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A Literature Review on Methods Being Used for Hot Tearing and Shrinkage Prevention in the Permanent Mold Casting of Aluminum Alloys

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Abstract

Statement of the Problem: What can be done to eliminate the threat of hot tears and shrinkage in the production of aluminum rims?

Research Questions:

The research being carried out will use a library research or a literature review methodology. The research will provide answers to the following questions:

1. What do sources of authority cite as being the most effective ways to prevent hot tearing and shrinkage in the production of aluminum rims?

2. Is there a way to predict where hot tearing and shrinkage will occur in a casting before any castings are poured?

3. What is being done with mold design to prevent shrinkage and hot tearing?

4. Are there ways to differentially cool a mold to allow all the sections of a casting to solidify at the same rate?

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A LITERATURE REVIEW ON METHODS BEING USED FOR HOT TEARING AND SHRINKAGE PREVENTION IN THE PERMANENT MOLD CASTING OF ALUMINUM ALLOYS

In Partial Fulfillment of the Requirements for

The Non-Thesis Master of Arts Degree

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CHAPTER 1

INTRODUCTION

Background

Shrinkage and hot tears are major problems in the production of aluminum automobile rims. According to Chiesa (1995), due to the highly demanding requirements placed on an automobile rim they are probably the most difficult automobile part to manufacture. Due to the high mechanical requirements, aluminum wheel production poses a particular challenge to the manufacturer. Aluminum automobile rims vary in shape, size, and design. Solidification characteristics will vary due to these differences between rims.

In a study conducted by Liu, Smith, and Sahoo (1993) it was found that hot tearing is the formation of cracks on the surface of the casting above the solidus temperature and is caused by non-simultaneous solidification between thick and thin sections. In a literature review done by Sigworth (1996), it was found that hot tearing normally occurs when there is a long-freezing range (slow solidification rate). Long freezing ranges occur in the thick hub section of aluminum wheels.

Significance of the Study

A rim may have a wide range of wall thickness throughout. In most cases, however, a rim will have a thick hub with thinner spokes protruding out. Shrinkage and hot tearing usually occurs where the hub intersects with the spokes (Fuoco, Correa, Correa, & Chiesa, 1997). Figure 1 shows the relationship of the thick hub and thinner spokes. Shrinkage and hot tearing occurs here because the thick and thin sections do not solidify at the same rate. During the sixties and seventies, aluminum-alloys received great developments in casting techniques. The use of aluminum-alloys has become a strong alternative to cast iron and steel in the manufacturing of some automobile parts.

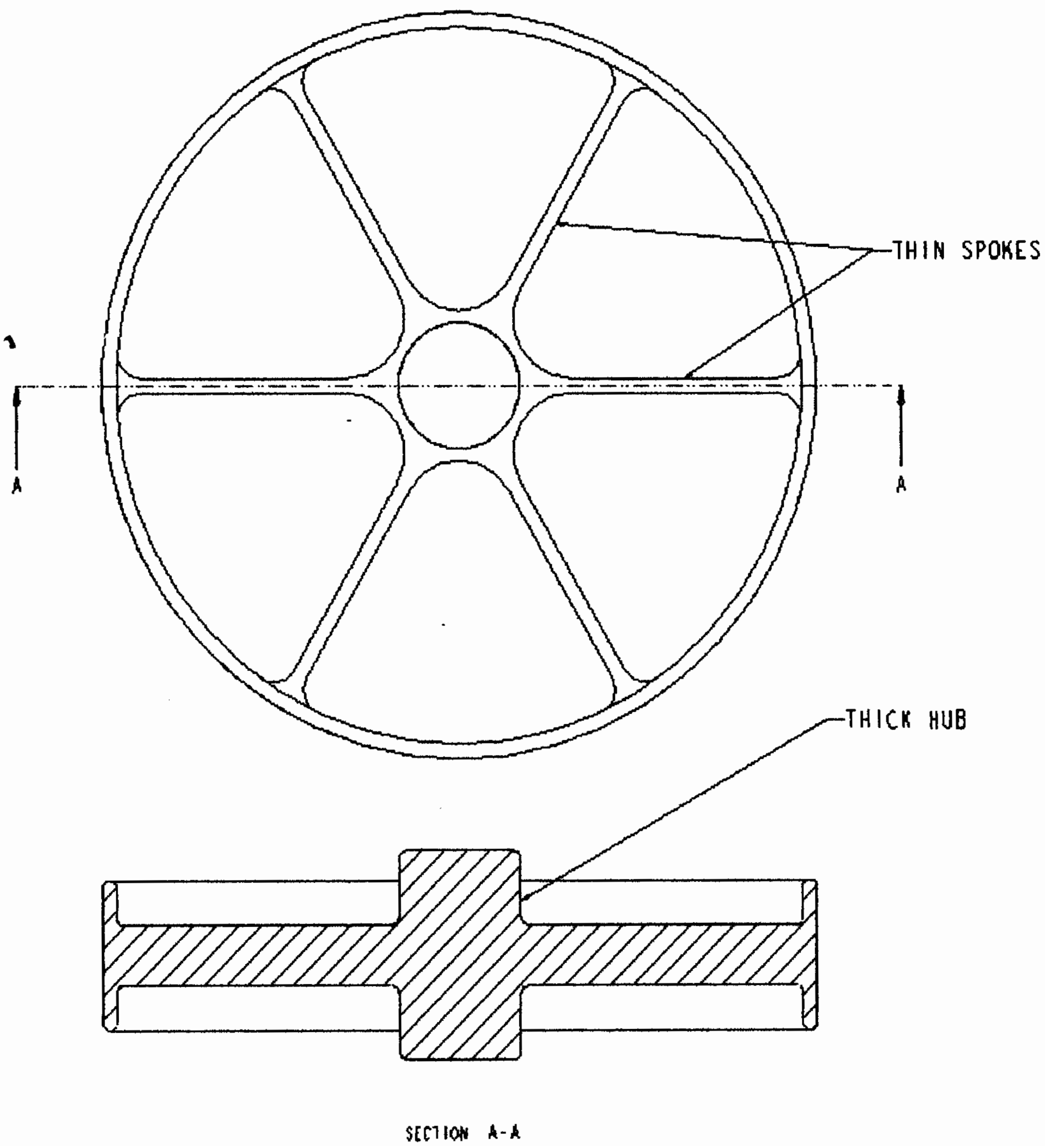

Figure 1. Rim that has a thick hub and thin spokes.

Statement of the Problem

What can be done to eliminate the threat of hot tears and shrinkage in the production of aluminum rims?

Research Questions

The research being carried out will use a library research or a literature review methodology. The research will provide answers to the following questions:

1. What do sources of authority cite as being the most effective ways to prevent hot tearing and shrinkage in the production of aluminum rims?
2. Is there a way to predict where hot tearing and shrinkage will occur in a casting before any castings are poured?
3. What is being done with mold design to prevent shrinkage and hot tearing?
4. Are there ways to differentially cool a mold to allow all the sections of a casting to solidify at the same rate?

Definition of Key Terms

Hot Tears: Hot tearing is a defect in the production of aluminum rims. Hot tearing normally occurs in cast sections that have a low cooling rate that is adjacent to a section with a high cooling rate. At this intersection the metal tears during solidification.

Shrinkage: A defect in the production of aluminum rims. Shrinkage occurs in sections of the casting which also have a low solidification rate. If the proper risering system is not established the metal will shrink inside the mold during solidification.

CHAPTER 2

LITERATURE REVIEW

Background of the Problem

An analysis of rejected aluminum automobile rims was conducted by Fuoco et al. (1997). It was found that two failures common in the production of aluminum cast wheels are hot tears and shrinkage. They also found that hot tears are primarily an external failure and shrinkage mainly internal. Out of the rejected castings evaluated, they found that nearly all the failures were due to defects at the spoke/hub intersection. The report also offered some suggestions that might help reduce the number of failures at the spoke/hub intersection. They suggested that a properly located air-cooling device might help reduce the threat of hot tears and shrinkage by removing the heat from the hub at a faster rate.

In a study on solidification of aluminum alloys, Dickhaus, Engler, and Ohm (1993) found that hot tearing and shrinkage are likely to happen during solidification when the temperature is close to the solidus temperature. Hot tearing and shrinkage are also likely to occur in castings that have thick and thin sections.

It is evident from the background of this problem that shrinkage and hot tearing can cause serious failures in the production of aluminum automobile rims. The research shows that hot tearing and shrinkage are a major concern in the production of aluminum castings. The following section will discuss the methods currently being used and new innovations taking place that help eliminate these failures in aluminum castings.

The primary focus will be to reveal ways to prevent shrinkage and hot tearing in permanent mold aluminum rims. Some methods may not be specific to aluminum castings but the knowledge may be transferable to aluminum casting practices.

Solidification Modeling

Solidification modeling is a relatively new technique being used to predict how the casting cavity will fill and how the casting will solidify. Solidification modeling is not a cure to shrinkage and hot tearing, however, it is a tool to predict where it will occur. Once this information is known, one can determine how they want to go about solving the problem. A report published by the National Center for Excellence in Metalworking Technology or NCEMT (1990) revealed that by using these predictions, the optimal gating and risering system could be designed. "Solidification modeling will allow one to design the defects out of the casting before any are poured," (http://www.ncemt.ctc.com/thrustAreas/casting/hottears/in_main.html, p. 1).

In a report published by Northwestern University in 1995 on aluminum castings, researchers were currently using commercial software called MAGMASOFT, which is another simulation software, to predict casting defects. In their study, solidification simulations and 3-D fluid flow analysis were combined to provide a complete system for all casting processes. The researchers at Northwestern University believe this will help predict casting defects in aluminum castings. "The prediction of such defects would be useful in preventing them without carrying out the costly trial-and-error process," (http://www.mech.nwu.edu/MFG/jgc/group/cast.html, p. 1).

A study conducted by Upadhya and Paul (1994) found that solidification modeling is indispensable when it comes to predicting mold-filling characteristics.

Information from these simulations will determine where the hot spots are in the casting. By knowing where the hot spots are located one can determine what parts of the casting are going to have the longest solidification range. The purpose of this study was to find ways at which solidification modeling is helping mold designers. The study covered such topics as heat transfer, fluid flow during mold filling, solidification kinetics and micro-structural evolution. Mathematical models are used in solidification modeling programs that simulate heat transfer rates, fluid flow, and solidification kinematics.

Lee, Lee, Choi, and Hong (1999) found that the proper gating ratio (area ratio of sprue, runner, and gate) is a must to produce high quality castings. They used a computer simulation program, SOLA-VOF, to simulate how a mold fills and how fast it will fill with a variety of gating ratios. By running multiple simulations with a variety of gating ratios they found that a ratio of 1:3:3 for aluminum permanent mold castings would minimize shrinkage defects. Typically gating ratios vary from 1:1.5:1.5 to 1:5:5 in practice. Higher gating ratios are being used for alloys that easily form oxides. They found that finding the optimal gating ratio could have a dramatic effect on casting quality with respect to shrinkage.

Metallic Inserts or Heat Sinks

Using a metallic insert that has a higher thermal conductivity is another way to reduce the threat of hot tearing and shrinkage in permanent mold, aluminum castings. In a study conducted by Lerner and Westendorf (1996), it was found that by placing a metallic insert made of a material with higher thermal conductivity than the mold material in the mold, one will be able to draw the heat away from the adjacent cast material faster. These inserts are commonly called heat sinks. The heat sinks are typically made out of copper, graphite, alloyed iron, or tool steel. These materials have a higher thermal conductivity level, which means they can transfer the heat out of the mold faster. Table 1 shows each material with it's corresponding heat conductivity value at 212 °F.

Table 1. Common insert materials with conductivity value.

Material	Thermal Conductivity [Btu/(hr-ft^2 °F/ft)]
Aluminum	119
Copper	218
Graphite	87
Iron	30
Steel	26

Placing the insert in the mold at the location will allow the insert to draw the heat from the hub during solidification. Figure 2 illustrates using a flat-ended insert on one side of the casting at the hub location. The insert will draw heat out of the hub so the hub and adjacent rims can solidify simultaneously.

In a different report by Lerner (1996), it was found that using a copper heat sink in the production of thick hub pulleys will help reduce hot tearing at the spoke hub intersection. The copper heat sink allows the hub and spoke to come closer to solidifying at the same rate. If this occurs, the root cause of hot tearing has been eliminated. The main advantage to using inserts is that one has a wide selection as to the size, shape, and material of the inserts. Figure 3 shows how a projected-end insert is used to draw heat out of one side of the hub of an aluminum rim.

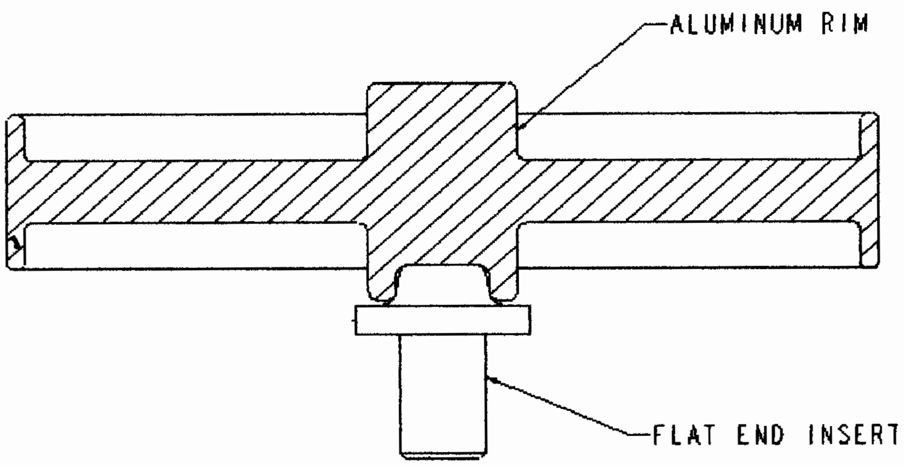

Figure 2. Flat-end insert used to draw heat from the hub.

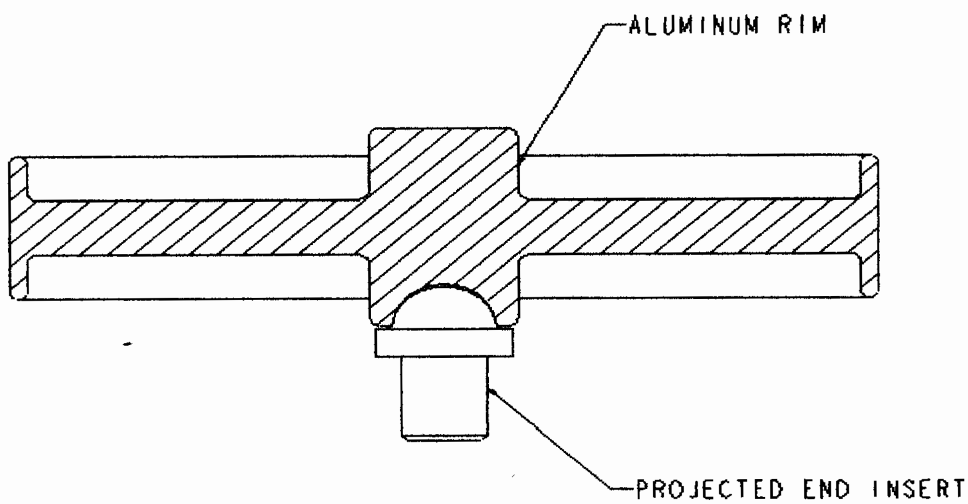

Figure 3. Projected-end insert used to draw heat out of one side of the hub.

The advantage to this compared to the flat-ended insert is that the projected-end can reach further into the casting to draw the heat out more effectively. If this setup is not sufficient at drawing heat from the hub, two inserts can be used. One can place an insert on both sides of the hub as shown in Figure 4. This setup can obviously be used with the flat-ended insert design as well.

If more rapid cooling is needed, a water-cooled insert could be used as shown in Figure 5. This setup is the same as a single projected-end insert design. However, this insert has water passages inside which allows cool water to pass, and in turn draw heat from the hub at a faster rate.

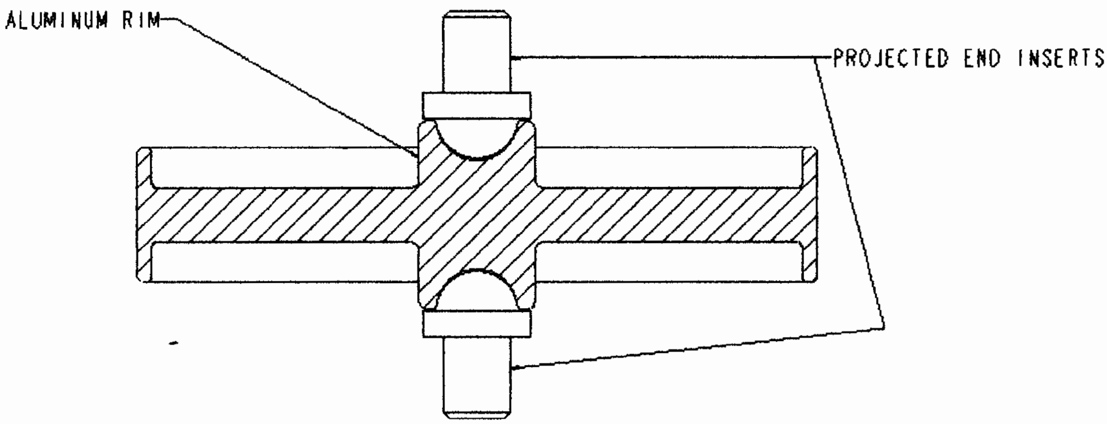

Figure 4. Two projected-end inserts used to draw heat from the hub.

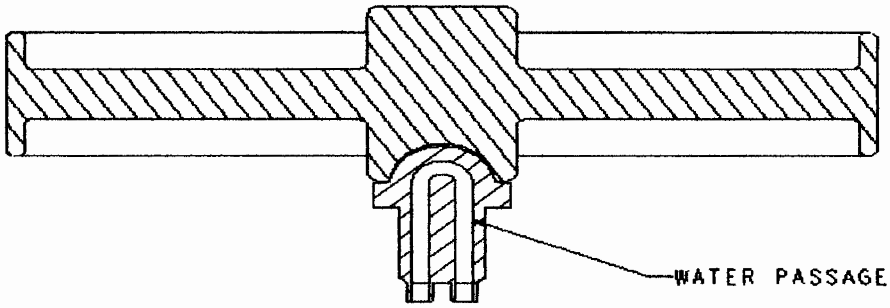

Figure 5. Projected-end insert with water passages used to draw heat from the hub.

Water is not the only liquid that can be used in conjunction with this type of insert. Other types of liquids that do not draw heat away as fast, such as oil, are also used, however, water is the most common liquid used. The main disadvantage to using any type of insert is that they deteriorate and need replacing. New methods need to be developed to allow for easy replacement when this occurs. If an insert can be replaced efficiently one will minimize downtime.

According to Fuoco et al. (1997), altering the heat transfer rate out of thick sections of the casting with a properly located heat sink or other form of cooling device will help reduce hot tearing in that area. The goal is to get the casting to directionally solidify. To do this, a proper risering system is normally used. If this technique is not efficient enough, an insert can be placed in thicker casting section areas to enhance the solidification process in that area. They went on to say that figuring out the ideal location for such a device before pouring a casting and would be to run a solidification simulation.

In the 1990 ASM Casting Handbook it is noted that heat sinks, inserts, and chills are used to accelerate the solidification process in that area of the casting (West, Grubach, 1988). Normally, when these devices are used they are intended to create a simultaneous solidification between two sections of the casting. If using heat sinks, inserts, or chills is not functionally possible, for one's application, another alternative to accelerate the solidification process is to remove the coating inside the mold in that area. Having the molten metal come in direct contact with the mold will alter the solidification characteristics in that particular area. The report went on to discuss the use of anti-chills in this process. Basically, an anti-chill does the exact opposite of a chill. An anti-chill is located in the mold so as to be adjacent to a section of the casting one doesn't want to solidify very rapidly. The anti-chill will look much like a regular chill or metallic insert. However an external gas burner, or some other heating device will heat the anti-chill.

Using metallic inserts as a way to prevent hot tears in aluminum castings is a logical and effective solution. As mentioned earlier, there are a few different materials being used to make the inserts. The primary materials being used are copper, graphite, iron, and steel. Inserts can be made into a variety of different physical characteristics. One must decide what type of insert would best benefit their application.

Water Cooling Methods

According to the 1990 ASM Casting Handbook, auxiliary cooling is another option to eliminate the threat of hot tears and shrinkage in permanent mold, aluminum castings (West, Grubach, 1988). Water can be forced through passages throughout the mold to increase the solidification of the casting. The size and location of the passages determines how fast the casting will solidify. The drawback to this method is that overtime; the passages will become clogged with scale from minerals in the water. To combat this issue, one can use de-mineralized water or clean out the passages regularly with a cleaning solution. Another drawback to using this method is the issue of safety. When using water or any other type of a liquid as a method of cooling, it must never come in contact with the molten metal. If this were to occur, a steam explosion would be the result. The higher the temperature of the molten metal, the more intense the explosion will be. By using water-cooled permanent molds, the passages are concentrated in areas where more cooling is desired.

According to Lerner and Westendorf (1996), there are multiple ways that water is used as a heat sink. One way is to attach a cooling jacket on the back of the mold. Water is circulated through the jacket to establish a desired solidification rate. The water is set to a desired temperature that will allow the casting to solidify at the desired. One draw back to this method is that the entire casting will solidify at the same rate. However, in some situations the back of the mold will be contoured. With a contoured mold back the heat conductivity rate varies with the thickness of the mold. If the mold design is correct, the casting will solidify simultaneously. This method of simultaneous solidification is hard to achieve.

The second water-cooling method Lerner and Westendorf mentioned was drilled water passages in the mold. This method involves drilling passages in the mold that allow water to flow through. By doing this one can, to some degree, locate their water passages in areas where they need more rapid solidification of the casting. The drawback to this method is that one is limited to the amount they can machine passages in the mold. And while machining such passages, it is hard to go around areas that do not need more rapid casting solidification. Another drawback to this method is that high costs are incurred to machine the water passages in the mold.

The last method presented by Lerner and Westendorf was prefabricated piping in the permanent mold. This method is much like the second method except one has more control as to where they want the water to flow throughout the mold. This is possible due to the prefabrication aspect of this method. The main advantage is that since the passages are prefabricated one no longer has the cost of manufacturing the passages.

In all water-cooled options mentioned there was one common disadvantage. This advantage is that water-cooled molds are limited in their ability to provide more cooling in specific areas and less cooling in other areas. Water-cooled molds have a water supply that supplies a constant amount of water to the mold. This can be disadvantageous because the mold may need more water at some times during the solidification process and less water at other times.

CHAPTER 3

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

Summary

The purpose of this research paper was to review and synthesize methods on how to reduce hot tearing and shrinkage and/or eliminate it in the production of permanent mold, aluminum castings. This paper can be used as a reference for those in this field who are struggling with hot tearing and shrinkage in their operation. The practices mentioned are a good reference of ideas to look into if one is having problems with hot tearing and shrinkage in their operation.

When one discusses hot tearing and shrinkage in the parts they produce they must decide if those defects are detrimental to the function of the part. If that is in fact the case they need to decide on a method that will help remove those defects. As one can see, there is a wide variety of set ups to choose from out of the methods mentioned.

Conclusions

Solidification modeling is the way things are headed in the metal casting industry. Solidification modeling saves time, money, and other valuable resources. By predicting where hot tears and shrinkage will occur in the casting one can design a method to prevent them from happening. The key to preventing a failure is to predict where it will occur from the start. This is why solidification modeling plays a major role in the elimination of hot tears and shrinkage in aluminum castings. Solidification modeling is a very cheap option when it comes to the overall prevention of shrinkage and hot tearing in the production of aluminum rims.

Metallic inserts are also powerful weapons against hot tears and shrinkage. Metallic inserts are highly effective and are the lowest cost option available out of the ones mentioned. There is a wide range of uses for inserts. They can vary in shape and sizes to best suit one's application. One also has the option to cool the insert with water or some other liquid agent. Inserts are another very cheap and also a low-technical option for reducing shrinkage and hot tearing in aluminum rims. Metallic inserts are capable of providing rapid solidification in specific areas.

There are a variety of water-cooling methods available that will help reduce and/or reduce hot tears and shrinkage in aluminum castings. The best way to choose what method to use is to determine what method is most economical for one's application. It would make no sense to have an elaborate water-cooled system for a part that mechanical properties are of no concern. Water-cooled systems are one of the most expensive options available. They can also require the most maintenance to keep in good working order. Water-cooled systems are also limited in their ability to differentially cool a casting due to the passages the water must travel through. The water-cooled options available only have a constant flow of water to the mold.

Recommendations for Future Study

As stated earlier, metallic inserts can deteriorate after multiple cycles in the mold. New insert designs need to be developed to help eliminate this problem. If the insert can't be designed to extend the life of the insert, a new design needs to be developed to allow for easy replacement. One possible design is shown in Figure 6. This insert could be easily replaced in case of insert deterioration. The insert can be inserted through the face of the mold and locked into place with a wedge from the back of the mold. The slots can be used for the wedge.

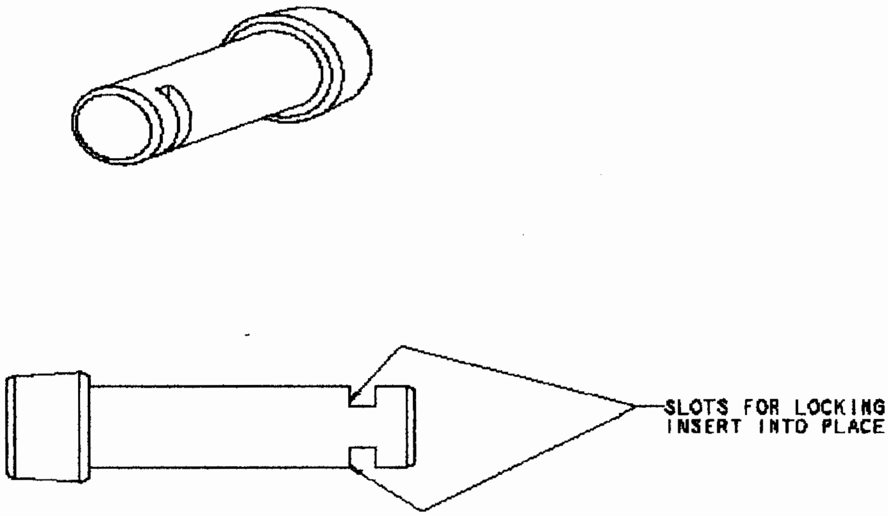

Figure 6. Replaceable insert using external slots and a wedge.

A possible limitation to this design is that there is not sufficient room for the wedge on the back of the mold due to the external slots. To overcome this limitation an insert with an internal slot could be used in the same fashion as shown in Figure 7. An internal wedge could save valuable space on the back of the mold. By using wedges to fasten the inserts into the mold there is a chance of the wedges coming loose. A possible solution to this problem would be to use a threaded insert and nut to fasten the insert into place as shown in Figure 8. This method also has limitations due to lack of space on the back of the mold. There may not be sufficient room for the nut. If this is the case, a tapped hole could be drilled into the mold and the insert could be fastened this way. This insert design would most likely be more expensive due to machining costs. The insert would have to be tightened from the face of the mold as shown in Figure 9.

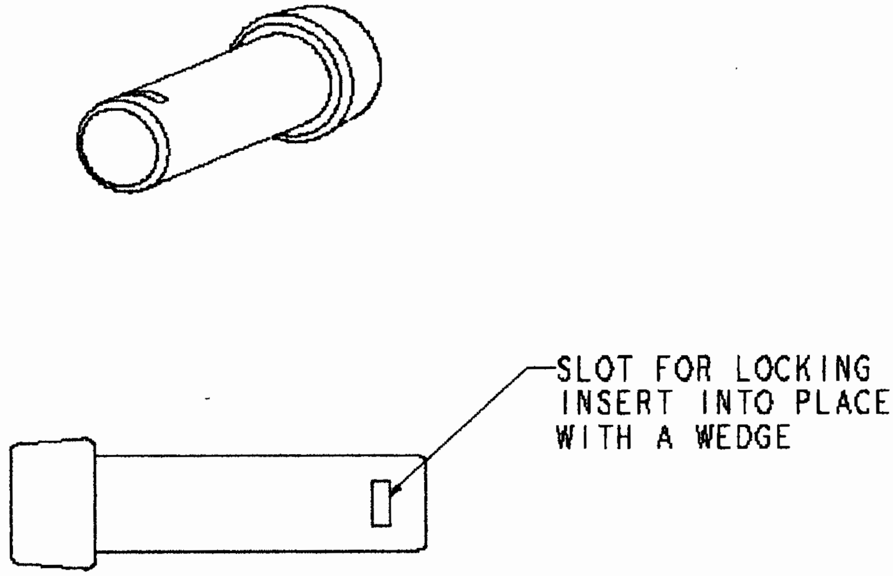

Figure 7. Replaceable insert using an internal slot and a wedge.

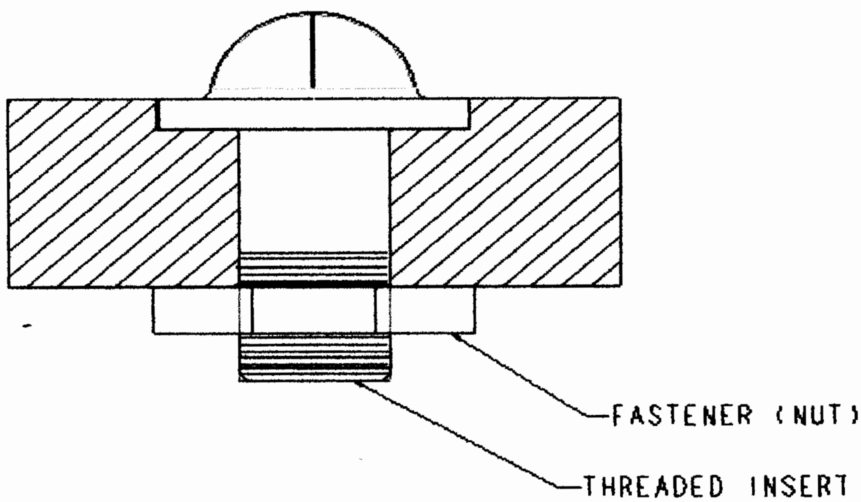

Figure 8. Insert design fastened from the back of the mold with a nut.

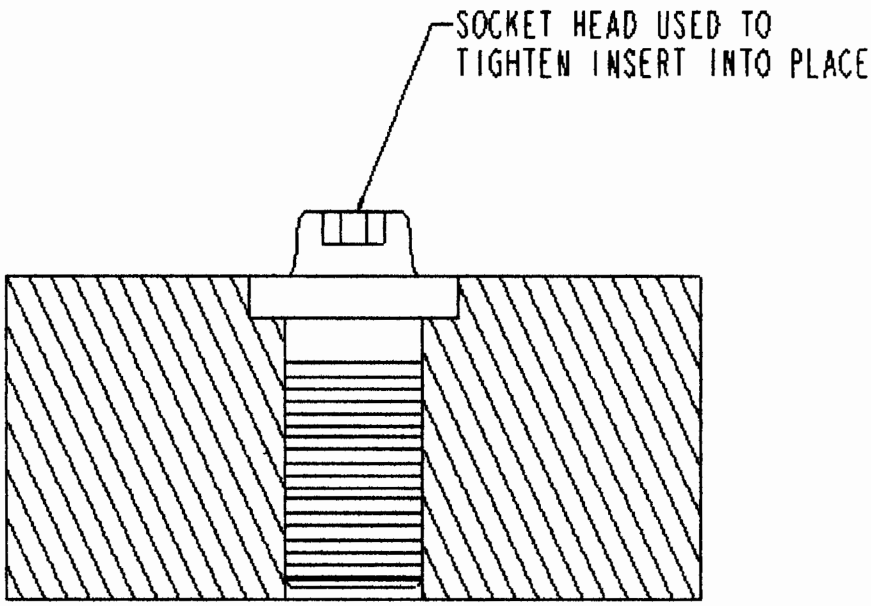

Figure 9. Threaded insert design fastened with a socket head.

In water-cooled molds the major disadvantage to all the methods mentioned was the lack of water-flow control throughout the solidification process. Some future work to be conducted in this area would be to include a computer-controlled system that will monitor the temperature at various locations throughout the mold with thermal-couples that will input temperature readings to the computer. The computer will in turn send a signal to the water flow-control unit to vary the flow of water to the insert. The computer will supply more flow when temperatures are the highest and less flow when temperatures are the lowest. The system could be set up as shown in Figure 10.

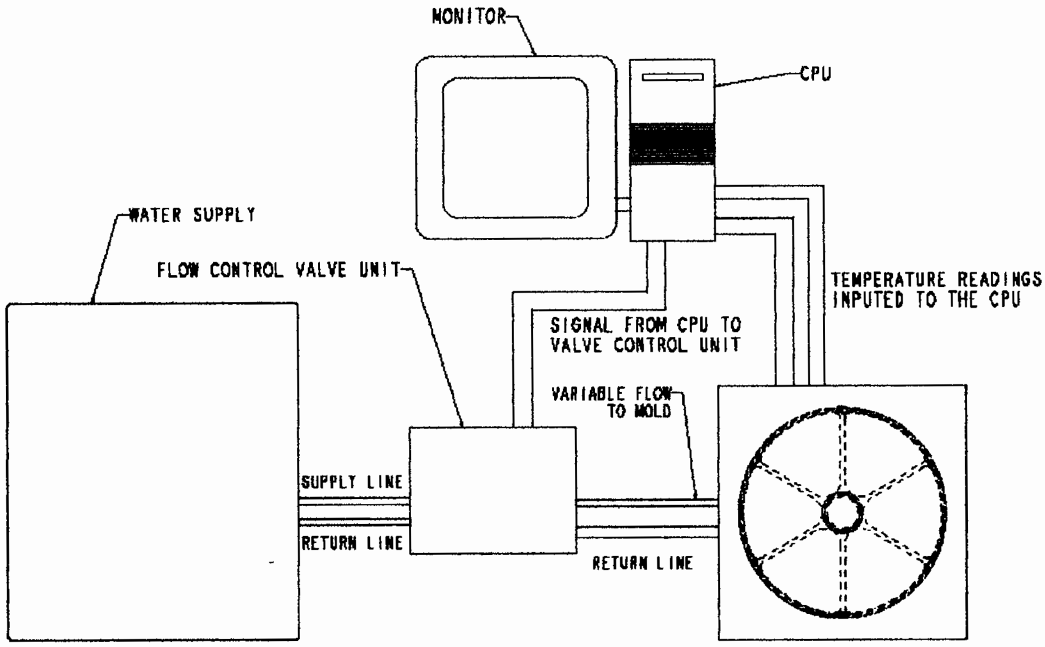

Figure 10. Computer controlled water-cooled system.

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