FEASIBILITY STUDY OF INVESTMENT CASTING PATTERN DESIGN BY MEANS OF THREE DIMENSIONAL PRINTING

by

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Abstract

Investment casting is one of the oldest manufacturing processes known to man. In this material-conserving process, wax patterns are coated with heat-resistant refractory material to form a mold shell. The wax is, in turn, melted from the mold. Metal is poured into the mold for parts with good surface finish and geometric tolerances.

Due to the time to make molds, this process is relatively expensive. In a manner to reduce time to produce prototypes for wax patterns, 3-D printing can produce intricate patterns straight from a CAD/CAM system. A feasibility study will be conducted to determine the economic cost reduction and mechanical integrity of this new process.

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Dedication

The author would like to express sincere thanks to her faculty advisor, Professor Ernesto E. Blanco for his untiring efforts of guidance, support, and expertise through my years at M.I.T. The author would also like to thank her thesis advisor, Professor Emanuel Sachs for his immense cooperation and support.

This project is dedicated to God and to three of the most loving people in my life: my parents, Mr. and Mrs. Henry Williams, Jr., and my boyfriend and best friend, Robert L. Boone, Jr.

Biography

The author, Kendra Ann Williams, was born on July 12, 1966, in Trenton, South Carolina to Mr. and Mrs. Henry Williams, Jr. The author is a candidate for the Bachelor of Science Degree in Mechanical Engineering from the Massachusetts Institute of Technology. She is a NACME - E. I. DuPont Scholar. In addition to M. I. T., the author has attended Clemson University and Aiken Technical College.

As of September, 1989, the author will be a candidate for the Master of Science Degree in Manufacturing Engineering from Rensselaer Polytechnic Institute. She is the holder of the Patricia Roberts Harris Fellowship in Mechanical Engineering.

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Chapter 1

Introduction

Investment casting is one of the oldest and most commonly used manufacturing processes in the world. It dates back to the Chinese to as early as 2000 B. C. Development and improvement in technique which followed this time period led to widespread usage of the process by the jewelry industry in the middle 1930's. The value of investment casting as a manufacturing process is derived from the production of intricate, detailed parts in industrial experience.

The process of investment casting does not closely resemble any of the other casting methods. The closest resemblance to another casting process is to permanent-mold casting. In general the process of investment casting consists of the following basic steps: (1) Forming the expendable pattern, (2) gating and assembling patterns, (3) investing the pattern, (4) melting out of patterns and drying the investment mold, (5) pouring the castings, and (6) removing and cleaning up the castings. Production of accurate expendable patterns is all-important in order to obtain the necessary results.

This process is quite costly. The labor cost component is high because the wax positives, after being made from a pattern, must be assembled onto a tree, which is dipped into refractory material to form a shell. This shell is the mold for the molten metal after it has been dried and hardened. The pattern costs are also high; consequently, the process is used mainly to produce components that require the special characteristics of the process (good surfaces, tolerances, high complexity, etc.) Examples are metals that are difficult to machine or to deform plastically.

When designing a component for casting, several main factors must be considered, since if forgotten they can each contribute to considerably increased cost. The most important factors are:

1. Pattern and pattern costs (plane parting surface, simple, draft, etc.)
2. Mold production (method and properties)
3. Core production (simplicity, methods, and properties)
4. Casting (gating system, risers as a function of geometry)
5. Cleaning (easy access to core cavities, easy removal of gating system)
6. Machining (where, how, and what allowances)
7. Thermal stresses (reduced by uniform section thickness or when changes are necessary, gradual changes, by permitting the contraction to take place without restraint)
8. Mechanical loadings (in the shaping of the component, proper force transfer must be considered along with the characteristics of the casting process)
9. Appearance

The term investment refers to a cloak, or a special covering apparel, in this case a refractory mold, surrounding a wax pattern. The wax used in the patterns are made of blends of beeswax, carnauba, ceresin, acrawax, or parraffin. The wax is injected into the pattern mold at 150 to 170 ^{o} F at a pressure of 500 to 1000 psi. Polystyrene may be used in place of wax. It is injected at 300 to 600 ^{o} F at pressures up to 12,000 psi. Frozen mercury is also another material to be used.

Whatever the individual wax material of the patterns, the pattern must be assembled by hand before being coated with the refractory material. The requirements for the mold is that it dissipates heat from the molten metal, and it is not susceptible to mechanical and thermal stresses.

In general, almost any of the metals used in machine structures can be selected for use in a cast part on the basis of physical properties suited to the stresses and environmental conditions involved. Contrary to popular opinion, the major factor which influenced application of the process from the start was its outstanding fidelity of reproduction rather than any actual dimensional accuracy or repetitive accuracy.

The ink-jet prototype of three dimensional printing has been proposed to produce the pattern to form the wax mold which is coated with refractory material. This process is repeated until the shell has a desired thickness. The wax with shell is heated until the wax is melted out. The shell is further heated until it hardens and is free from wax. From the same hole that the wax left the shell, molten metal is introduced into the shell. The metal solidifies and reproduces the shape of the shell interior design. This design is very close in dimensional tolerance to the wax positives since this design was built directly on top of the positive.

So in the application of 3D printing to investment casting, the difference from conventional methods will be the production of dies to cast the wax. But the production of dies produce the highest component of cost in investment casting. By the reduction of time and labor to produce these dies, there will be a reduction of cost of the total process. The dies will be made quicker so that more molds can be made in a preset amount of time. With more molds, there is a higher lot size. With increased production, the process becomes more economically feasible. The initial investment will be the institution of the CAD/CAM system, but in due time, the investment will make a return of better quality prototypes since the printing process can produce prototypes with tolerances of 15 to 20 microns. Also the process is quicker and reduces the amount of labor necessary to produce cast parts.

Among the multitude of processes utilized in the design of machines, those of casting receive the least attention and consideration. One of the earliest processes for forming metals, casting provides a versatility and flexibility which have maintained its position throughout the years as a primary production method for machine elements. With the addition of 3D printing, the factory will become even more flexible since the programs can produce different prototypes rapidly with the addition of little to no extra tooling.

The concept of 3D printing is new and is in the research stage. It is projected to become comercially available in the next five years.

Chapter 2

Cost Factors in Investment Casting

The kinds of parts presently made by investment casting are those which require detailed intricacies. With investment casting, the major cost is derived from the production of the wax positives. This component makes up over 50% of the total cost per part. With 3D printing instituted to produce wax positives, this 50% of the cost can be drastically reduced.

The influence of quantity on selection possibilities is an important consideration in design for economy. Because of tooling and set-up costs as well as overhead, quantity is important in determining the most suitable methods. Except for intermediate areas, quantity requirements are generally good indicators of suitable production methods. Among the effects on design specifications on costs, those of tolerances are perhaps most significant. Tolerances in design influence the producibility of the end product in many ways, from necessitating additional steps to adjust the surfaces of the end product. Those surfaces which require closer tolerances than investment casting provides must be machined, and an allowance for this operation must be accounted for in the production of the mold.

The estimating department of a company would be responsible for determining the costs for investment casting. This department is only one of several functions responsibile for manufacturing costs. These costs are primarily determined by the engineering design. In the investment casting process, there are two types of costs: direct (e.g. cost of labor, material, and labor) and indirect (e.g. janitorial services, forklift operation, machine maintenance, utilities, and general and administrative overhead). The cost incurred in relation to production volume is either fixed, variable, or step-variable. The material costs are variable according the number of units produced, whereas administration is fixed since the same secretary would be necessary if 1 or 1000 units are produced. Cost estimates are one of two types: preliminary or final. Preliminary estimates are used for product design guidance and to provide cost information to management in the early stages of product planning.

To estimate castings, the estimator should acquaint himself or herself with material specifications, heat treatment specifications, final inspection requirements, and the casting design as specified in the cost estimate request. Material and heat treatment specifications, which add to the cost of castings, are often called out in notes on engineering drawings without being mentioned in the estimate request.

The total cost of making castings is comprised of the following cost items; (1) materials, (2) foundry tooling, (3) molding costs, (4) core costs, (5) machining and cleaning costs, (6) heat treatment costs, (7) inspection costs, and (8) foundry burden. The total manufacturing cost includes tooling, equipment, and facilities costs. To develop the costs, the time required to accomplish each manufacturing step is tabulated or calculated, and this time is multiplied by the ongoing cost rate for each particular step.

Foundry tooling includes patterns, pattern plates, blow plates, and flasks, as well as various types of core-making tooling. The cost of foundry tooling required for a particular job is estimated, and the cost added to the overall estimate. A tooling cost per casting is obtained by dividing the total tooling cost by the number of castings produced.

The cost of patterns is assigned directly to the part being cast because patterns designed for one job are not generally usable for future orders.

Foundry burden, applied on the basis of pounds of finished castings, is computed by the use of a burden factor supplied by the accounting department. For example, if 545,000 pounds of finished castings are produced and the burden factor is $0.11 per pound of finished castings, the burden cost for the production lot of castings is $59,950.

Investment casting offers no competitive advantage for large quantities of parts which can be produced in several setups on automatic machinery. Where the quantity is small, however, the lower cost of tooling can often make the casting more economical. Where overall cost of parts, machining, fasteners, and assembly can be eliminated by one investment casting requiring but a small amount of finishing, highly economical results can be obtained. Cost savings per piece as high as 95 per cent have been recorded in numerous cases. Many otherwise expensive operations can often be eliminated. Typical of these are precision operations such as drilling, threading, tapping, tapering, grinding, etc., usually necessary for assembly purposes.

The final cost of a casting involves far more than merely the cost of the metal. It is the ultimate cost of the machine part itself that is of most importance. Maximum economy in the final analysis may evolve from a casting design of greater rather than lesser weight, more machining rather than less, etc.

It not only provides economy for unusual designs in the more common metals but makes possible many otherwise impossible machine parts in metals not machinable to any great degree.

Chapter 3

Improvements of Cost Factors

There will be a reduction of time and labor by the addition of three dimensional printing for the production of melt molds in investment casting. The printing could produce ceramic molds directly from the CAD/CAM software. The molds would already be assembled on the trees, as specified by the program, and there would not necessarily be a need for the meltout of the wax at all. This system is highly flexible since many different prototypes may be produced with little lead time and little extra tooling modifications. With either the dry powder deposition system or the liquid dispersion, the production of molds would be possible.

However, it is proposed that the investment casting process begin with the fabrication of an aluminum die which is used to mold wax positives of the parts to be cast. This would reduce the time to physically machine the dies and plates. The posssible limitation of 3D prototypes for the production of melt molds is that the mechanical integrity of the mold may be less than optimal. With the present mode of production, the binder is applied to the powder which is later fired in a furnace. The bond between the powder granules and binder must withstand the heat dissipated from the wax and the mechanical stress induced from the shrinking and swelling of the metal powder.

In principle, no limit exists regarding the size or geometry of the parts that can be produced by investment casting. The limitations are set primarily by the material properties, the melting temperatures, the properties of the mold materials (mechanical, chemical, thermal) and the material production characteristics (i. e. whether the mold equipment is used only one or many times). There is no limitation on the range of metals to be cast by investment casting. The tolerances allowed per dimensional unit are approximately 0.003 to 0.005. The normal mass range of casted parts is a few grams up to 10 kilograms. The minimum section thickness within a parts is 0.5 to 0.8 millimeters. The surface roughness for the parts is 1.5 to 2 micrometers. For an economical lot size, 100 to 5000 units must be produced per batch.

Physical properties of investment cast metals are generally equal to the mean between the transverse and longitudinal values for rolled bars of the same metal or alloy. On an average they are about 10% greater than the properties of sand-cast metal.

Chapter 4

Conclusion

It has been recommended that three dimensional printing would be feasible for the production of aluminum dies for wax positives in the investment casting process. This process is at least five years in the future for its completion, but in principle, it would be a great enhancement for investment casting as well as a manufacturing process onto itself. In design, the time from engineering design to the building of a prototype could take as long as months to see the results with which one could improve on the original design. Now that a prototype can be made in the manner of hours and days, the process has been quickened to the point of increased productivity and efficiency.

The process is not only feasible but is desirable. The reduction in time and labor,as well as the equality or improvement of dimensional tolerances, make for a most desirable new manufacturing process.

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