.1 Part Fabrication Cost Modeling

A TCM model previously developed at the Materials Systems Laboratory was used to analyze the impact of the sheet cost on the final part fabrication cost. The principles behind the model are the same as for the aluminum rolling model previously described. Common economic assumptions were set equal for both models.

Parts are formed by the use of stamping presses that from sheet metal into the desired shape and trim off extraneous material. The presses use tools that perform a number of different operations depending on the requirements of the final part. The operations can be divided into the two main functional categories blanking and stamping.

Blanking refers to the initial cutting into of the shaped form from the coil in which the alloy sheet arrives from the manufacturer. Coiled sheet is fed into blanking presses where it is unrolled and cut into blanks that are the input materials for the stamping operations. Blanking is a fairly simple and undemanding process step and generally occurs at a relatively high production rate. The blank is subsequently turned into a finished part by stamping operations. Stamping involves a number of different procedures including trimming, forming, drawing and flanging. The desired shape of the part determines the number and type of operations that must occur. Please refer to the forthcoming thesis by Ashish Kelkar for a detailed description of aluminum part fabrication modeling and the specific TCM model used for this analysis[11].

7.2 Economic Analysis of Part Fabrication Costs

The purpose of this section is to see the impact of the different cost ranges of aluminum sheet calculated in Section 6. The Ford P2000 experimental car with an all aluminum body was used in the analysis. Specifications for each body part was provided by Ford and used to model the production cost. Three main cost scenarios were constructed: a reasonable scenario, a best case scenario and a worst case scenario. The cost of sheet for these different possibilities is displayed in Table 7.1. All the scenarios assume the same cost of alloy and the same economic parameters. The sheet price is given for 1.0 mm (0.039 in) sheet. The price does not vary significantly with small changes in the gauge, and the thickness used is an approximate average thickness.

The reasonable scenario assumes continuous casting and a high level of output resulting in 97.5% utilization. The best case scenario also assumes continuous casting, but assumes 100% utilization. Most importantly, it accounts for the possibility to skip the hot-rolling step and go directly from casting to cold rolling resulting in an additional cost saving of 0.10 $/lb. The worst case scenario assumes DC casting and 97.5% utilization. Except for the casting method, these assumptions are identical to the reasonable case scenario and essentially represent where the aluminum industry is today.

		5754	6111
Reasonable	(97.5% Utilization)	1.16 $/lb	1.44 $/lb
Best Case	(Directly Cold Rolled)	1.04 $/lb	1.32 $/lb
Worst Case	(DC Cast, 97.5% Utilization)	1.34 $/lb	1.62 $/lb

Table 7.1 The cost of aluminum sheet for different scenarios assumed in this section.

Figure 7.1 shows the range of total sheet costs for various scenarios and alloy selections. The annual output is assumed to be 200,000 automobiles for all other varying possibilities. The costs of forming and joining the sheets are assumed to be the same regardless of which aluminum alloy is being used. When 6xxx series sheet is used in exterior panels and 5xxx sheet is used for interior panels, 39% of the material is 6111 and 58% is 5754. A small number of steel parts accounting for 3% of the total weight are necessary in all the possible solutions analyzed. Please refer to Appendix B for a list of data for part forming production cost for the various assumptions.

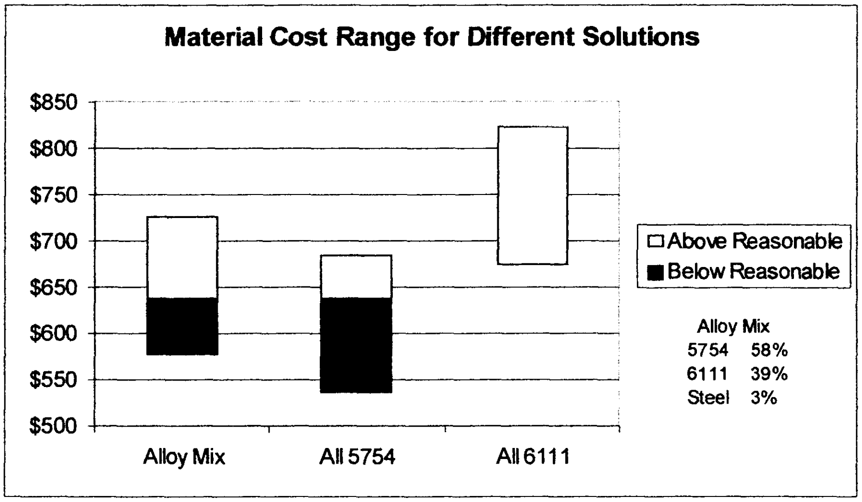


Figure 7.1: Different possible ranges of total cost of sheet used in production of the aluminum autobody.

For the reasonable scenario and the alloy mix described, the part fabrication cost is $1502 per vehicle of which the material cost represents $637. For this alloy combination, the worst and best case scenarios result in costs ranging from $89 higher to $60 lower. The reader should note that the current DC casting technology therefore implies a material cost of $726.

Although 5xxx series alloys currently do not exhibit the necessary dent resistance for exterior panels, the possibility of substituting the 6xxx series by 5xxx series alloys was analyzed. This could also represent the possibility of an elimination of most of the cost penalty associated with fabrication and alloying of the 6xxx series sheets. The TCM model indicates that by switching entirely to 5754, a material cost ranging from \$536 to \$684 is achieved. The best case scenario therefore indicates that cost savings of \$191 can be achieved for the aluminum unibody.

Another advantage by using the same alloy in the entire autobody is that there is great ease of recycling. Since the scrap material is uniform it can be used for higher grade alloys. However, although previously assumed, the 5xxx series alloys can currently not be used for exterior panels. The only way to achieve a uniform alloy composition throughout the car is by using the 6xxx series for interior panels. The best case scenario results in a minimum sheet cost of \$674 for this solution. Figure 7.1 clearly indicates that this is very costly and that the recycling gains will not be sufficient to justify this solution.

All previous analyses has assumed a constant cost of aluminum ingot of 0.76 \$/lb. As discussed in Section 6.4, the price of aluminum is known to be very volatile. There is a \$100 cost difference between the reasonable mixed alloy solution and the best case all 5754 solution. This cost difference is entirely achieved by technological and production improvements. Further cost reduction can be achieved if the price of aluminum goes down. Assuming that the price of alloying elements and scrap vary proportionately with the price of aluminum, the question of where the price of aluminum ingot has to go in order to obtain additional cost savings of $100 was asked. An ingot price of 0.53 $/lb achieved this cost reduction and resulted in a minimum cost of a best case all 5754 body of approximately $1300 with a material cost of $436. The price of aluminum ingot was in the range of 0.52 $/lb to 0.55 $/lb over a period as recently as mid January to mid March 1999. An important note is that the price of aluminum was considered very low during this period. The ingot price is probably equally likely to increase in the future. Nevertheless, this shows that the price has a large influence of the cost of the autobody and is a crucial determinant of the profitability of large scale aluminum vehicle production.

7.3 Cost of Additional Paint Bake Hardening of 6xxx Series Alloys

Section 4.2 described how the final precipitation hardening of 6xxx series alloys is achieved in paint curing furnaces after the body is assembled. The alloy is formed in the solution heat treated condition designated by T4. In order to reach the full T6 precipitation hardened state, the alloy has to be annealed for 4-6 hours in conjunction with the paint bake. Conventional paints typically need one curing cycle for 30 minutes in the temperature range of precipitation hardening [12]. A compromise between the hardness of the exterior sheets and the annealing time has to be made. Engineers at Ford believe that the necessary hardening usually can be achieved during the 30 minute heat treatment of the regular painting cycle. However, if further hardness is desired, additional curing furnaces have to be installed. The cost of an in-line curing furnace is assumed to be 6000 $/ft [12]. The other main cost driver is the gas costs for heating the furnace. It was found that an additional hour of heat treatment beyond the normal painting cycle costs approximately $18 per vehicle. The costs increase linearly with the additional furnace length necessary. A 0.30 $/min cost is accumulated for extra heat treatment time. Please refer to Appendix C for a complete display of the assumptions and cost results.

8 Aluminum Alloy as An Alternative to Steel

8.1 Comparison of Part Fabrication Cost Between Aluminum and Steel

Assuming the very best case conditions described in Section 6 (that all cost cuts can be made and that the price of aluminum ingot is extremely favorable), the total part fabrication cost of a Ford P2000 aluminum unibody still amounts to $1300 at a production volume of 200,000. The comparable steel counterpart, the Ford Countour, has a total part fabrication cost of $770 at the same production volume. Figure 8.1 shows the total part fabrication costs using reasonable case assumptions for several production volumes for the Ford P2000 and the Ford Countour. Although the aluminum body design exhibits significantly larger economies of scale, the cost of the aluminum body is much higher for all levels of output. The aluminum design is far from being cost competitive with steel. The reader should note that the P2000 and the Contour are not perfectly comparable vehicles. The P2000 is 4 inches longer and there are several other differences between the cars. Nevertheless, these differences are relatively insignificant and do not account for a large fraction of the cost difference between the two autobodies.

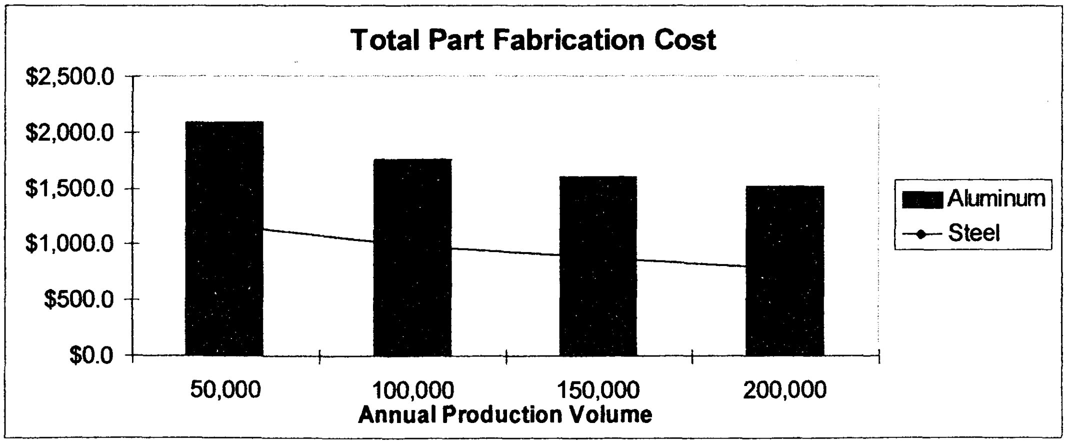


Figure 8.1: Total body part fabrication cost of Ford P2000 (aluminum) and Ford Countour (Steel).

Because of secondary cost and weight savings, higher costs can be tolerated for the aluminum body than for the steel body. Other load bearing parts of the vehicle will also contribute to the weight and production cost savings since they can be downsized as the vehicle weight goes down. A lighter vehicle requires a smaller engine, which then will itself be lighter. The engine will be cheaper and savings are generated as a result of less fuel consumption. Fuel exhaust emissions will also be reduced with the reduction in fuel consumption. As the fuel prices increase and the consumers and governments become more sensitive to vehicle fuel consumption, aluminum will become more competitive with steel. This study does not intend to identify the extent of secondary cost savings and can therefore not be used to quantify the competitive cost of an aluminum body. However, it is reasonable to believe that the costs calculated in this analysis are not sufficiently low to justify a replacement of steel by aluminum in the autobody.

8.2 Steel Re-Challenging Aluminum Alloy

With the increasing challenge from aluminum alloys, the steel industry has responded by developing a range of high strength steel products. These allow both the body and structural steels to be manufactured from thinner sheets, leading to reduced weight and improved fuel efficiency. A steel light-weighting program has been undertaken by 32 steel producers worldwide. They commissioned Porsche Engineering Services to design a lightweight steel body incorporating current standards of structure rigidity, crash-worthiness and manufacturability [10]. The design is known as the Ultra Light Steel Auto Body (ULSAB). Although the weight savings are not as dramatic as those achieved by alternative materials, the design can potentially be accompanied by a manufacturing cost reduction offsetting the cost penalty implied by the more expensive steels.

Demonstration vehicles built using the ULSAB design exhibited weight reductions of approximately 25%. The reduction was achieved through the use of tailored blanks, tubular hydroforming, hydro-mechanical sheet forming, laser welding and high-strength steels [12]. The body structure design was accomplished with far fewer parts. This parts consolidation contributed to relatively low production costs in spite of higher material costs and more expensive forming technologies. Technical cost modeling has shown that the production costs of the ULSAB autobody are comparable to those of regular commercial steel bodies.

Although the potential weight savings are not as high for steel bodies as for aluminum bodies, the attempt to lightweight steel vehicles shows great potential to meet fuel efficiency requirements at least in the immediate foreseeable future. This further increases the competitive demand to reduce production costs and improve the design of aluminum autobodies.

9 Conclusions

This study has addressed several issues that could affect the prospects of rolled aluminum sheets as a cost efficient alternative to steel in automotive unibodies. The cost of aluminum sheet is currently far to high to be a viable replacement of steel.

Advances in sheet casting technology have resulted in the opportunity to make continuously cast automotive sheet. To switch away from the traditional DC casting process which involves numerous gauge reducing hot and cold rolling steps, is the single most important change that could contribute to the reduction in cost of aluminum alloy sheet. This analysis suggests that this could result in a reduction of sheet costs of approximately 0.28 $/lb (17 %- 20%). The cost savings are generated as a result of a lower investments required for the continuous casting process which replaces casting, heat treatment and a majority of the subsequent rolling steps. There are a few smaller technological hurdles that need to be overcome. Large capital investments are required to replace current DC casting facilities with continuous casting machinery. The gains from doing so will prove to be of such a magnitude that future large scale production of automotive aluminum sheet will almost certainly utilize continuous casting. The savings in sheet cost for the autobody is on the order of $90 as a result of switching to continuous casting.

The Ford P2000 autobody consists of 39% 6xxx series aluminum used in the exterior panels. The 6xxx series uses more expensive raw materials and requires a costly continuous heat treatment step. This results in a large cost gap between 5xxx and 6xxx series alloys. Substantial reduction in the overall cost of the body can be achieved if technical improvements are made such that either 5xxx series sheet can replace 6xxx sheet for exterior parts or the cost of 6xxx sheet approaches that of the 5xxx sheet.

The large fixed costs associated with aluminum sheet production result in economies of scale and favor large fabrication facilities. Carefully planned facilities with minimal over capacity at any stage of production is necessary. This has resulted in a few market players and recent consolidation in North America and Europe. Aluminum prices have generally been highly volatile. Price stability agreements are very important in order for auto-manufacturers to make the commitment to invest in aluminum manufacturing facilities. A decrease in the price is probably necessary to make aluminum competitive with steel.

Although this study has been highly quantitative and has calculated specific costs for different scenarios, it is important to keep in mind that the results are best used as an indication of where the industry is and where it might go. Estimates and uncertain inputs may result in numerical cost results that are different from actual costs. The analysis nevertheless shows clear trends of how the costs for aluminum production may change, and there is no doubt that there are great potentials for a large forward leap for aluminum alloy sheets in automobiles.

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Appendix A - The TCM Aluminum Casting and Rolling Model

Assumptions used for DC casting in the TCM model:

Material Related Information

Alloy Spec (see "Alloying Calcs" sheet)	2	
Alloy Name (from "Alloying Calcs" sheet)	5754	
Alloy Density	0.096	lb/in^3
Alloy Specific Heat	0.215	Btu/lb-°F
Unit Material Cost (from "Alloying Calcs" sheet)	$0.65	$/lb

Product Data

Total Monthly Sheet Production	25,000,000	lb
Fraction of Production requiring continuous heat treat	0.00	
Final Sheet Thickness	0.039	in
Final Coil Width	72	in
Ingot Thickness (DC Casting)	25	in
Ingot Width (DC Casting)	75	in
Target Ingot Length (DC Casting)	250	in

Exogenous Cost Factors

Hours Per Day	24	hr
Days Per Year	365	days
Downtime	10.0%	
Wage (including benefits)	$35.00	$/hr
Electricity Cost	$0.10	$/kWhr
Gas Cost	$2.25	$/million Btu
Gas Energy Efficiency	50%	
Interest	12.0%	
Equipment Life	20	yrs
Fixed Overhead	35.0%	
Building Costs	140	$\$/\text{ft}^2$
Building Life	25	years
Maintenance Costs	20.0%	
Continuous Casting (1=yes, 0=no)	0	
Dedicated Equipment (1=yes, 0=no)	0	

Process Specifications

Alloying

Heel Material (%)	10%	
Time to Melt	2	hr
Melt Temperature	1200	°F
Heat Loss (%)	50%	
Dedicated Equipment (1=yes,0=no)	0	
Melting Furnace Cost	$2,000,000	
Auxiliary Equipment Cost	10.0%	
Equipment Space Requirement	1500	ft^2
Maximum Percent Scrap That Can Be Used	27%	
Scrap Purchase Price	$0.36	$/lb
Scrap Sell Price	$0.36	$/lb
Dross Price	$0.25	$/lb
Alloying Material Loss (%)	2%	

Casting

Workers per Ingot	4	
Casting Rate	120	in/hr
Set-up Time	0.5	hr
Casting Equipment Unit Cost	$2,000,000	
Holding Furnace Unit Cost	$0	
Holding Furnace Temperature	1200	°F
Holding Furnace Energy Loss (%)	50%	
Auxiliary Equipment Cost	10%	
Casting Space Requirement	1500	ft^2
Casting Material Loss (%)	5%	

Hot Mill

Workers per Hot Mill	10	
Time between Passes	0.25	hr
Number of Passes	3	
Metal Thickness After Final Pass	2.0	in
End Trim Los after Hot Mill (per end)	12	in/end
Milling Rate	10	ft/min
Hot Mill Energy Consumption Rate	1000	kW
Unit Mill Cost	$65,000,000	
Hot Mill Space Req'd (including roller storage)	50,000	ft^2
Auxiliary Equipment Cost	10.0%	

Multi-Stand Hot Tandem Mill/Coiler

Workers per Mill	6	
Number of Stands	3	
Cost per Stand	$35,000,000	
Multi Stand Mill Rate	25	ft/min
Multi Stand Setup Time	0.25	hr
Metal Thickness after Hot Tandem Mill	0.333	in
Side Trim Loss after Hot Mill (per side)	1	in/side
End Trim Los after Hot Mill (per end)	12	in/end
Mill Electricity Consumption Rate	1000	kW
Mill Space Requirement	15,000	ft^2
Auxiliary Equipment Cost	10.0%	

Cold Mill

Metal Thickness After Cold Mill	0.039	in
Side Trim Loss after Hot Mill (per side)	0.5	in/side
End Trim Los after Hot Mill (per end)	12	in/end
Number of Passes Required	4	
Cold Mill Rate (exit length/hr)	250	ft/min
Coil Setup Time	0.25	hr
Worker Per Cold Mill	4	
Cold Mill Electricity Consumption Rate	1000	kW
Unit Cold Mill Cost	$50,000,000	
Cold Mill Unit Space Requirement	50,000	ft^2
Auxiliary Equipment Cost	10.0%	

Annealing Processes

Continuous Heat Treat

Worker per Heat Treat Line	3	
Heat Treat Line Cost Intercept	$4,000,000	$
Heat Treat Line Cost Coefficient	5.600	$/lb/month
Set Line Capacity (0=auto scaling)	0	lb/month
Heat Treat Line Cost Override	0	$
Heating Efficiency	35%	
Heat Treat Line Electrical Power Requirement	5000	hp
Heat Treat Line Length	450	ft
Heat Treat Line Width	200	ft
Heat Treat Line Height	25	ft
Annealing Gas Refresh Rate	0	/hr
Annealing Gas Unit Cost	0.0025	$\$/\text{ft}^3$
Anneal Temperature	1040	°F
Greenfield ROI Requirement (0=use overall interest rat	0%	

Batch Anneal

Packing Efficiency	75%	
Heat Up Time	2	hr
Hold Time	12	hr
Cool Down Time	2	hr
Anneal Temperature	750	°F
Batch Furnace Length	25	ft

Output for 5754 DC cast sheet:

AUTOMOTIVE SHEET

COST SUMMARY - Non-Heat-treated sheet - 5xxx
DC CASTING

VARIABLE COST ELEMENTS	per lb	percent
Material Cost	$0.66	50.41%
Labor Cost	$0.11	8.45%
Energy Cost	$0.02	1.69%
Total Variable Cost	**$0.80**	**60.55%**

FIXED COST ELEMENTS	per lb	percent	investment
Main Machine Cost	$0.26	20.01%	$590,741,561
Tooling Cost	$0.00	0.00%	$0
Fixed Overhead Cost	$0.14	10.84%	
Building Cost	$0.03	1.98%	$61,427,839
Auxiliary Equipment Cost	$0.02	1.85%	$54,574,156
Maintenance Cost	$0.06	4.77%	
Total Fixed Cost	**$0.52**	**39.45%**	

Total Fabrication Cost	**$1.32**	**100.00%**

AUTOMOTIVE SHEET COST BREAKDOWN

Non-Heat-treated sheet - 5xxx

	Alloying	Casting	Scalping	Homogen.	Hot Mill	Cont. Cast.	Multi Stand	Cold Mill	Heat Treat	Total
VARIABLE COST ELEMENTS										
Material Cost	0.664	0.000	0.000	0.000	0.000	na	0.000	0.000	0.000	0.66
Labor Cost	0.027	0.009	0.011	0.027	0.017	na	0.007	0.013	0.000	0.11
Energy Cost	0.003	0.001	0.001	0.001	0.004	na	0.003	0.008	0.001	0.02
Total Variable Cost	**0.695**	**0.010**	**0.011**	**0.028**	**0.021**	**na**	**0.010**	**0.021**	**0.001**	**0.80**
FIXED COST ELEMENTS										
Main Machine Cost	0.002	0.002	0.000	0.065	0.047	na	0.056	0.071	0.020	0.26
Tooling Cost	0.000	0.000	0.000	0.000	0.000	na	0.000	0.000	0.000	0.00
Fixed Overhead Cost	0.012	0.001	0.001	0.033	0.024	na	0.026	0.037	0.008	0.14
Building Cost	0.000	0.000	0.002	0.008	0.005	na	0.001	0.010	0.000	0.03
Auxiliary Equipment Cost	0.000	0.000	0.000	0.006	0.005	na	0.006	0.007	0.000	0.02
Maintenance Cost	0.000	0.000	0.000	0.016	0.011	na	0.013	0.018	0.004	0.06
Total Fixed Cost	**0.015**	**0.004**	**0.004**	**0.128**	**0.092**	**na**	**0.101**	**0.143**	**0.033**	**0.52**
Total Fabrication Cost	**0.709**	**0.014**	**0.015**	**0.156**	**0.113**	**na**	**0.112**	**0.164**	**0.034**	**1.32**

Assumptions used for CC casting in the TCM model:

Material Related Information

Alloy Spec (see "Alloying Calcs" sheet)	2	
Alloy Name (from "Alloying Calcs" sheet)	5754	
Alloy Density	0.096	lb/in^3
Alloy Specific Heat	0.215	Btu/lb-°F
Unit Material Cost (from "Alloying Calcs" sheet)	$0.65	$/lb

Product Data

Total Monthly Sheet Production	25,000,000	lb
Fraction of Production requiring continuous heat treat	0.00	
Final Sheet Thickness	0.039	in
Final Coil Width	72	in
Ingot Thickness (DC Casting)	25	in
Ingot Width (DC Casting)	75	in
Target Ingot Length (DC Casting)	250	in

Exogenous Cost Factors

Hours Per Day	24	hr
Days Per Year	365	days
Downtime	10.0%	
Wage (including benefits)	$35.00	$/hr
Electricity Cost	$0.10	$/kWhr
Gas Cost	$2.25	$/million Btu
Gas Energy Efficiency	50%	
Interest	12.0%	
Equipment Life	20	yrs
Fixed Overhead	35.0%	
Building Costs	140	$/ft^2
Building Life	25	years
Maintenance Costs	20.0%	
Continuous Casting (1=yes, 0=no)	1	
Dedicated Equipment (1=yes, 0=no)	0	

Process Specifications

Alloying

Heel Material (%)	10%	
Time to Melt	2	hr
Melt Temperature	1200	°F
Heat Loss (%)	50%	
Dedicated Equipment (1=yes,0=no)	0	
Melting Furnace Cost	$2,000,000	
Auxiliary Equipment Cost	10.0%	
Equipment Space Requirement	1500	ft^2
Maximum Percent Scrap That Can Be Used	27%	
Scrap Purchase Price	$0.36	$/lb
Scrap Sell Price	$0.36	$/lb
Dross Price	$0.25	$/lb
Alloying Material Loss (%)	2%	

Continuous Casting

Workers per Caster	6	
Casting Rate	10	ft/min
Metal Thickness After Casting	0.121	in
Casting Width	75	in
Caster Energy Consumption Rate	1000	kW
Equipment Unit Cost	$15,000,000	
Holding Furnace Unit Cost	$0	
Holding Furnace Temperature	1200	°F
Holding Furnace Energy Loss (%)	50%	
Auxiliary Equipment Cost	10%	

Multi-Stand Hot Tandem Mill/Coiler

Workers per Mill	6	
Number of Stands	1	
Cost per Stand	$35,000,000	
Multi Stand Mill Rate	25	ft/min
Multi Stand Setup Time	0.25	hr
Metal Thickness after Hot Tandem Mill	0.067	in
Side Trim Loss after Hot Mill (per side)	1	in/side
End Trim Los after Hot Mill (per end)	12	in/end
Mill Electricity Consumption Rate	1000	kW
Mill Space Requirement	15,000	ft^2
Auxiliary Equipment Cost	10.0%	

Cold Mill

Metal Thickness After Cold Mill	0.039	in
Side Trim Loss after Hot Mill (per side)	0.5	in/side
End Trim Los after Hot Mill (per end)	12	in/end
Number of Passes Required	1	
Cold Mill Rate (exit length/hr)	250	ft/min
Coil Setup Time	0.25	hr
Worker Per Cold Mill	4	
Cold Mill Electricity Consumption Rate	1000	kW
Unit Cold Mill Cost	$50,000,000	
Cold Mill Unit Space Requirement	50,000	ft^2
Auxiliary Equipment Cost	10.0%	

Annealing Processes

Continuous Heat Treat

Worker per Heat Treat Line	3	
Heat Treat Line Cost Intercept	$4,000,000	$
Heat Treat Line Cost Coefficient	5.600	$/lb/month
Set Line Capacity (0=auto scaling)	0	lb/month
Heat Treat Line Cost Override	0	$
Heating Efficiency	35%	
Heat Treat Line Electrical Power Requirement	5000	hp
Heat Treat Line Length	450	ft
Heat Treat Line Width	200	ft
Heat Treat Line Height	25	ft
Annealing Gas Refresh Rate	0	/hr
Annealing Gas Unit Cost	0.0025	$/ft^3
Anneal Temperature	1040	°F
Greenfield ROI Requirement (0=use overall interest rat	0%	

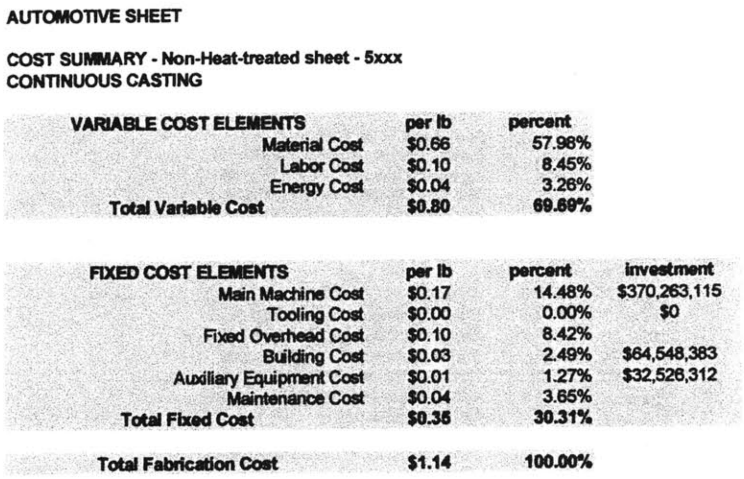
Batch Anneal

Packing Efficiency	75%	
Heat Up Time	2	hr
Hold Time	12	hr
Cool Down Time	2	hr
Anneal Temperature	750	°F
Batch Furnace Length	25	ft
Batch Furnace Width	15	ft
Unit Batch Furnace Cost	$20,000,000	$
Coil Inner Diameter	12	in
Idle Space Around Furnace	100%	
Workers per Batch Furnace	0.1	
Heating Efficiency	35%	
Gas Refresh Rate	0	/hr

Finish Mill/Tensioning

Metal Thickness After Finishing Mill	0.036	in
Side Trim Loss after Finishing Mill (per side)	0	in/side
End Trim Loss after Finishing Mill (per end)	0	in/end

Output for 5754 CC cast sheet:



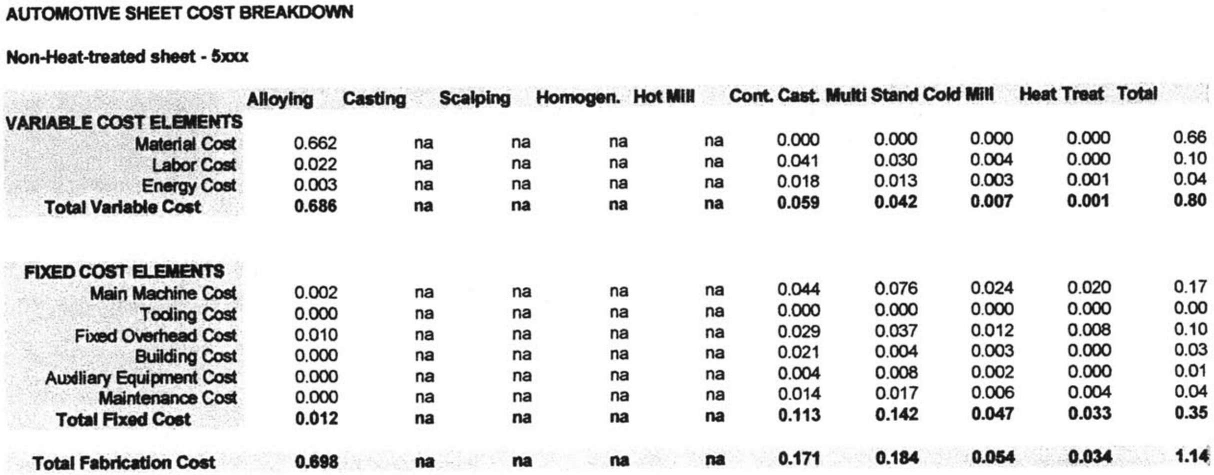
AUTOMOTIVE SHEET

COST SUMMARY - Non-Heat-treated sheet - 5xxx
CONTINUOUS CASTING

VARIABLE COST ELEMENTS	per lb	percent
Material Cost	$0.66	57.98%
Labor Cost	$0.10	8.45%
Energy Cost	$0.04	3.26%
Total Variable Cost	**$0.80**	**69.69%**

FIXED COST ELEMENTS	per lb	percent	investment
Main Machine Cost	$0.17	14.48%	$370,263,115
Tooling Cost	$0.00	0.00%	$0
Fixed Overhead Cost	$0.10	8.42%	
Building Cost	$0.03	2.49%	$64,548,383
Auxiliary Equipment Cost	$0.01	1.27%	$32,526,312
Maintenance Cost	$0.04	3.65%	
Total Fixed Cost	**$0.35**	**30.31%**	

Total Fabrication Cost	**$1.14**	**100.00%**



AUTOMOTIVE SHEET COST BREAKDOWN

Non-Heat-treated sheet - 5xxx

	Alloying	Casting	Scalping	Homogen.	Hot Mill	Cont. Cast.	Multi Stand	Cold Mill	Heat Treat	Total
VARIABLE COST ELEMENTS										
Material Cost	0.662	na	na	na	na	0.000	0.000	0.000	0.000	0.66
Labor Cost	0.022	na	na	na	na	0.041	0.030	0.004	0.000	0.10
Energy Cost	0.003	na	na	na	na	0.018	0.013	0.003	0.001	0.04
Total Variable Cost	**0.686**	**na**	**na**	**na**	**na**	**0.059**	**0.042**	**0.007**	**0.001**	**0.80**
FIXED COST ELEMENTS										
Main Machine Cost	0.002	na	na	na	na	0.044	0.076	0.024	0.020	0.17
Tooling Cost	0.000	na	na	na	na	0.000	0.000	0.000	0.000	0.00
Fixed Overhead Cost	0.010	na	na	na	na	0.029	0.037	0.012	0.008	0.10
Building Cost	0.000	na	na	na	na	0.021	0.004	0.003	0.000	0.03
Auxiliary Equipment Cost	0.000	na	na	na	na	0.004	0.008	0.002	0.000	0.01
Maintenance Cost	0.000	na	na	na	na	0.014	0.017	0.006	0.004	0.04
Total Fixed Cost	**0.012**	**na**	**na**	**na**	**na**	**0.113**	**0.142**	**0.047**	**0.033**	**0.35**
Total Fabrication Cost	**0.698**	**na**	**na**	**na**	**na**	**0.171**	**0.184**	**0.054**	**0.034**	**1.14**

Appendix B - Total Part Forming Cost Data

Breakdown of total part forming cost for the various production scenarios:

	Price Steel	Price 5754	Price 6111	Output	Sheet Cost	Labor Cost	Energy Cost	Main Machine Cost	Tooling Cost	Overhead Cost	Building Cost	Maintenance Cost
All steel	$0.66			200,000	$237.0	$12.0	$7.0	$35.4	$542.3	$204.5	$6.8	$58.4
					21.5%	1.1%	0.6%	3.2%	49.1%	18.5%	0.6%	5.3%
	$0.66			150,000	$237.0	$12.0	$7.0	$35.4	$607.1	$227.3	$6.8	$64.9
					19.8%	1.0%	0.6%	3.0%	50.7%	19.0%	0.6%	5.4%
	$0.66			100,000	$237.0	$12.1	$7.0	$35.5	$713.3	$264.5	$6.8	$75.6
					17.5%	0.9%	0.5%	2.6%	52.8%	19.6%	0.5%	5.6%
	$0.66			50,000	$237.0	$12.2	$7.0	$35.8	$944.7	$345.6	$6.9	$98.7
					14.0%	0.7%	0.4%	2.1%	56.0%	20.5%	0.4%	5.9%
Reasonable	$0.66	$2.56	$3.18	200,000	$637.0	$12.0	$7.4	$34.4	$542.7	$204.3	$6.6	$58.4
CC cast 97.5%					42.4%	0.8%	0.5%	2.3%	36.1%	13.6%	0.4%	3.9%
	$0.66	$2.56	$3.18	150,000	$637.0	$12.0	$7.4	$34.5	$607.7	$227.1	$6.6	$64.9
					39.9%	0.8%	0.5%	2.2%	38.1%	14.2%	0.4%	4.1%
	$0.66	$2.56	$3.18	100,000	$637.0	$12.0	$7.4	$34.6	$714.2	$264.4	$6.6	$75.5
					36.4%	0.7%	0.4%	2.0%	40.8%	15.1%	0.4%	4.3%
	$0.66	$2.56	$3.18	50,000	$637.0	$12.1	$7.4	$34.9	$946.6	$345.8	$6.6	$98.8
					30.5%	0.6%	0.4%	1.7%	45.3%	16.6%	0.3%	4.7%
Best Case	$0.66	$2.29	$2.91	200,000	$576.8	$12.0	$7.4	$34.4	$542.7	$204.3	$6.6	$58.4
Direct Cold Roll 100%					40.0%	0.8%	0.5%	2.4%	37.6%	14.2%	0.5%	4.0%
Worst Case	$0.66	$2.95	$3.57	200,000	$725.5	$12.0	$7.4	$34.4	$542.7	$204.3	$6.6	$58.4
DC Cast 97.5%					45.6%	0.8%	0.5%	2.2%	34.1%	12.8%	0.4%	3.7%
All 5754	$0.66	$2.56	$2.56	200,000	$595.3	$12.0	$7.4	$34.4	$542.7	$204.3	$6.6	$58.4
Reasonable					40.7%	0.8%	0.5%	2.4%	37.1%	14.0%	0.4%	4.0%
All 6111	$0.66	$3.18	$3.18	200,000	$734.7	$12.0	$7.4	$34.4	$542.7	$204.3	$6.6	$58.4
Reasonable					45.9%	0.7%	0.5%	2.2%	33.9%	12.8%	0.4%	3.6%
1 $/lb	$0.66	$2.21	$2.21	200,000	$515.5	$12.0	$7.4	$34.4	$542.7	$204.3	$6.6	$58.4
					37.3%	0.9%	0.5%	2.5%	39.3%	14.8%	0.5%	4.2%
Same as Steel	$0.66	$0.95	$0.95	200,000	$233.3	$12.0	$7.4	$34.4	$542.7	$204.3	$6.6	$58.4
					21.2%	1.1%	0.7%	3.1%	49.4%	18.6%	0.6%	5.3%
All 5754	$0.66	$2.29	$2.29	200,000	$535.3	$12.0	$7.4	$34.4	$542.7	$204.3	$6.6	$58.4
Best Case					38.2%	0.9%	0.5%	2.5%	38.7%	14.6%	0.5%	4.2%
All 5754	$0.66	$2.95	$2.95	200,000	$684.0	$12.0	$7.4	$34.4	$542.7	$204.3	$6.6	$58.4
Worst Case					44.1%	0.8%	0.5%	2.2%	35.0%	13.2%	0.4%	3.8%
All 6111	$0.66	$2.91	$2.91	200,000	$674.1	$12.0	$7.4	$34.4	$542.7	$204.3	$6.6	$58.4
Best Case					43.8%	0.8%	0.5%	2.2%	35.2%	13.3%	0.4%	3.8%
All 6111	$0.66	$3.57	$3.57	200,000	$822.8	$12.0	$7.4	$34.4	$542.7	$204.3	$6.6	$58.4
Worst Case					48.7%	0.7%	0.4%	2.0%	32.1%	12.1%	0.4%	3.5%
How to get $100	$0.66	$1.85	$1.85	200,000	$436.1	$12.0	$7.4	$34.4	$542.7	$204.3	$6.6	$58.4
off body cost					33.5%	0.9%	0.6%	2.6%	41.7%	15.7%	0.5%	4.5%

Appendix C - Cost of Additional Paint Bake

Cost calculations and assumptions for time required for precipitation heat treatment beyond the regular paint curing time:

COST CALCULATION OF ADDITIONAL PAINT BAKE FACILITIES

ADDITIONAL COST OF IN LINE HEAT TREATMENT FURNACE

VARIABLE COST ELEMENTS	**per piece**	**per year**	**percent**
Material Cost	$0.000	$0	0.00%
Labor Cost	$0.000	$0	0.00%
Energy Cost	$4.382	$876,307	24.71%
Total Variable Cost	**$4.382**	**$876,307**	**24.71%**

FIXED COST ELEMENTS	**per piece**	**per year**	**percent**	**Investment**
Main Machine Cost	$6.868	$1,373,596	38.73%	$10,260,000
Tooling Cost	$0.000	$0	0.00%	
Fixed Overhead Cost	$3.461	$692,293	19.52%	
Building Cost	$0.000	$0	0.00%	
Auxiliary Equipment Cost	$1.374	$274,719	7.75%	$2,052,000
Maintenance Cost	$1.648	$329,663	9.30%	
Total Fixed Cost	**$13.351**	**$2,670,271**	**75.29%**	

Total Additional Cost	**$17.733**	**$3,546,578**	**100.00%**
Additional Cost per Minute	**$0.30**	**$59,110**	

Additional Anneal Time Required 60 min

Cost Factors & Calculations

Production Volume	200,000	/yr	
Line Speed	28.5	ft/min	
Gas Energy Consumption per Length	0.0585	Mbtu/ft/hr	
Gas Cost	2.2500	$/MBtu	
Electric Consumption	0	kW	
Equipment Investment	6,000	$/ft	
Number of Additional Workers	0		
Interest Rate	12%		
Equipment Life	20	yr	
Fixed Overhead	35%		
Building Cost	0	$/ft²	Part of Line Cost
Building Life	25	yr	
Maintenance Costs	20%		
Days per Year	365	day/yr	
Hours per Day	24	hr/day	
Additional Line Length	1710	ft	
Auxilliary Equipment Cost	20%