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Comparison Study of Cooling Fins and Chills Effectiveness in Aluminum Sand Mold Casting

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Comparison Study of Cooling Fins and Chills Effectiveness in Aluminum Sand Mold Casting

Abstract

Besides proper design of gating and risering systems, there are several methods used to control and modify solidification behavior of cast alloys. Within these methods, the most widely used are local cooling aids employing cooling fins (thin segments attached to problematic areas of casting) or external chills (metal inserts placed into mold walls to accelerate heat withdrawing from potential hot spot). The later helps to promote directional solidification when traditional methods are not possible to use due to limitations related to the casting design. Despite relatively wide application in aluminum foundries, there are no specific recommendations on cooling aids parameters selections have been published.

The objective of the study was to compare effectiveness of different local cooling aids and to develop practical recommendations on their applications. The research has been conducted via computer modeling of solidification process, based on finite difference computation method (FDM).

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COMPARISON STUDY OF COOLING FINS AND CHILLS EFFECTIVENESS IN ALUMINUM SAND MOLD CASTING

A Research paper presented

to the advisor

of the Department of Industrial Technology

University of Northern Iowa

In Partial Fulfilment of the Requirements

for the Non-Thesis Master of Arts Degree

by

Vladimir E. Kouznetsov

Date: May, 2 2003

Approved by:

Yury Lerner

Dr. Yury Lerner, Advisor

05-07-03

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05/08/03

Date

ABSTRACT

Besides proper design of gating and risering systems, there are several methods used to control and modify solidification behavior of cast alloys. Within these methods, the most widely used are local cooling aids employing cooling fins (thin segments attached to problematic areas of a casting) or external chills (metal inserts placed into mold walls to accelerate heat withdrawing from potential hot spot). The later helps to promote directional solidification when traditional methods are not possible to use due to limitations related to the casting design. Despite relatively wide application in aluminum foundries, there are no specific recommendations on cooling aids parameters selections have been published.

The objective of the study was to compare effectiveness of different local cooling aids and to develop practical recommendations on their applications. The research has been conducted via computer modeling of solidification process, based on finite difference computation method (FDM). Results of modeling were compared with experimental. Fourteen different fin sets and twenty-six different chills were studied. As an integral indicator of the fins / chills effectiveness, normalized solidification time of aluminum (A206) test casting in shape of rectangular (4x4x0.75 in) plate was used. Normalized solidification time was calculated as the ratio between the actual solidification time and the solidification time of test casting with no fins or chills. Established as a result of the study, nonlinear relations between fin sets and chills parameters and their impact on solidification behavior allowed developing general guideline for cooling aids selection depending upon particular casting solidification conditions. Practically, it allows selecting optimal geometry of a chill depending on chill material properties (thermal conductivity and specific heat) and desirable effect. It also enables to calculate parameters of fins with the similar effect.

Table of content

INTRODUCTION

Among the methods allowing to influence metal solidification behavior in local areas, attaching of cooling fins to the casting or installing of chill inserts into the mold wall are the most widely used. Despite of completely different mechanism, both approaches serve to reach the same goal: to locally increase the solidification rate at problematic areas of a casting. Both approaches have technological and economical advantages and disadvantages. Both approaches have found relatively wide application in metal casting industry, however, in spite of this, there are no general recommendations of cooling means selection and of the tuning of their parameters in order to achieve a particular goal have been published so far.

The problem addressed in this study was to find the relations between cooling means parameters (overall fins number in a fins set, or contact surface area and volume of a chill) and their effectiveness.

The purpose of the study was to develop the methodology allowing to switch from one cooling means to another (from cooling fins to chills or backward) with same or similar effectiveness.

The research was conducted in two phases:

- Phase 1 compared cooling fins and chills (the phase was realized via employment of computer aided solidification modeling system);
- Phase 2 compared results of virtual and physical experiments (conducted both by real aluminum alloy pouring and solidification modeling).

The research hypothesis, confirmed in the first phase, was: it is possible to achieve an equal result in solidification rate increasing by applying of different cooling means with properly selected parameters.

The research question, stated in the second phase, was: how are results achieved via solidification modeling different from those, achieved in real life. The purpose of the second phase was to confirm the solidification modeling validity, or to develop modeled results adjustment procedure in order to get more reliable data.

As the result of the research, all stated goals were reached. Employment of computer-aided modeling and realization of Rapid Tooling concept allowed to conduct the research in short period of time with minimal material and energy expenses.

LOCAL MEANS IMPACTING SOLIDIFICATION RATE (LITERATURE REVIEW)

The major problems commonly seen in casting of aluminum based alloys possessing medium to long freezing range are porosity type defects and high levels of residual stresses often resulting in hot tearing.

A number of techniques have been developed to address these problems. In addition to the control of gas content and the diminution of oxide incorporation, a special key element in producing a quality, defect-free aluminum casting is the promotion of directional solidification. Typically, this can be accomplished through good casting design and correct placement of the feeding system.

However, in many cases casting design adjustment does not permit directional solidification, for example, in the casting of wheels and pulleys with large hubs, directional solidification is difficult to accomplish without special chills or heat sinks (Lessiter & Nagel, 2003).

As well as enhancing directional solidification and helping eliminate shrinkage-related defects they may also help reduce the level of residual stresses and the associated hot tears in thin-thick walls junctions. Placing the insert in the mold at the specific location will allow drawing the heat from the hub during solidification. As a result, the hub and spoke will come closer to solidifying at compatible rates. If this occurs, the root causes of porosity and hot tearing will be eliminated. The main advantage to using such inserts is that a wide selection of sizes, shapes, and materials becomes available. A positive effect of chills on microstructure improvement of silicon containing aluminum cast alloys has also been reported.

It has recently been already established that cooling fins of various configurations can also assist in local heat transfer and the reduction of porosity.

Kim and Berry (1989) studied the effect of cooling fins on acceleration of solidification rate of pure lead, zinc and copper poured into no-bake sand molds. Cooling fins with 10 mm thickness and variable length were attached symmetrically to both sides of 100x250x70 mm experimental plates. These researchers employed a pour-out methodology, in which a test casting is allowed to solidify for a given time and then the remained liquid is decanted off, and the thickness of solidified layer measured. Different solidification times for different metals were chosen: 1.5, 2, 4, 6, and 8 min for lead, 4, 6, 8, 10, and 12 for zinc, 1, 2, and 3 for copper. The fin effect was interpreted as increases in solidified area in comparison to that, which has been solidified under similar conditions (temperature, time), but without fins. The fin effect was then expressed as the enhanced of solidified area (A_f), divided by the width of the adjacent planar solidification front (S), and was plotted against the solidification time, expressed as the dimensionless ratio (S/T, there T is the fin thickness), as shown in Figure 1. It was concluded that cooling fins have considerable potential for the local control of solidification rate.

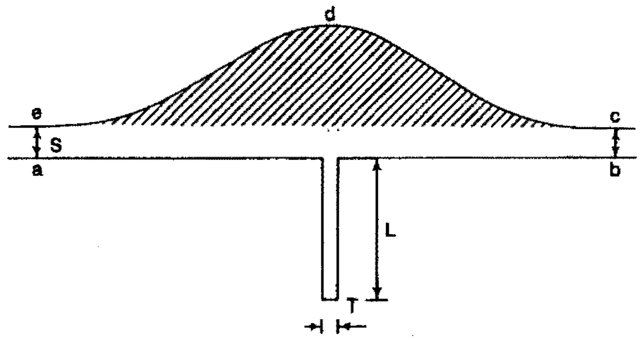


Figure 1. Schematic figure, showing the increased cross section area solidified adjacent to the fin with a given size of LxT, when the solidified thickness at the planar surface is S (Kim & Berry, 1989)

Wright and Campbell (1997) studied the effect of cooling fins on solidification behavior of 100x100x20 mm plate cast of pure aluminum poured in no-bake molds. Two cooling fins were attached symmetrically to the thermal center on both sides of the plates (as shown in Figure 2).

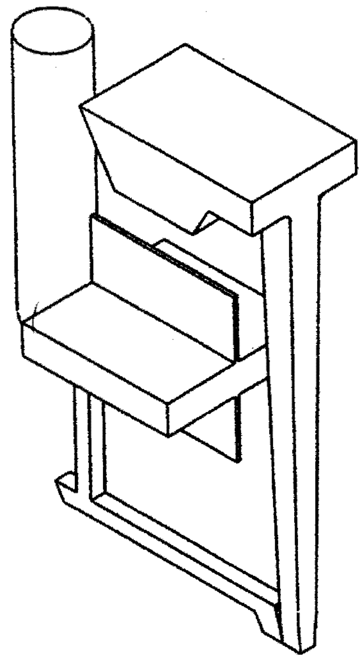


Figure 2. Experimental casting used in work (Wright & Campbell, 1997)

The solidification rate was measured directly by a K-type thermocouple placed in the thermal center of each experimental casting. Experimental results were compared with those obtained from AFSolid simulations as shown in Figure 3, where the normalized solidification time is the solidification time of the casting divided by the solidification time of an equivalent casting with no fins.

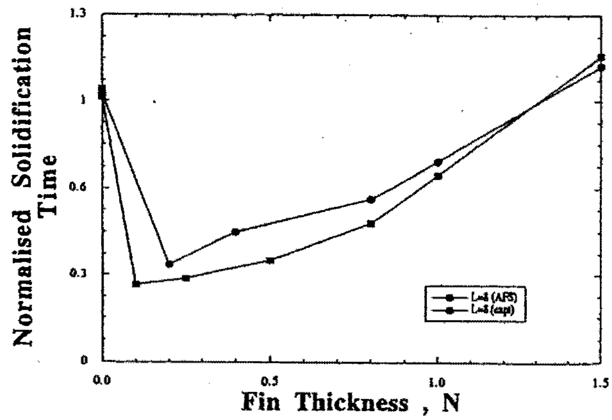


Figure 3. Comparison of prediction (AFSolid simulation result) and experiment of solidification time as a function of fin geometry (Wright & Campbell, 1997)

It was found that the cooling fin having thickness 0.1 times, or less, of the half plate thickness and length of 4 times the half plate thickness, increases in the local solidification rate by nearly ten times.

A paper presented by Dimmick (1997) contains some examples of successful industrial applications of cooling fins instead of chill inserts in aluminum sand casting foundry.

In spite of number of published works, so far there is no information about numerically expressed correlation between parameters of having same effectiveness chill inserts and cooling fins. Thus, this work aimed to fill up this gap via conducting of comparison research.

PHASE 1. COMPARISON OF COOLING FINS AND CHILLS EFFECTIVENESS VIA SOLIDIFICATION MODELING

Methodology

Test casting and gating system design

The test casting used in the first phase of the study incorporates 4x4x0.75 (in) plate, as it shown in Figure 4. The test material was aluminum cast alloy A206.

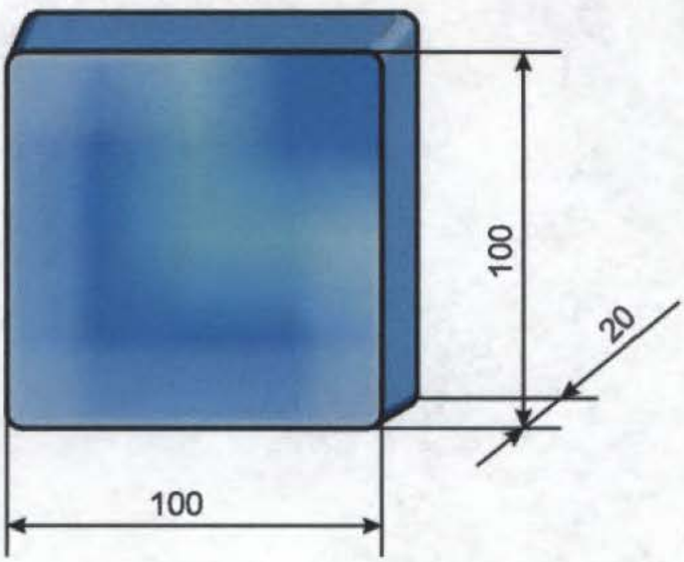


Figure 4. Experimental casting (all sizes in mm)

Solid model of the casting and gating system was prepared in Pro/ENGINEER environment in following sequence:

- model of the casting with required drafts and fillets was generated;
- using data of Al206 alloy density, weight of the casting was calculated;

- based on the calculated weight of the casting, selected gating ratios, and other known data, general parameters of gating system were calculated (all calculations are presented bellow);
- gating system components were added to model;
- model was exported into STL format, which was used directly in the solidification modeling system.

During designing of gating system following calculations were executed.

1. Pouring time:

$t = A\sqrt[3]{\delta M}$,

where: t – pouring time, sec

δ – predominant wall thickness of the casting, mm

M – weight of the casting, kg

A – coefficient selected in respect to cast alloy properties (A = 2.0 for Al 206 alloy).

Weight of the casting calculated in Pro/ENGINEER system has made 0.5 kg (1.1 lb).

$t = 2\cdot\sqrt[3]{20\cdot 0.5}$ = 4.3 sec (for further calculations and simulations rounded to 4 sec).

2. Choke area:

$$A_{choke} = \frac{W}{d\cdot t\cdot c\cdot\sqrt{2gH}},$$

where: A_{choke} – choke area, in^2

W – weight of the casting, lb

d – density of cast alloy, lb/in^3

t – pouring time, sec

c – efficiency factor of the sprue (c = 0.88 for round tapered sprue)

g – gravity acceleration (g = 386.4 in/sec)

H – effective height of the sprue (while the whole casting is placed in the drag part of the mold, the effective sprue height is equal to full height of the sprue, which has been selected as 4 in)

$$A_{choke} = \frac{1.233}{0.1 \cdot 4 \cdot 0.88 \cdot \sqrt{2 \cdot 386.4 \cdot 4}} = 0.126 \text{ in}^2$$

$$d_{choke} = \sqrt{\frac{4 \cdot A_{choke}}{\pi}} = 0.400 \text{ in}$$

3. Runners and ingates. Typical for non-pressurized gating systems ratios 1:4:4 were selected. Thus, total area of runners (as well as of ingates) was four times greater than area of the choke:

$$\Sigma A_{runners} = \Sigma A_{ingates} = 4 \cdot A_{choke} = 0.504 \text{ in}^2$$

Using gating system design with two symmetrical runners/ingates, area of each runner/ingate was the total area divided by two (0.252 in^2).

4. Sprue base. Area of the sprue base must be approximately five times greater than area of the choke. Thus, the diameter of the sprue base was selected as 0.8 in. Depth of the sprue well was selected as 1.5 times of runners height (0.6 in).

Model of the casting with attached gating system is shown in Figure 5.

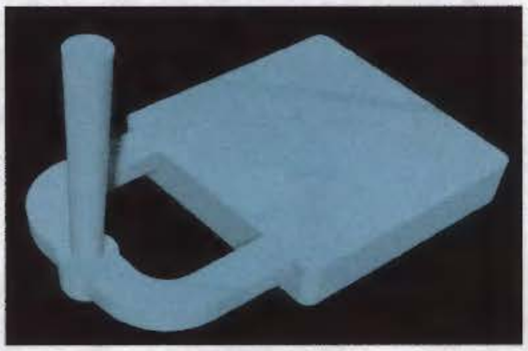


Figure 5. 3D model of the test casting with attached gating system

Simulation parameters

Simulations of mold filling and casting solidification were conducted using SolidCast software package with installed FLOWCast module. SOLIDCast software package is an improved version of AFSolid system. As well as its predecessor, SOLIDCast is based on the finite difference method (FDM) and operates with three-dimensional models. Besides heat transfer calculations, SOLIDCast simulates density changes and the movement of molten metal during solidification of the casting, taking into account gravity and dendritic crystal growth. SOLIDCast has build-in algorithm of mold filling simulation, however it is not very accurate. Improved algorithm of mold filling simulation is used in an extension software module named FLOWCast.

Created in Pro/ENGINEER system, STL file containing model of casting with gating system was imported into SOLIDCast environment. After adjustment of imported model position in the SOLIDCast three-dimensional coordinate system, mold in shape of rectangular block was added. In order to fill mold properly, in respect to SolidCast interface, thin section of "fill material" was attached to the top of the sprue.

All significant for SolidCast software parameters of the casting alloy (A206) are listed in Table 1, all significant parameters of mold materials are listed in Table 2.

Table 1. Casting alloy (A206) parameters using during the simulation

Thermal conductivity, BTU/hr·ft·°F	70.1
Specific heat, BTU/lbm·°F	0.2
Density, lbm/ft^3	174.5
Initial temperature, °F	1220
Solidification temperature, °F	960
Freezing range, °F	243
Latent heat of fusion, BTU/lbm	167
Fill time (pouring time), sec	4

Table 2. Parameters of mold materials using during the simulation

	Thermal conductivity, BTU/hr·ft·°F	Specific heat, BTU/lbm·°F	Density, lbm/ft^3	Initial temperature, °F
Silica sand	0.341	0.257	95	80
Copper chill	223	0.092	559	80
Iron chill	26	0.11	489.6	80

In order to obtain comparable data, all simulations were run using same meshing parameters. Mesh was generated with node size equal to 0.1 in. An exception was submitted for tryout of gating system reliability, which was executed in FlowCast module. In order to acquire smooth animation of mold filling simulation, the mesh resolution was increased and the node size was reduced to 0.05 in.

Experiment design

Cooling fins

Optimal geometry of cooling fins for sand casting of aluminum alloys has been established already. In according to (Wright & Campbell, 1997) optimal fin for this size casting should be approximately 0.04 in thick and 1.5 in length. In this work for practical purpose the thickness of applied fins was increased up to 0.1 in. The length of fins was selected in according to mentioned above recommendations. Since fins geometry was beyond the scope of the study, the only valuable variables were total number of fins and their attachment (one or both sided).

Totally fourteen configurations of fin sets were considered in this research. Sets of one, two, three, four, five, six, and seven fins were attached to one or to both sides of the casting. In all sets having more than one fin on one side the distance between the next fins was kept by a constant and was equal to half of inch.

Chills

Two different materials of chills (copper and iron) were considered in the study. All chills employed in the research were completely plunged into the wall of the mold; therefore there was no contact with air besides the one side faced to the mold cavity. Thus, the only significant parameters of chills besides their material properties are their volume (or weight), representing their heat capacity, and contact surface area, representing thermal exchange between chill and the casting.

For both considered materials same experimental matrixes consisting of thirteen experiments were designed (Figure 6). Chills contact surfaces sized 1, 1.5, 2, 2.5, and 3 in^2 and chills volumes 1, 1.5, 2, 2.5, and 3 in^3 were considered. Due to the symmetry of the matrixes, possible self-correlation between independent variables has been avoided.

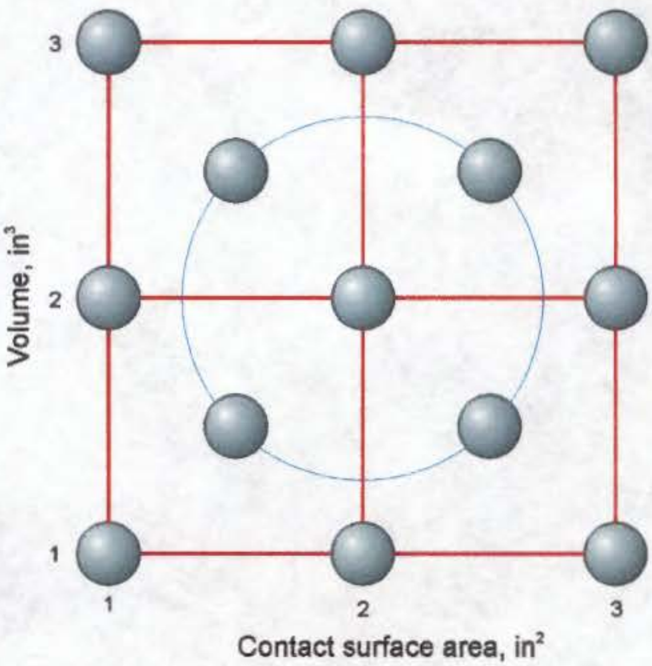


Figure 6. Matrix of the experiment used for both copper and iron chills effectiveness study

Experimental results

Baseline data

The first series of solidification analysis was done for test casting with no extra cooling aids (fins or chills) in order to obtain baseline data for further comparisons (Figure 7).

Figure 7. Test casting used for the establishing of the baseline data (color shows temperature distribution after completion of the solidification)

Figure 8 shows solidification time distribution through the casting (central vertical and horizontal cross-sections are shown). The thermal center (last freezing point) is insignificantly shifted from the geometrical center of the casting due to influence of attached gating system. Solidification time, observed in the thermal center was 2.61 min.

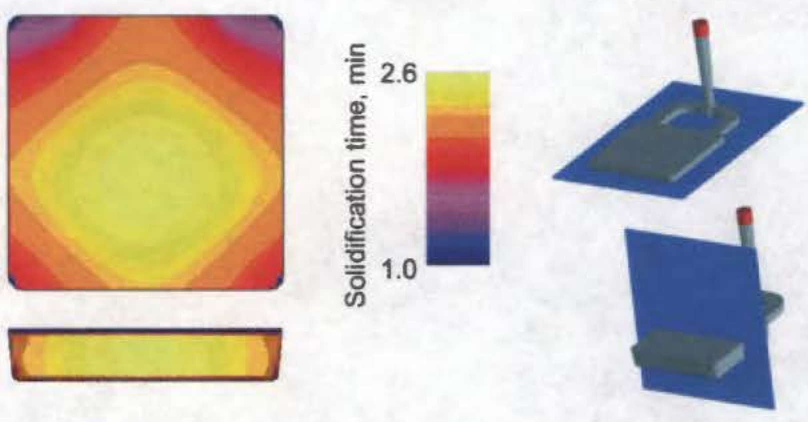


Figure 8. Solidification time distribution through the cross-sections of the test casting

Cooling fins

Numerical data of fins effectiveness is compiled into Table 1. Solidification time has been recorded for the last freezing point (solidification time of the casting) and for the geometrical center of the casting (solidification time in the center of casting). Hereinafter, dimension less factor entitled "normalized solidification time" is the ratio between actual solidification time and solidification time of the casting solidified with no extra heat reducers (base data).

Table 3. Numerical expression of the fins effectiveness

Both sided	Overall fins number	Solidification time of the whole casting, min	Solidification time in the center of the casting, min	Normalized solidification time of the whole casting	Normalized solidification time in the center of the casting
FALSE	1	2.34	2.34	0.90	0.88
TRUE	2	2.14	1.91	0.82	0.73
FALSE	2	2.18	2.10	0.84	0.80
TRUE	4	1.92	1.53	0.74	0.59
FALSE	3	2.06	1.95	0.79	0.75
TRUE	6	1.77	1.29	0.68	0.49
FALSE	4	1.97	1.92	0.76	0.74
TRUE	8	1.63	1.16	0.63	0.45
FALSE	5	1.83	1.70	0.70	0.65
TRUE	10	1.49	1.09	0.57	0.42
FALSE	6	1.80	1.74	0.69	0.67
TRUE	12	1.49	1.17	0.57	0.45
FALSE	7	1.70	1.60	0.65	0.61
TRUE	14	1.38	1.03	0.53	0.39

Graphical expression of fins effect in form of solidification time distribution through vertical cross-section of the casting is shown in Figure 9.

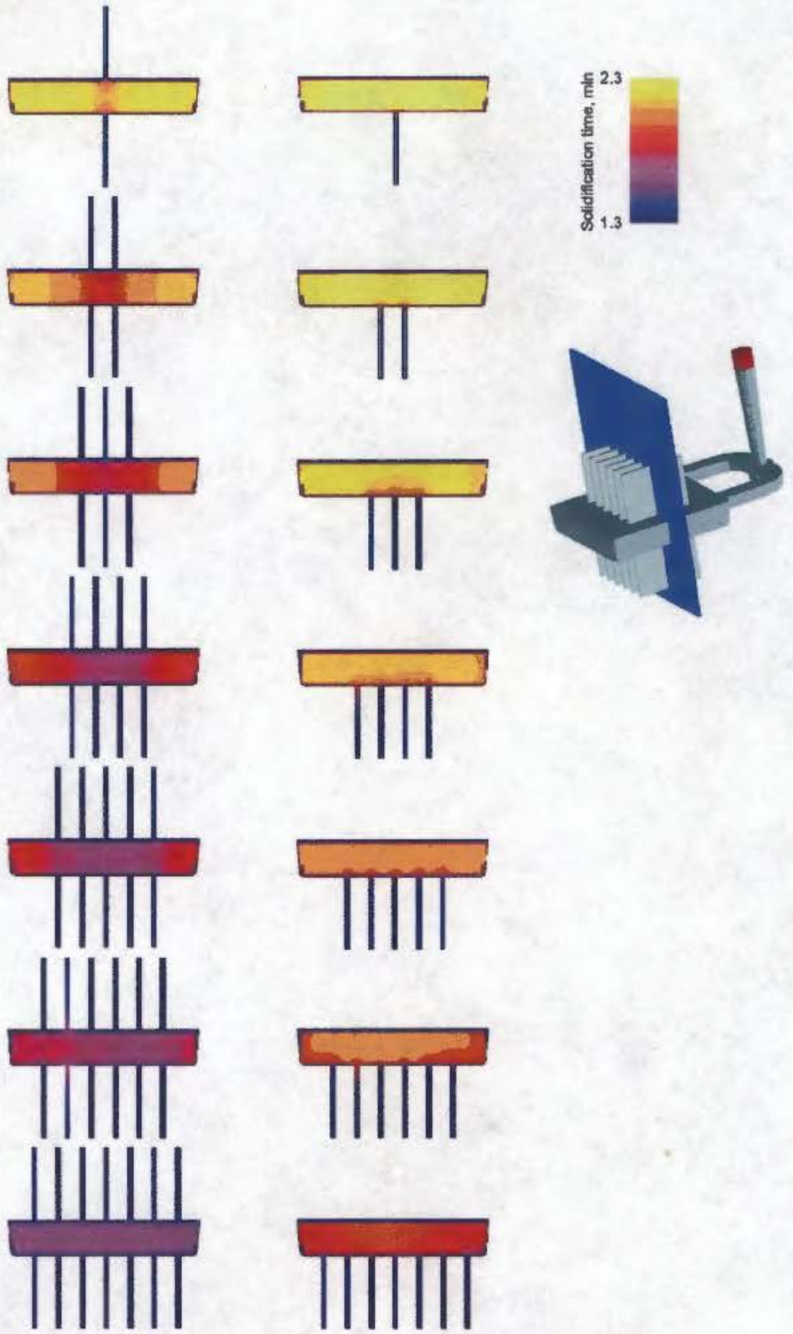


Figure 9. Solidification time distribution through the cross-sections of castings with different number of attached cooling fins

Copper chills

Numeric explanation of chill inserts effectiveness is represented in Table 4.

Table 4. Numerical expression of the copper chill inserts effectiveness

Contact surface area, in^2	Volume of the chill, in^3	Solidification time of whole casting, min	Solidification time in the center of the casting, min	Normalized solidification time of the whole casting, min/min	Normalized solidification time in the center of the casting, min/min
1	1	1.86	1.82	0.71	0.70
1	2	1.37	0.16	0.53	0.06
1	3	1.19	0.13	0.46	0.05
2	1	2.02	1.99	0.77	0.76
2	2	1.42	1.03	0.55	0.39
2	3	1.01	0.17	0.39	0.06
3	1	2.12	2.18	0.81	0.84
3	2	1.49	1.35	0.57	0.52
3	3	1.15	0.15	0.44	0.06
1.5	1.5	1.64	1.49	0.63	0.57
1.5	2.5	1.23	0.14	0.47	0.05
2.5	1.5	1.75	1.70	0.67	0.65
2.5	2.5	1.28	0.17	0.49	0.07

Examples of chill effect in graphic form are given in Figure 10.

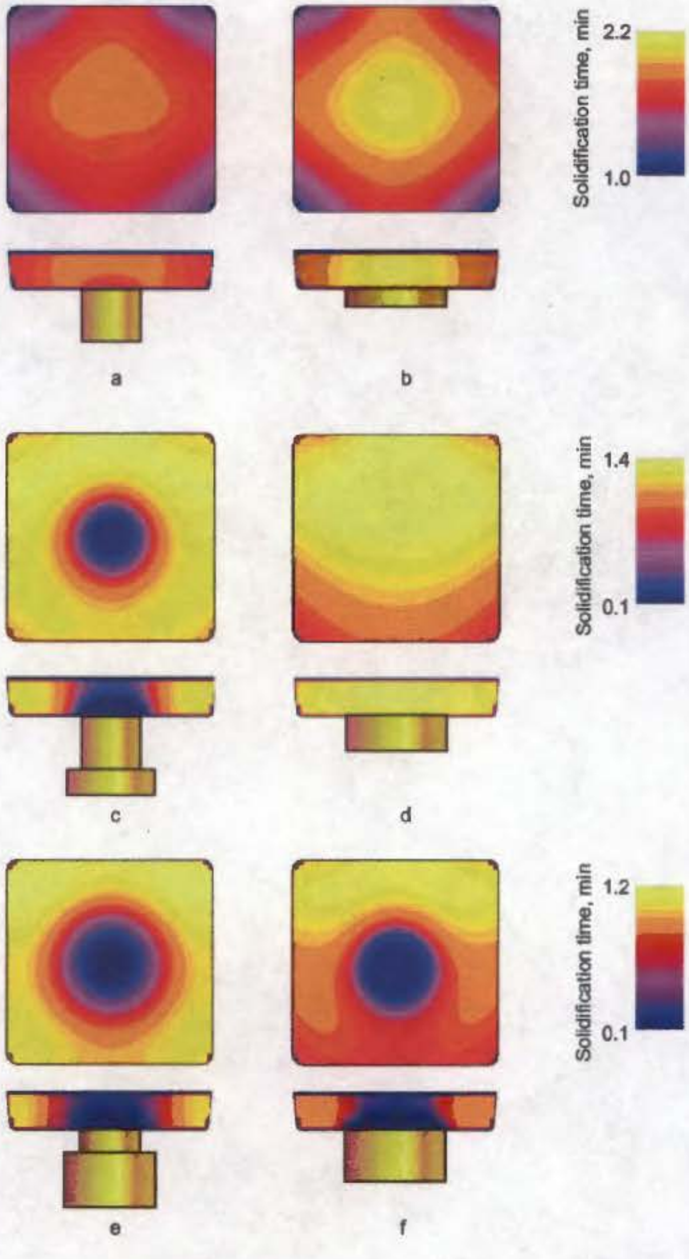


Figure 10. Solidification time distribution through the casting caused by applying of copper chills with different geometrical parameters (see Figure 8 as the reference of cross-sections locations). Pairs a-b, c-d, and e-f have volume of the chill equal to 1, 2, and 3 in^3 accordingly. Chills on pictures a, c, and e have contact surface area equal to 1 in^2, b, d, and f — equal to 3 in^2.

Iron chills

Numerical data of iron chills effectiveness gathered in the study is compiled in Table 5.

Table 5. Numerical expression of the iron chill inserts effectiveness

Contact surface area, in^2	Volume of the chill, in^3	Solidification time of whole casting, min	Solidification time in the center of the casting, min	Normalized solidification time of the whole casting, min/min	Normalized solidification time in the center of the casting, min/min
1	1	1.90	1.71	0.73	0.66
1	2	1.70	0.93	0.65	0.36
1	3	1.60	0.65	0.61	0.25
2	1	1.96	1.96	0.75	0.75
2	2	1.44	0.39	0.55	0.15
2	3	1.33	0.36	0.51	0.14
3	1	2.11	2.11	0.81	0.81
3	2	1.42	0.38	0.54	0.15
3	3	1.21	0.29	0.46	0.11
1.5	1.5	1.65	1.01	0.63	0.39
1.5	2.5	1.50	0.54	0.58	0.21
2.5	1.5	1.67	1.61	0.64	0.62
2.5	2.5	1.31	0.32	0.50	0.12

Examples of chill effect in graphic form are given in Figure 11.

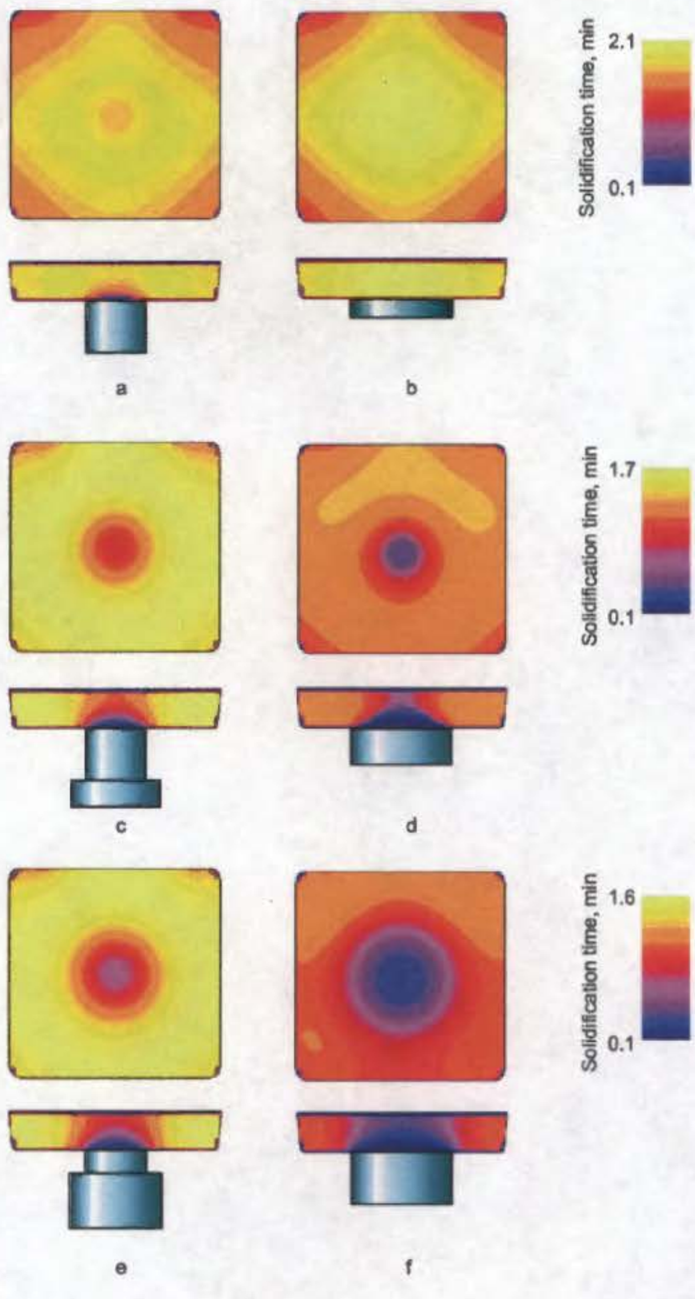


Figure 11. Solidification time distribution through the casting caused by applying of iron chills with different geometrical parameters (see Figure 8 as the reference of cross-sections locations). Pairs a-b, c-d, and e-f have volume of the chill equal to 1, 2, and 3 in^3 accordingly. Chills on pictures a, c, and e have contact surface area equal to 1 in^2, b, d, and f — equal to 3 in^2.

Experimental data processing

Correlation analysis and non-linear estimation conducted utilizing STATISTICA software allowed to digitally express the relationship between solidification time of the casting and size of a fins set, as well as chill inserts (both copper and iron) parameters. All relations can be submitted by the logarithmic approximation (Figure 12, Figure 13, and Figure 14) with high reliability for fins and copper chills (coefficients of determination (R^2) are 0.98 and 0.95 accordingly) and with acceptable reliability (R^2=0.78) for iron chills.

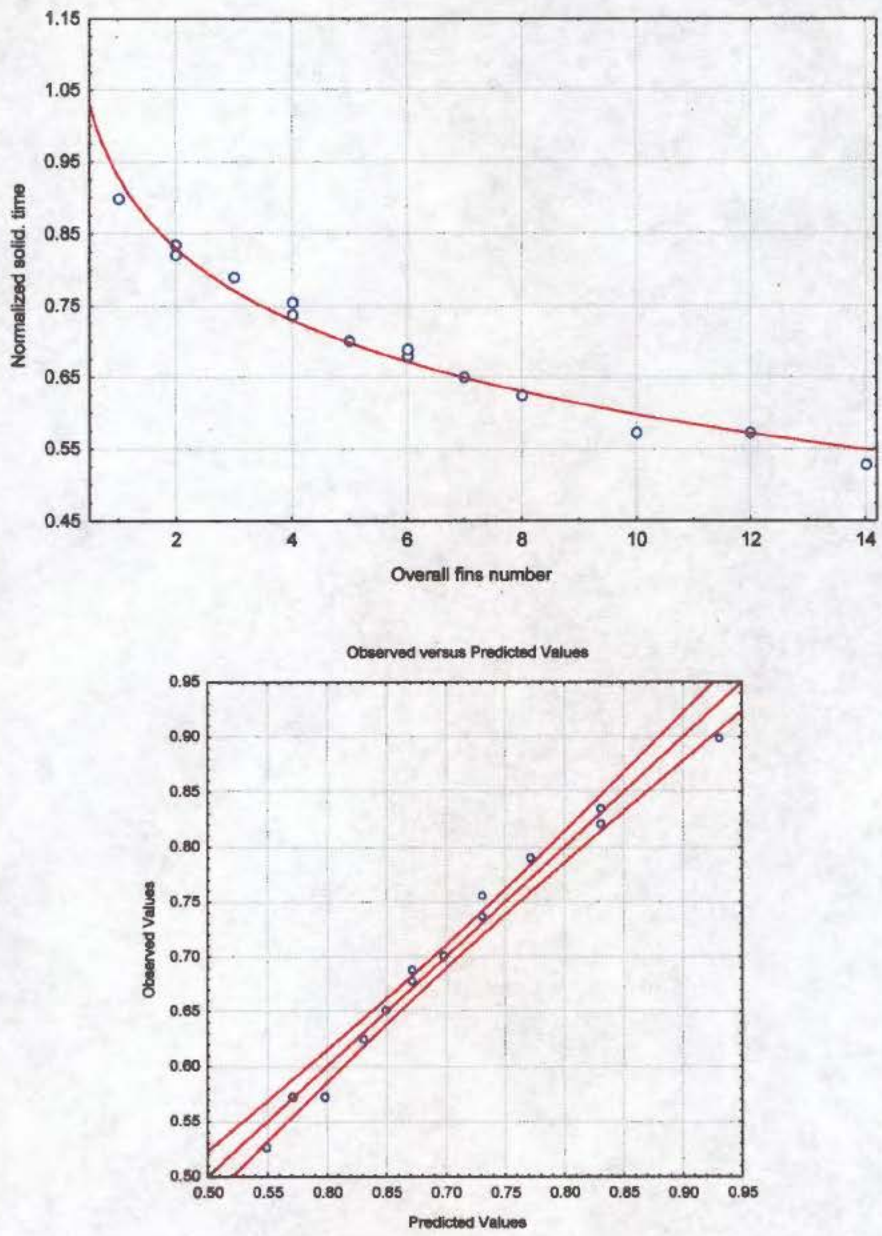


Figure 12. Logarithmic approximation of relationship between normalized solidification time and number of attached cooling fins

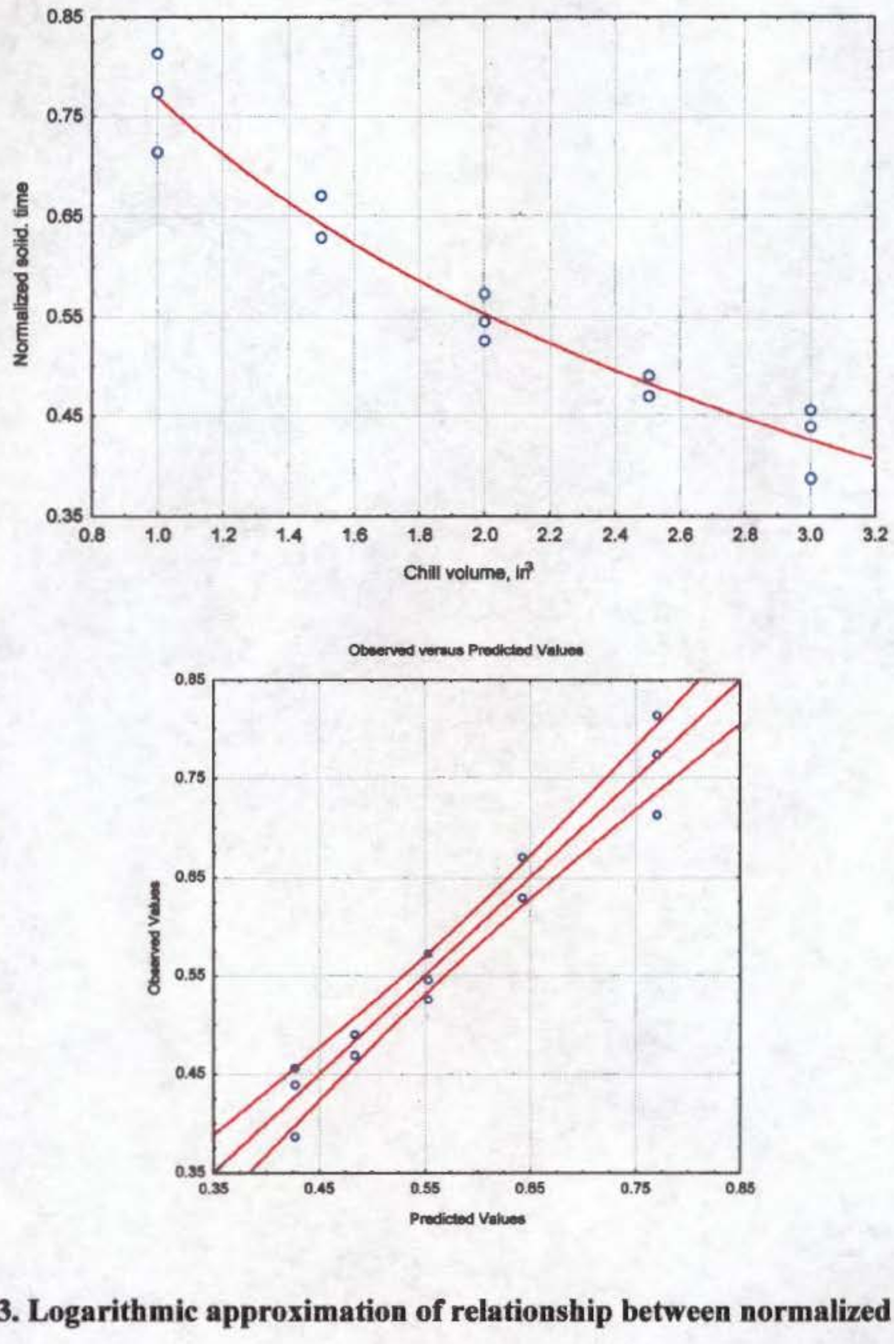
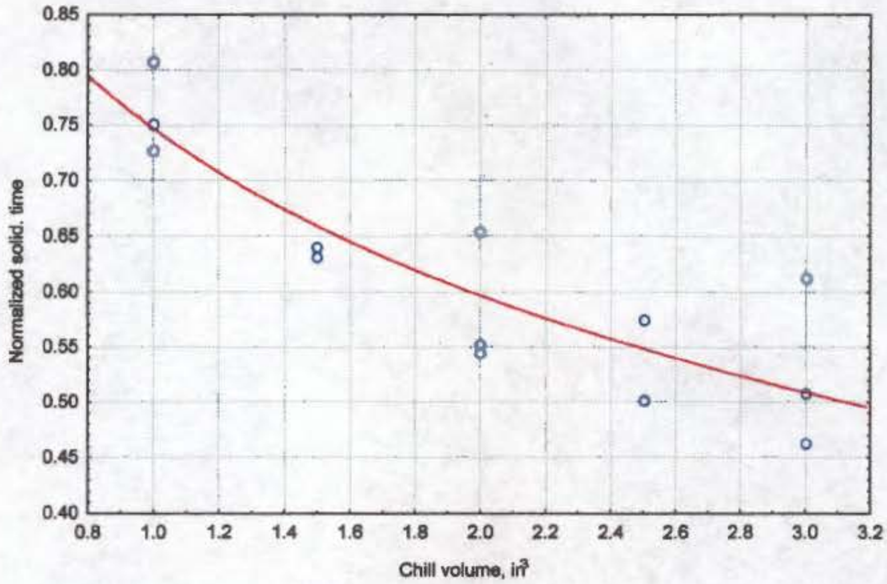


Figure 13. Logarithmic approximation of relationship between normalized solidification time and volume of copper chill inserts



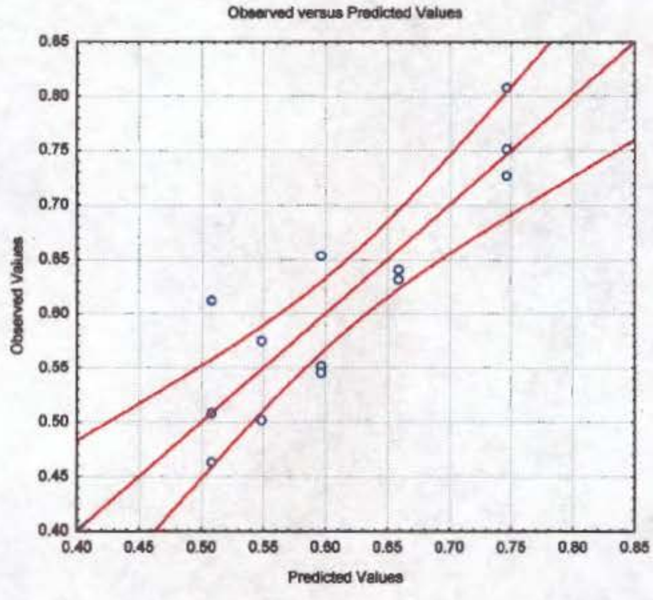


Figure 14. Logarithmic approximation of relationship between normalized solidification time and volume of iron chill inserts

Achieved models have the following view:

$$\begin{cases} T = 0.930 - 0.144\,ln(N) \\ T = 0.769 - 0.313\,ln(V_C) \\ T = 0.747 - 0.216\,ln(V_I) \end{cases};$$

where T is the normalized solidification time, N is overall number of fins, and V_C and V_I are volumes of copper and iron chills accordingly.

Pairwise solution of equations of given system provides the math expressions for switching from fins number to volume of chill having equal effectiveness (volume of a chill as a function of overall fins number with equal effectiveness):

$$\begin{cases} V_C = \dfrac{N^{0.46}}{1.67} \\ V_I = \dfrac{N^{0.67}}{2.33} \end{cases}$$

In similar manner, mathematical expression for replacing copper chills by iron and backward can be found:

$$V_I = \frac{V_V^{1.45}}{1.11}.$$

PHASE 2. COMPARISON OF VIRTUAL (SOLIDIFICATION MODELING) AND PHYSICALS EXPERIMENTS

Methodology

Test casting and gating system design

The test casting used in the second phase incorporates two identical wages connected together (Figure 15).

Figure 15. CAD model of the test casting

The ingates were symmetrically attached to thin sections of the casting. No risers were used. This inappropriate from the practical standpoint gating system design allows to generate a hot spot in the center of the casting and to concentrate shrinkage in that area. Pressurized gating system with ratios approximately 2:3:1 was chosen. The pressurized gating system has been selected in order to maintain relatively small cross-section of the gates. The test casting with attached gating system is shown on Figure 16.

Figure 16. Test casting with attached gating system (the pressurized gating system with ratios 2:3:1 was used)

Pattern for sand molding

Pattern for no-bake sand molding was generated on Stratasys Dimension 3D-printer using same 3D CAD model, which was involved into solidification modeling. Using of the 3D-printer based on fused deposition modeling (FDM) build principle is an example of Rapid Tooling (RT) approach (Lerner, Rao, & Kouznetsov, 2002), which is an extension of Rapid Prototyping (RP). Generally, the Rapid Tooling is the usage of RP-generated models as an actual tooling in manufacturing processes (direct RT), or as an intermediate means in tool making (indirect RT).

In order to use single pattern to make different molds (with different fin sets attached, as well as with no fins) special design of compound pattern has been developed. The compound pattern consists of three parts: main body with attached gates, runners, and the bottom sprue, and two exchangeable pieces inserting in central dimples of the main body. Totally three variants of inserts (Figure 17) were created for this study:

- plain (for making the initial mold with no fins),
- with one fin attached,
- with three fins attached.

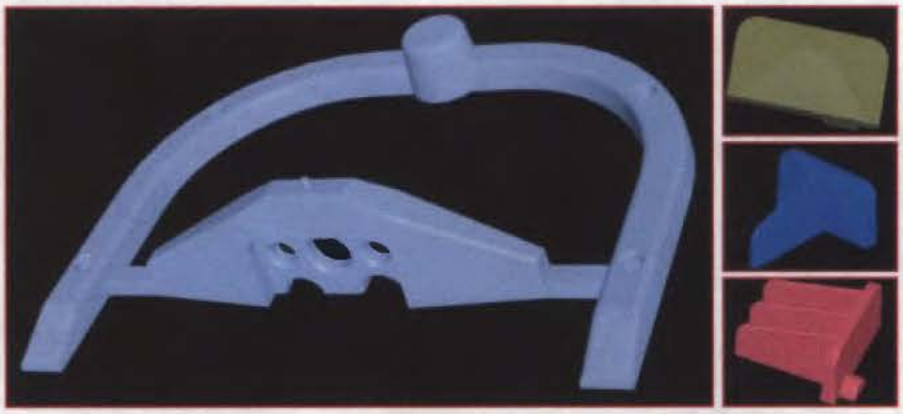


Figure 17. CAD model of the compound pattern: main body (on the left) and three different designs of inserts

Model of the compound pattern has been created using Pro/ENGINEER 2001 software package. Completed models of the main body and of all variants of the inserts have been converted to STL (standard triangular language) format using maximum allowed resolution (chord height was equal to 0.0009). STL files has been processed by special software and then transferred to the 3D printer. The building process of main body and both plain inserts took about 8 hours. The generated model is shown in Figure 18.

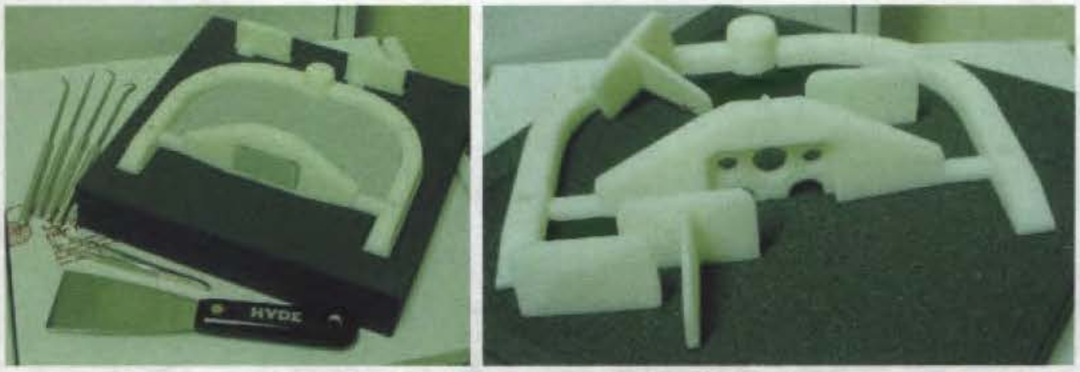


Figure 18. RP-generated compound pattern as built (left) and after removing off the support material (right)

The Stratasys 3D printer has sufficient geometrical accuracy, however, because of the layer-by-layer build principle, surface of generated objects is stepped. In order to reduce the roughness, the pattern was covered by special putty, and then ground with fine sandpaper. After that, the pattern was mounted on wooden matching board by acrylic glue and eight screws (all holes for the screws were included into the CAD model, thus, there were no needs to drill the pattern). The pattern along with the matching board was painted in order to increase its durability. Turned out of hard wood conical sprue was inserted into special hole from the opposite side of the matching board. As a result of experiment, RP-generated pattern proved appropriate reliability. After making of several no-bake molds no defects were found on the pattern.

Mold making

Experimental molds were made out of no-bake sand (Figure 19). Standard steel flask with dimensions 12x18x8 (in) was used. Zip-slip coating was used in order to easy removal of the pattern.

Finally, six molds were made (two per each casting design). Three molds (one mold from each casting design) had K-type thermocouples embedded. The thermocouples were inserted from the bottom of the mold through specially drilled hole placed in the center of casting cross-section. All of the thermocouples were placed in same way with the measuring tip located half of inch bellow the parting line. In order to provide venting, cope side of each mold was drilled by the 1/8 in bit.

Figure 19. Experimental molds made out of no-bake sand

Melting and pouring

Pigs of certified A206 aluminum alloy were melted in a gas furnace. Pouring was done using 2-lb ceramic handle ladle (one mold in time). The pouring temperature was maintained in the level of 1400 °F.

During the pouring and solidifying of the casting cooling curves were recorded from the molds having thermocouples installed using data acquisition system containing of ADC (analog-to-digit converter), laptop computer, and special software (Figure 20).

Figure 20. Data acquisition system in front of the pouring deck

Simulation parameters

Same solidification modeling system (SOLIDCast) was used in this phase.

Most of simulation parameters were kept same as in the first phase (Table 1, Table 2), except for the initial temperature (1310 °F) and filling time (2 sec). These changes were submitted in order to accurate represent conditions of the physical experiment.

In order to record cooling curve during the simulation, virtual thermocouples were embedded to the model at same point as in the actual experiment.

For each simulation mesh was generated with node size equal to 0.075 in. Such resolution provided appropriate accuracy.

Experiment design

The scope of the second phase was to compare results achieved by solidification modeling with those gathered from physical experiment, or to evaluate simulations results reliability. Solidification time observed in the thermal center of the casting was selected as the main parameter for the comparison. Three different design of test casting (with no fins, with one fin attached to both sides, and with three fins attached to both sides) were used both in physical and virtual experiments.

Experiment results

Physical part

As it can be seen from the Figure 21, all the poured molds were completely filled including fin sections.

Figure 21. Experimental castings (gating components are removed)

Cooling curves, recorded from the thermocouples are shown in Figure 22.

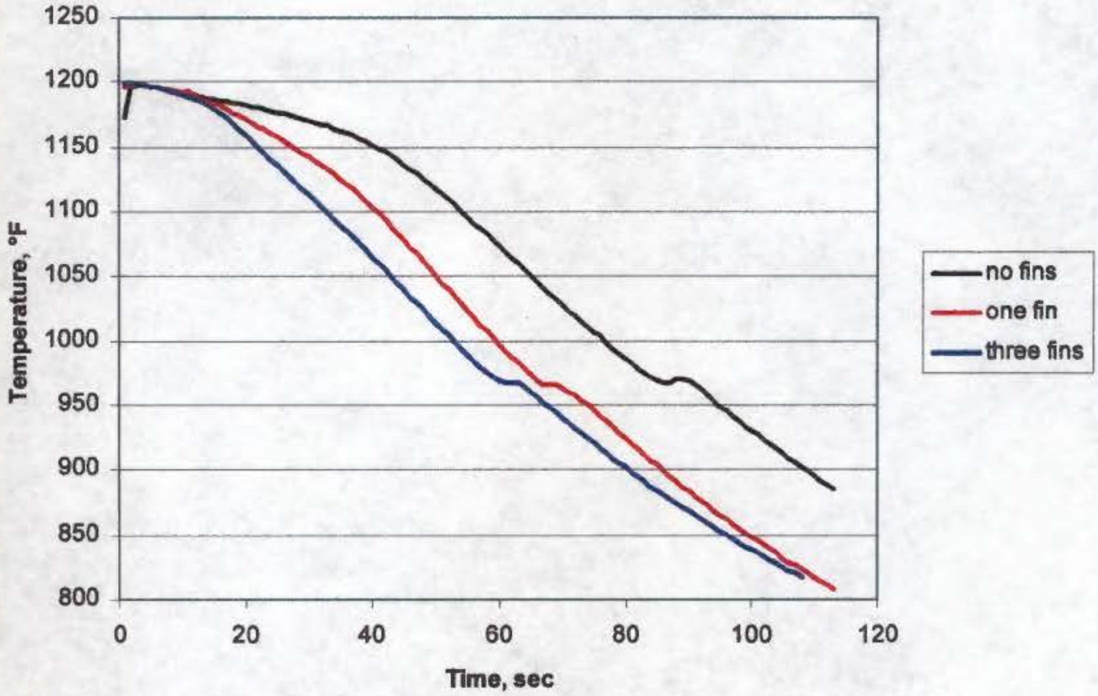


Figure 22. Temperature changing observed in the center of each test casting during the solidification

As it can be seen from the plot, application of fins led to significant shift of the solidus point on the cooling curve in direction of time axis.

Solidification modeling

Usage of FLOWCast (Figure 23) filling algorithm during the simulations allowed to precisely calculate the temperature distribution of liquid metal through the mold cavity at the beginning of solidification, which perform achievement of more reliable resulting data (Figure 23).

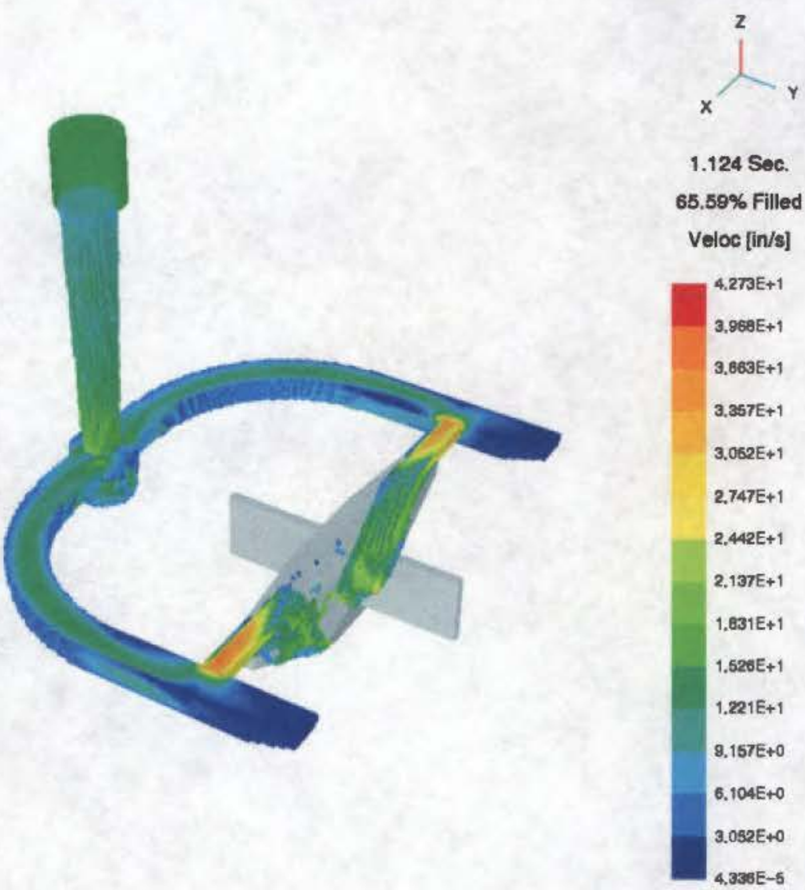


Figure 23. Simulation of mold filling using FLOWCast (color shows metal velocity)

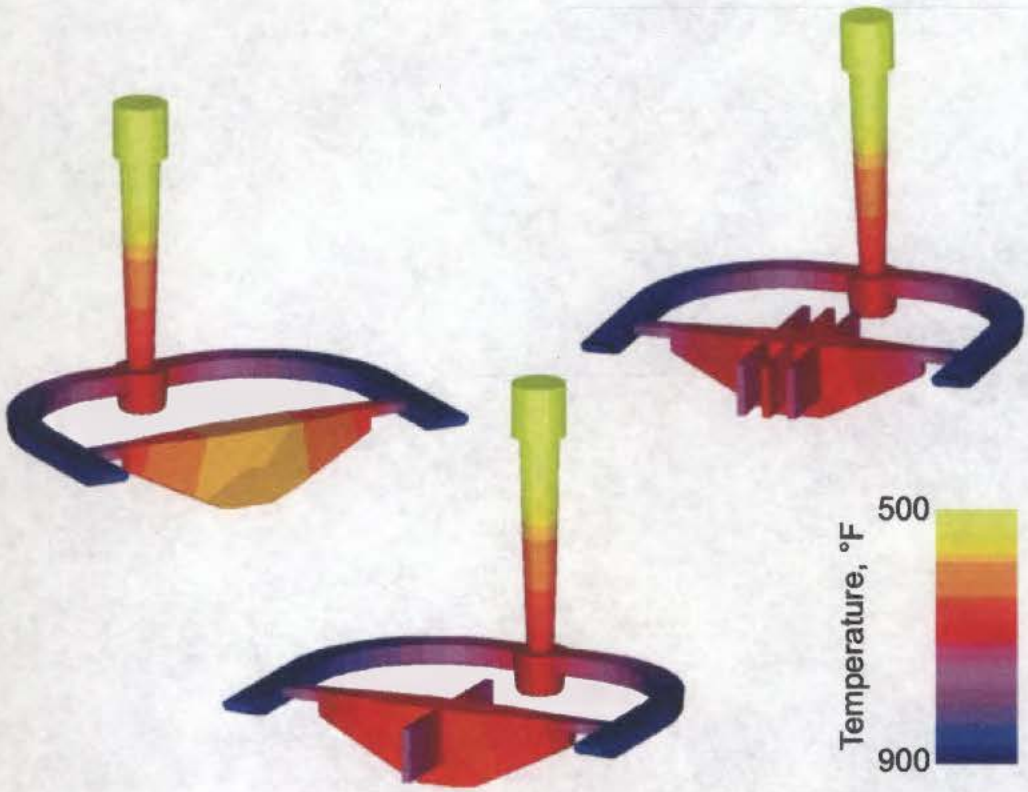


Figure 24. Temperature distribution through the experimental castings at the end of solidification

Plot in Figure 25 shows the cooling curves recorded from virtual thermocouples.

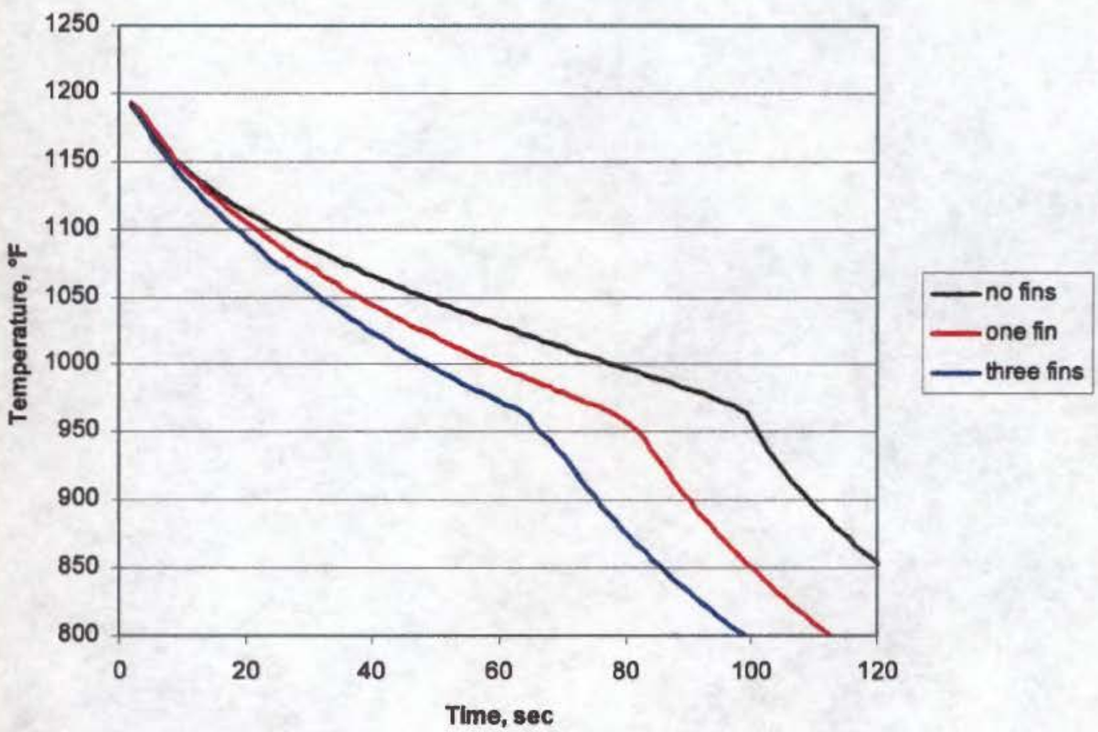


Figure 25. Temperature changing observed in the center of each test casting during the simulation

RESULTS DISSCUSSION

Cooling fins: one-sided versus two-sided

Figure 26 and Figure 27 show the relationship between the solidification time and fins number.

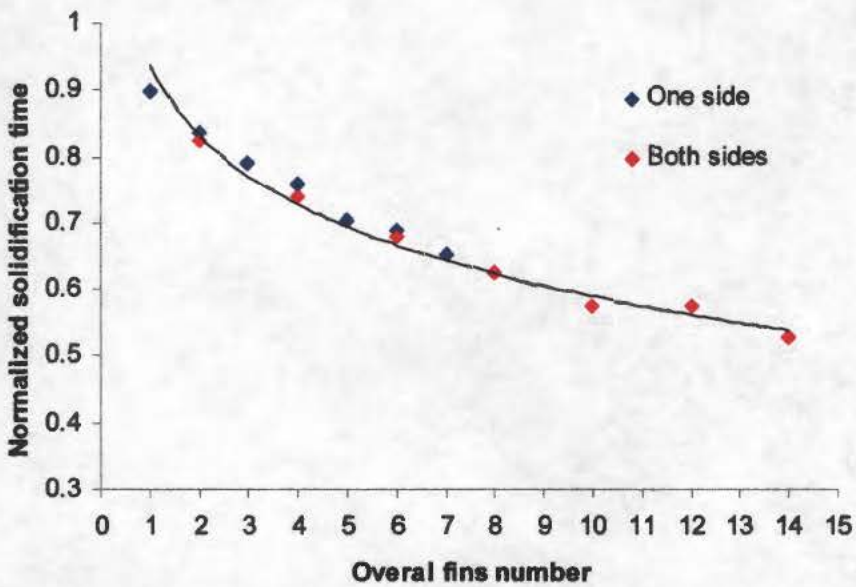


Figure 26. Relationship between the number of attached fins and normalized solidification time of the whole casting

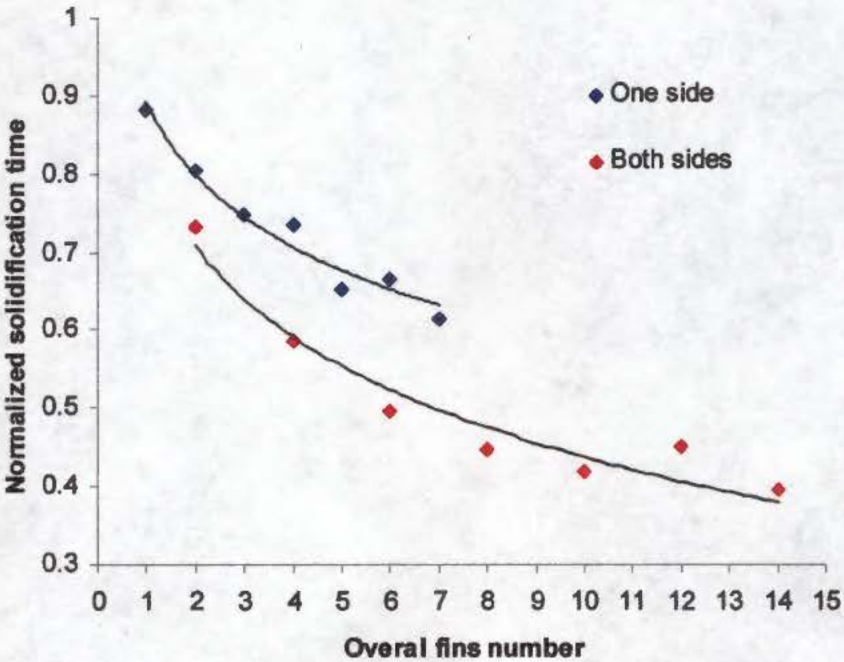


Figure 27. Relationship between the number of attached fins and normalized solidification time in the center of the casting

As it can be seen from the figures, the way of fins attachment has no significant influence on the solidification time of the whole plate. However, difference in one/both side attachment appears to be significant when solidification time in local area (in the center of the casting) is considered. In this case fins attached to both sides allow to reach greater improvement than same quantity of fins attached to one side. Obviously, it is due to simple fact that in the case of both sides fins attachment fins junctions are closer to the plate center.

Geometry of copper chills

Figure 28 shows relationship between geometrical parameters of copper chill insert and normalized solidification time observed in the center of the casting and in the last freezing point.

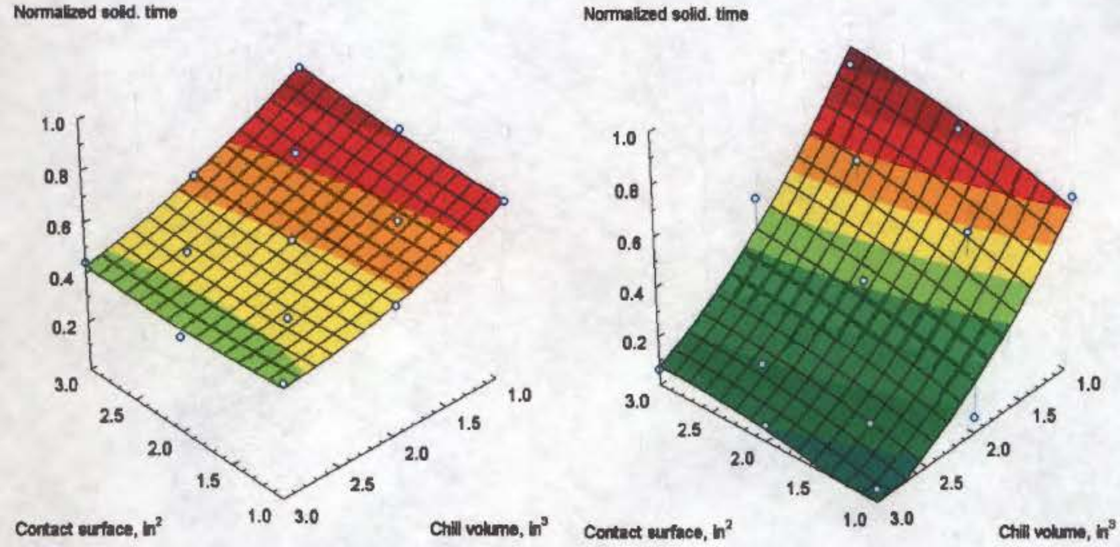


Figure 28. Relationship between chills geometry and solidification time of the whole casting (left plot) and solidification time in the center of the test casting (right plot)

As can be seen from Figure 28, area of contact surface practically has no influence on the solidification time of whole plate. In this case the volume, representing heat capacity of the chill, is the only significant factor. In mean time, both considered factors influence on solidification time in the center area of casting. By reduction of the contact surface area along with keeping constant volume of the insert, it is possible to achieve substantial increase of chill efficiency in local area of its attachment.

Geometry of iron chills

Figure 29 shows relationship between geometrical parameters of chill insert and solidification time.

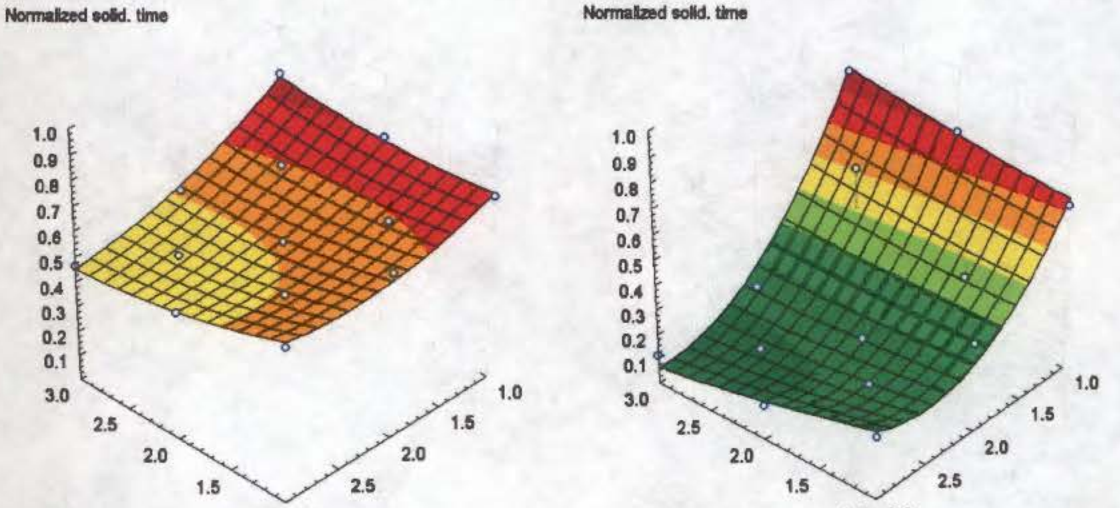


Figure 29. Relationship between chills geometry and solidification time of the whole casting (left plot) and solidification time in the center of the casting (right plot)

In contrast with copper chills, in case of usage of iron ones, both factors (volume and contact surface area of the chill) have significant influence on solidification time of the whole plate. This difference between copper and iron chills is due to different thermal conductivity of these two materials. In case of copper, due to high thermal conductivity, whole chill is working, no matter what is the shape of the chill. In case of iron, having relatively low thermal conductivity, the cross-section of the chill, through which heat is transferred, becomes more important. For example, if a chill has large volume, but small contact surface area, then only part of chill, which is closed to the casting, receives heat from the solidifying metal, while another end of the chill remains cold (certain part of a chill remains ineffectual). That is why, in order to involve all volume of an iron chill to heat withdrawing, the contact surface area of the chill must be relatively large (the volume to contact area ratio must be maintained on a certain level, approximately about 1:1).

Difference in thermal conductivity also influences on effect of solidification rate enhancement, achieved in the central area of casting by applying of copper and iron chills. In case of copper chills, contact surface area unambiguously influences on solidification time in the center: less the area, faster the solidification. In other words, if contact surface of a copper chill is reduced while its volume remains the same, the cooling effect becomes stronger in local area of chill's attachment. The same relationship was observed for iron chills having small volume, but for large volume chills reduction of contact surface area will lead to reducing of chill effectiveness (part of the chill appears to be useless because, due to low thermal conductivity, heat from the casting does not reach remote portions of the chill).

Fins versus chills

Both approaches (cooling fins and external chills) have certain technological advantages and disadvantages. Apparently, using of fins leads to appearance of extra operation during post-processing of castings, and insignificantly reduces the casting yield. In meantime, using of chills leads to additional operations during mold making (chills installation) and during shakeout (chills must be separated from the sand and collected). Figure 30 graphically represents effectiveness of copper and iron chills in comparison with fins set with different number of fins.

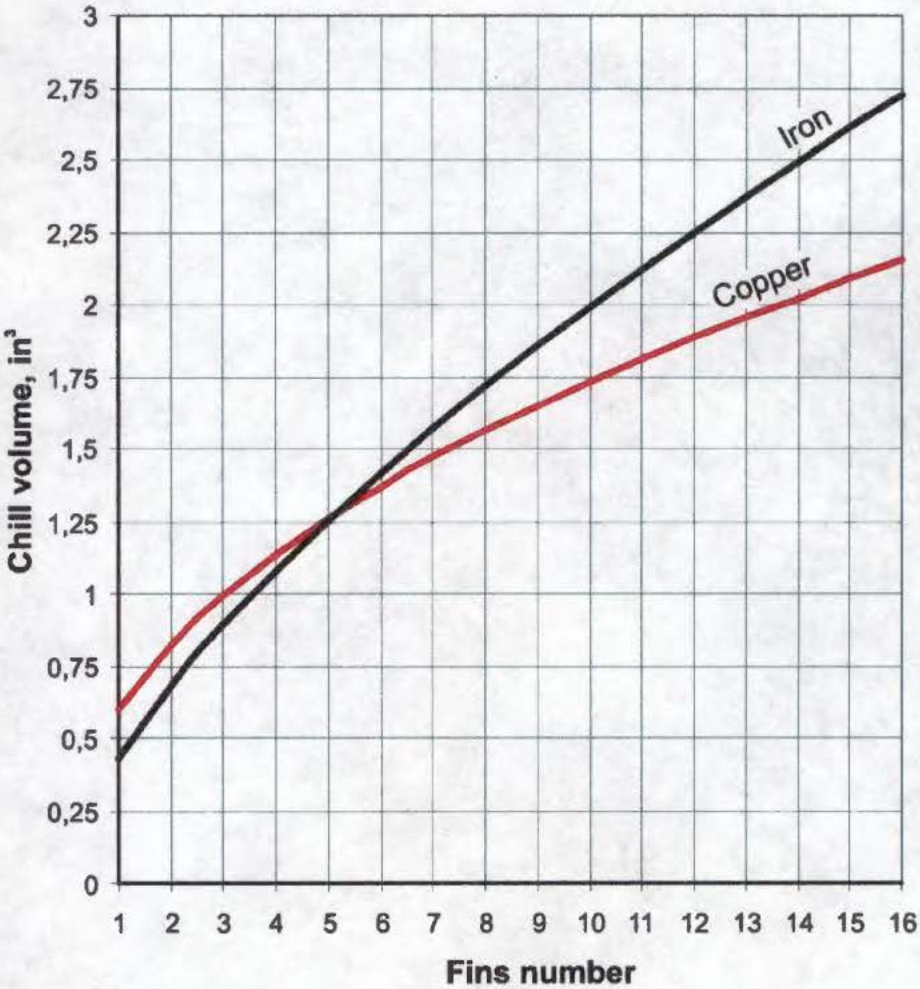


Figure 30. Diagram for switching between cooling fins and copper/iron chill inserts

Basically, these diagram shows that both approaches are interchangeable. However, from technological standpoint, chills are more flexible than fins. Analysis of plots in Figure 9, Figure 10, and Figure 11, shows that by applying of chills with different contact surface area different (concentrated or distributed) effect can be achieved, while, it is not possible to achieve strong concentrated effect of heat withdrawing by applying of fins. The only way to increase the effectiveness of a fin set is to increase overall fins number, however fins must be distributed. The later will not allow achieving of the concentrated effect.

Copper chills versus iron chills

Neither iron chills, nor copper chills have absolute advantage. Copper has grater thermal conductivity (223 versus iron's 26 BTU/hr·ft·°F), but iron has greater specific heat (0.11 versus copper's 0.092 BTU/lbm·°F). Thus, iron chill has greater heat capacity than having same volume copper one. However, because of relatively lower thermal conductivity of iron (relatively slow heat distribution through the iron chill body), not all the heat withdrawing potential of an iron chill can be realized.

Figure 31 shows comparison between iron and copper chills effectiveness depending on their volume.

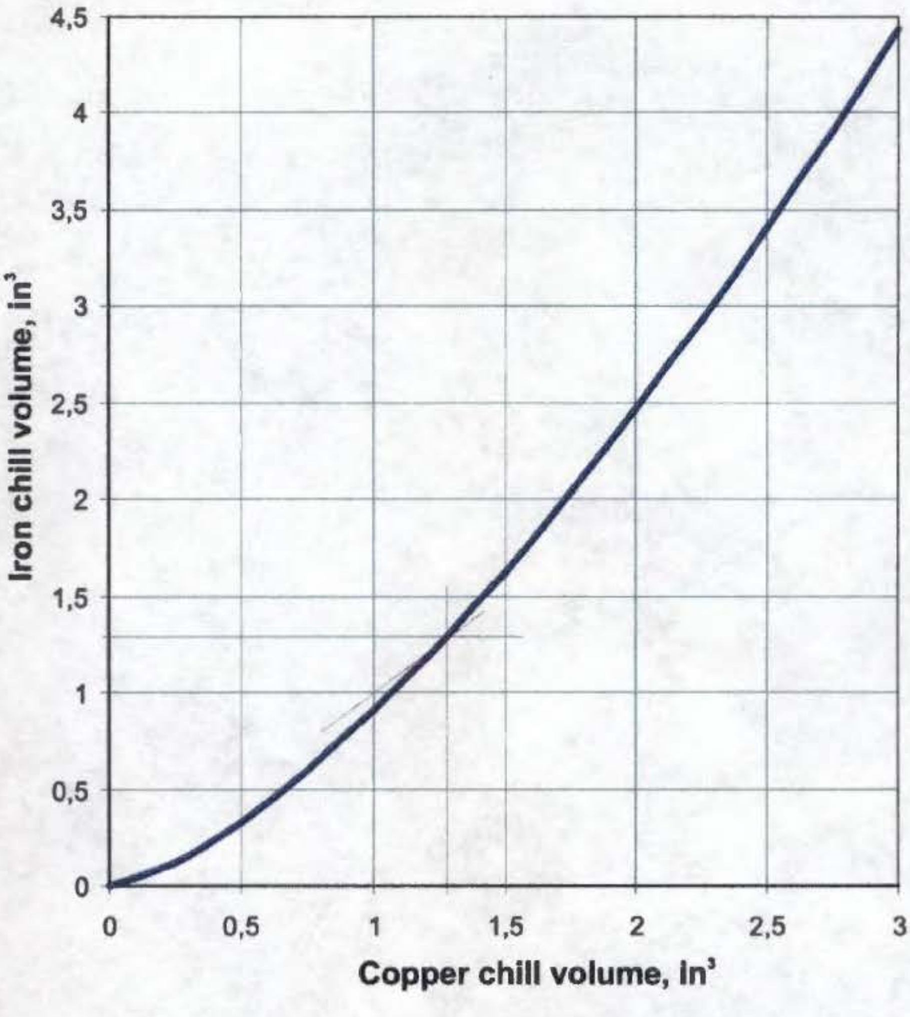
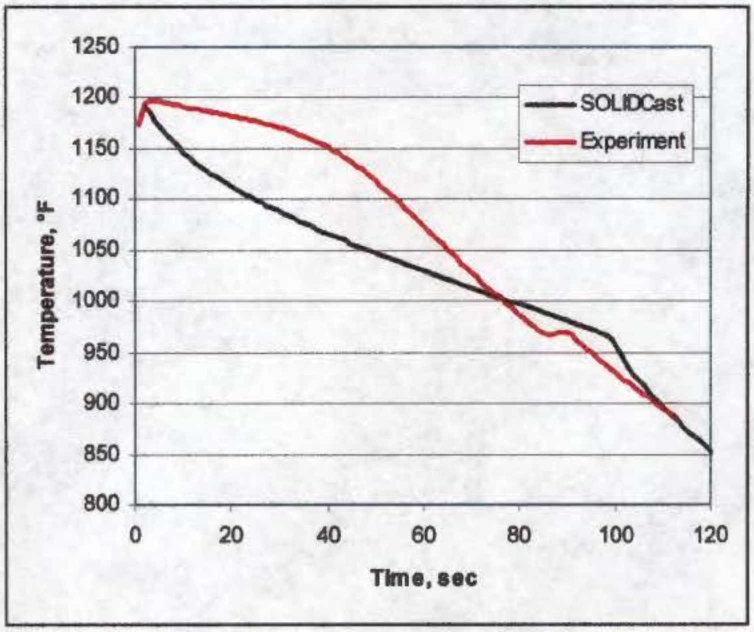


Figure 31. Diagram for switching from copper to iron chills

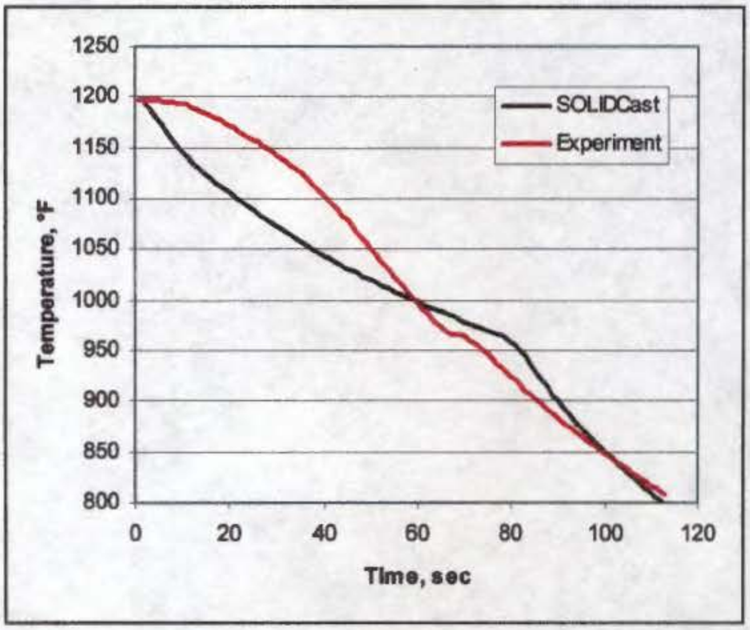
As can be seen from the diagram, for chills having relatively small volume, iron is more appropriate material. Using of copper appears to be beneficial only in cases when it is necessary to use relatively large chills, especially when it is needed strong and concentrate heat-withdrawing effect by attaching chill having relatively small contact surface and large volume.

Experiment versus simulation

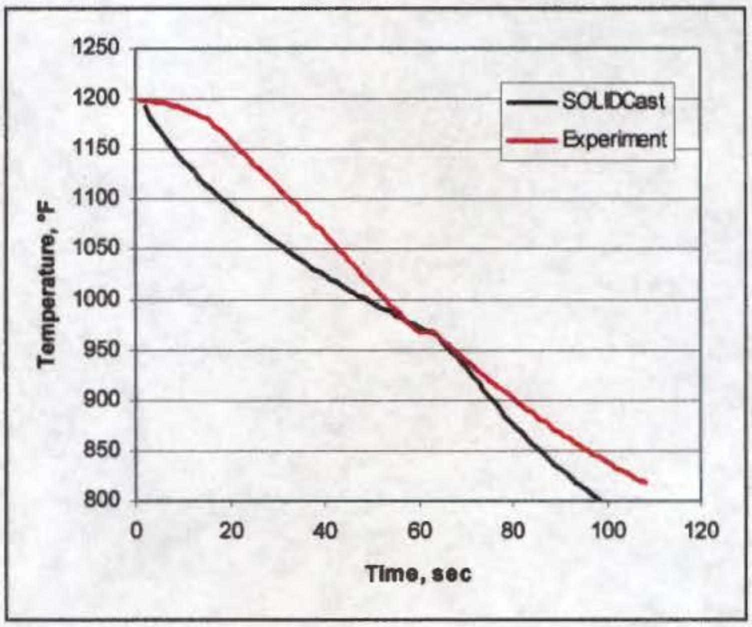
Figure 32 shows the conformity between results achieved by the modeling and the experiment. Experimental and modeled curves have different shape, however the locations of solidification points are very close, the divergence is inside 10% tolerance. Which is allowing to affirm that results gained from the simulations are reliable.



a)



b)



c)

Figure 32. Comparison of cooling curves recorded from physical and virtual experiments for castings with no fins (a), with one fin (b) and with two fins (c) attached to both sides

CONCLUSIONS

1. Both considered approaches of solidification rate enhancement (cooling fins and external chills) are partially interchangeable. From technological standpoint, chills are more flexible because by varying their geometrical parameters it is possible to achieve different cooling effect (distributed, as well as concentrated). At the same time it is not possible to get highly concentrated heat withdrawing effect by fins applying.
2. More expensive copper chills have no significant advantages in comparison with iron ones, unless using of relatively large chills is recommended. For relatively small chills, iron can be suggested as the optimal material.
3. Established relationships between efficiency of different cooling means (fins, or copper and iron chills) allowing substituting of one means by another with no significant difference in its effectivenes.
4. Developed and applied methodology based on combination of physical and virtual modeling has proved its efficiency, and can be efficiently used in study of solidification acceleration of other alloys.

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LIST OF FIGURES

LIST OF TABLES