Thermal Analysis and Optimization of a Cast Lattice-Structured Valve Spool

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Abstract

This research focuses on transient thermal analysis and optimization of a new casting process which will yield a defect-free valve spool. Typical spools are machined from a solid piece of steel, and the weight associated with this structure limits the possibilities for improved response to actuation. Utilizing a hybrid fabrication process encompassing rapid prototyping and investment casting, it is now possible to manufacture a spool comprised of a finely-detailed internal lattice. This structure is lightweight to increase response time, yet adequately stiff in order to withstand fluid pressures experienced inside the valve housing. A spool with this internal lattice structure has been cast in copper using a process developed at Milwaukee School of Engineering. Under the current casting configuration, however, macroscopic defects appear in the spool due to non-ideal solidification of the molten copper. The finite element method and heat transfer analysis are employed in this project to accurately model the thermal conditions experienced inside the casting furnace during solidification. This analysis provided a means for predicting potential defect areas of the casting with the aim of optimizing ceramic mold geometry in order to induce directional solidification. The transient behavior of molten copper is investigated through modeling of various ceramic mold geometries with the intention of testing this behavior experimentally in the future.

Keywords: Spool Valve, Hybrid Fabrication, Investment Casting, Finite Element Method, Heat Transfer Analysis, Directional Solidification

1. Introduction

Fluid power applications in industry today require valve spools which exhibit extremely quick and accurate responses to actuation. Current spools limit response capabilities due to their inherent weight. A new casting process developed in The Rapid Prototyping Research Department at Milwaukee School of Engineering (MSOE) has led to the production of a copper valve spool containing a finely-detailed internal lattice used to reduce weight.

Although the current casting configuration has yielded a spool with the desired geometric resolution, this spool exhibits macroscopic external defects in the form of hot tears. This research employs the finite element method and heat transfer analysis to accurately model the solidification stage of the MSOE casting process and provides a process for eliminating such defects through optimized ceramic mold geometry that induces proper solidification.

1.1. background information regarding spool valves

Spool valves are directional control valves used to route fluid to or from work ports connected to various components within hydraulic or pneumatic systems [1]. These valves are used in a wide variety of fluid power applications in various industries. The sliding spool valve which is the focal point of this research is used in pneumatic applications associated with robotic equipment and animatronics.

A cutaway view of a typical sliding spool valve is shown in Figure 1. Sliding spool valves are comprised of a **housing**, a cylindrical **spool**, and any number of **work ports**. Larger diameter portions of the spool, called **lands**, have a close fit to the housing to seal off regions within the valve. Because the lands are of the same diameter, pressurized fluid entering the valve from an inlet port acts equally on each land regardless of the spool position [2]. Therefore, the spool will not change position based on fluid pressure alone. This enables an electrical **actuator** to slide the spool back and forth inside the housing to open desired fluid ports and block others [3].

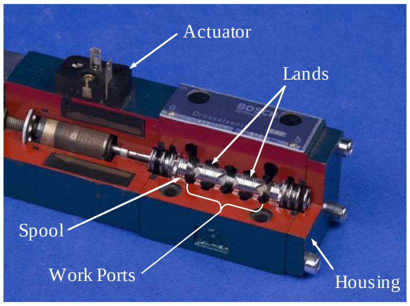

Figure 1 Diagram of a typical spool valve.

1.2. lattice-structured spool

All spool valve applications require a quick and accurate response to actuation; this requirement is particularly important in pneumatic systems which depend upon fluid routing at precise instances. Poor response can lead to inaccurate process execution and even equipment malfunction.

Because typical spools are machined from solid material, it is nearly impossible to reduce lag time due to the inherent weight of the spool itself. The only solution to this problem is to remove material from the internal structure of the spool, but in many cases a hollow spool cannot withstand the fluid pressure inside the valve housing. Prior research at MSOE, however, indicates that in many engineering applications, it is possible to replace solid material with a lattice comprised of an interlocking network of rods [4]. Utilizing the unique ability to develop optimized lattice structures with computer simulation, a spool provided by Enfield Technologies has been modified to include an internal lattice which maximizes its strength-to-weight ratio. The original machined spool is shown in Figure 2, with its size relation indicated by a penny. A section view of the modified spool is shown in Figure 3. The mass of this lattice-structured spool is 57 percent of the original solid spool, allowing for the reduction of lag time during actuation.

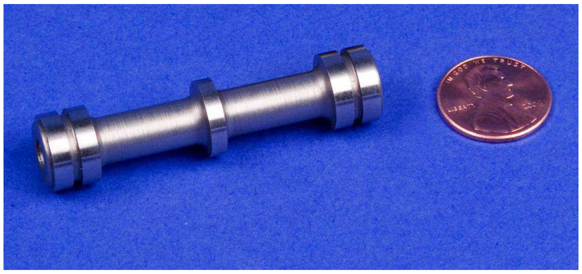

Figure 2 Original machined spool provided by Enfield Technologies.

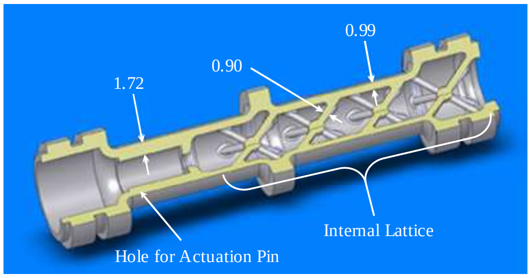

Figure 3 Section view of modified spool with dimensions shown in mm.

1.3. hybrid fabrication

The fabrication of a lattice-structured spool can only be made possible through a hybrid process of rapid prototyping (RP) and investment casting developed at MSOE. The general process is described herein:

1. Utilizing the additive nature of RP, a wax pattern of the lattice-structured spool is created with added wall thickness to account for shrinkage. Also, a wax pattern of the desired ceramic mold geometry is created.
2. A silicone mold is formed around the ceramic mold pattern.
3. The ceramic mold pattern is removed and the spool pattern is placed inside the silicone mold.

4. A ceramic slurry is poured into the silicone mold to create the desired ceramic mold geometry.
5. Once the ceramic has set, the silicone mold is removed, the spool pattern is thermally removed from the ceramic, and the ceramic is fired in a furnace.
6. The ceramic mold is heated to the desired temperature for casting, and the metal spool is cast under pressure in a furnace using a patent-pending process developed at MSOE.

The proprietary MSOE process is used to cast extremely small geometry, such as the lattice rods which are less than 1 mm in diameter. This procedure is currently used to cast various parts in copper, and developments are currently underway to cast ferrous alloys in the near future.

1.4. casting defects

The MSOE hybrid fabrication process has been used successfully to cast a lattice-structured spool in copper using a typical constant diameter cylindrical mold. However, this part exhibits macroscopic external defects in the form of hot tears, as shown in Figure 4.

Hot tears typically occur in castings due to constraint of the molten metal during solidification [5]. In the original ceramic mold configuration, the copper in the land closest to the metal feed point solidifies before the region behind it, effectively cutting off the metal feed from the spool. Therefore, as the copper behind the first land shrinks upon solidification, a tear forms in the surface of the part.

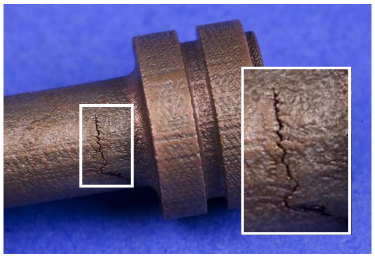

Figure 4 Hot tear in a copper spool casting.

2. Objectives

The goal of this research was to create an accurate transient finite element model of the thermal conditions experienced during the solidification phase of the MSOE casting process. The model was then to be used to optimize ceramic mold geometry in order to induce directional solidification and eliminate casting defects in a copper spool.

3. Analysis approach

To accurately model the solidification phase of the MSOE casting process, a study of heat transfer modes within the furnace was combined with finite element analysis (FEA) through MSC Software’s pre- and post-processor, Patran, and its nonlinear solver, Nastran. This research included an investigation of possible improvements to prior research, an examination of metal solidification mechanisms, and a study of accurate material properties and boundary conditions for analysis.

3.1. investigation of prior research

3.1.1. problems with previous analyses

Prior research was performed at MSOE by Matthew Ricker and Scott Kruepke in an attempt to eliminate hot tears through the use of FEA and ceramic mold alterations [6]. This research led to the design of new a new ceramic mold to induce proper solidification, but the mold thickness was insufficient to withstand firing. Each attempt at firing the ceramic yielded a cracked mold, so no actual castings were ever produced based on this design.

There were also a number of issues regarding finite element (FE) models which were not worked out completely due to time constraints on the previous research project. First, the FE models were created using simplified, axisymmetric lattice geometry and a mesh density which was not fine enough to accurately model the lattice rods. Second, all analyses were performed for the final expected spool material, AISI 4140 steel, rather than copper. Third, the results presented were interpreted by viewing both the metal casting and the ceramic mold in the post-processor, leading to less accurate temperature plots and an inability to view the solidification of the lattice rods. Finally, the optimized ceramic mold geometry was used to push any hot spots, and hence defects, into the center of the first land in the spool. This was feasible at the time because plans were made to post-machine a hole for the actuation pin. However, it is no longer possible to push defects into the center of the first land because the hole for the actuation pin has now been designed as a cast feature rather than a feature to be post-machined.

3.1.2. improvements to previous analyses

All of the problems associated with prior analyses have been accounted for in this current research. First, a proper minimum wall thickness of 5 mm was specified for all mold designs based on investigation of the cracked molds resulting from Ricker and Kruepke's research. Second, all FE models were run using the actual non-axisymmetric lattice structure necessary for the final prototype spool. Third, various iterations were run to define proper mesh parameters in the finite element models; this allowed the lattice rods to be meshed with elements small enough to yield accurate results for solidification within the lattice. Fourth, all analyses were performed using copper rather than AISI 4140 steel. This was deemed appropriate because MSOE is not yet casting ferrous alloys; hence, mold geometry created for a steel casting cannot yet be tested experimentally. Using copper, however, it will be possible to test all ceramic mold iterations with actual castings. In addition, copper is a good candidate for analysis because in general, pure copper is regarded as "difficult to cast as well as being prone to surface cracking" [7]. This issue is intensified by the small wall thicknesses of the spool, so if it is possible to eliminate defects in a copper spool through ceramic mold alterations, then it should be even more feasible for 4140 steel.

In addition to these improvements, a method for viewing only the metal casting in the Patran post-processor has been devised so that any inaccurate interpretations of temperature results can be avoided. Finally, because the new spool design includes a cast hole for the actuation pin, a gating system has been added to the casting assembly to provide a path for the exterior ceramic to attach to the interior ceramic. Therefore, all analyses for this research were run with the intention of pushing any possible defects into the gating system.

3.2. metal solidification mechanisms

Pure metals solidify over a narrow range of temperatures, while alloys (with the exception of a select few) solidify over a wide range of temperatures [8]. Pure metals also exhibit much simpler solidification than alloys, and they move directly from liquid to solid during phase transformation [9].

The copper used in the MSOE casting process is initially in powder form, and is 99 percent pure. Therefore, it was deemed appropriate that a solidification model could be created for a copper spool casting without concern for complex solidification mechanisms such as the growth of dendrites – tree-like growths typically seen in alloy castings. In addition, because this research focuses on overall heat transfer and the elimination of macroscopic defects, there was no need to be concerned with the microstructure formed during solidification.

3.3. finite element model setup

3.3.1. model slicing

Due to the complex geometry of the spool and gating system, it was not feasible to run FE models for a full 360 degree casting assembly. Attempts were made to run full 360 degree models, but with such small geometric features, it would take well over half a million finite elements to maintain a reasonable level of accuracy. With a model of this magnitude, computer hardware limitations become problematic.

Therefore, in order to run the analyses, a 72 degree longitudinal slice of each casting assembly was used. Because the lattice geometry is not axisymmetric, it was necessary to investigate various slice sizes. The 72 degree slice was chosen because it was the smallest possible slice which would still show all important features of the lattice geometry, as well as the overall spool and gating system.

3.3.2. material properties

The material properties used for all finite element models are listed in Table 1.

Table 1 Material properties used for finite element models [10, 11].

	Material Properties	**Ceramic**	**Copper**
Solid Properties	Thermal Conductivity (W/m-K)	2.94	385
	Specific Heat (J/kg-K)	950	385
	Density (kg/m^3)	3620	8960
Phase Change Properties	Reference Enthalpy (J/kg)	-	0
	Solidification Temperature Range (K)	-	1356.35 to 1356.95
	Latent Heat (J/kg)	-	-204,800

All properties for the ceramic were obtained from prior research at MSOE. These properties were generated for a general ceramic comprised of zircon and silica. It should be noted, however, that they are, in reality, only an approximation for the actual properties of the ceramic used in the MSOE casting process. Development of more accurate ceramic properties is planned for the future.

Properties for copper were obtained from the MatWeb material property database. Because the copper powder used in the MSOE process is 99 percent pure, properties for pure copper were deemed acceptable for analysis.

3.3.3. boundary conditions

The boundary conditions used for the transient analysis are shown in Figure 5. The outer ceramic surfaces were modeled to be the same temperature as the air in the furnace during cooling. Thermocouples were used to measure the air temperature in the casting furnace during the cooling stage for a copper casting over a period of 200 seconds. This data was fitted with an exponential function using MATLAB which was used to eliminate any noise in the data. This set of transient temperature data was then applied to the ceramic surfaces in the FE model. Because this method was used, convective heat transfer from the ceramic surfaces to the air in the furnace was excluded from the analysis. In addition, radiant heat transfer was considered negligible through a study of ceramic surface temperatures and furnace wall temperatures during the cooling process. Using thermocouple data for these temperatures, calculations were performed to obtain an approximate value for heat flux associated with radiation to the furnace walls. This heat flux was calculated to be only 3.4 W/cm^2, so it was deemed accurate to assume that radiation would not affect the solidification model.

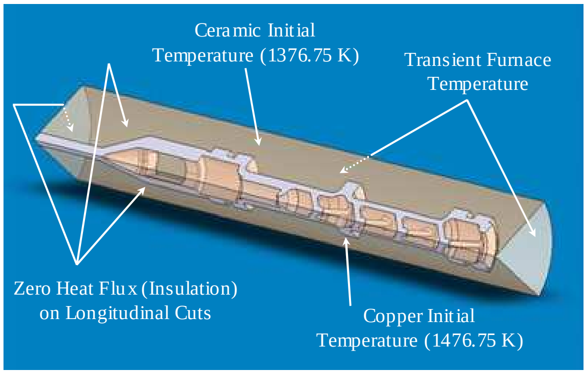

Figure 5 Boundary conditions specified for FE model.

The initial temperature of the ceramic was specified to be the same as the first datum point from the furnace cooling fit. The initial temperature of the copper was specified to be 100 K above the initial ceramic temperature, since the copper is superheated in the MSOE casting process. Finally, zero heat flux (insulation) was specified at the surfaces of the ceramic and copper which were sliced longitudinally. In addition, zero heat flux was specified at the bottom surface of the ceramic where the metal feed is located, since the actual furnace setup includes proper insulation of this surface.

4. Results and discussion

Three ceramic mold iterations were analyzed using Patran/Nastran. The transient solidification results for the copper casting were thoroughly investigated from the start of the cooling process through the entire phase change. In all three cases, the temperature distributions in the model changed with time until the first region of the spool was about to solidify. After this point, the temperature distributions remained the same during the phase change; the actual temperature in each region simply decreased. Therefore, a temperature plot shown just before solidification begins was deemed to be the most useful tool for predicting defects in the spool. All results are shown using a color scale in which the hottest portion of the casting is red, and the coldest portion of the casting is white.

4.1. original cylindrical mold

The initial transient thermal analysis was performed with a longitudinal slice of a cylindrical ceramic mold, as shown in Figure 6. This mold was based on the original geometry used for the casting exhibiting hot tears. A temperature plot of the copper within this mold is shown just before solidification in Figure 7.

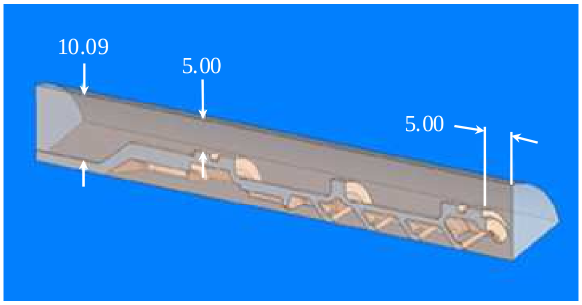

Figure 6 Longitudinal slice of cylindrical ceramic mold (dimensions in mm).

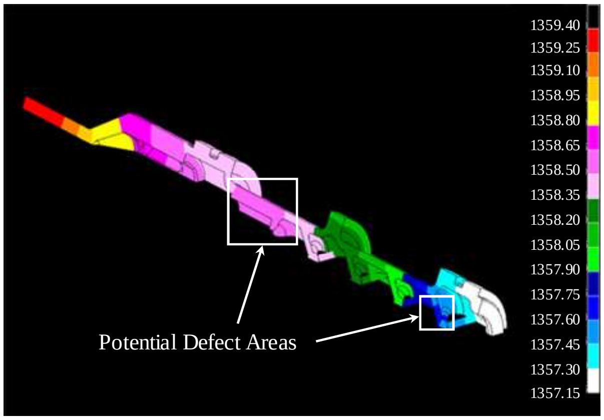

Figure 7 Temperature plot (in K) of copper just before solidification in the cylindrical mold.

There is a slight hot spot just beyond the first land of the spool, which indicates the possibility of a defect in that region because the first land will solidify first and could cut off the metal feed. However, the temperature difference between the land and the region in question is only 0.15 K. This may or may not be a large enough temperature gradient to cause a hot tear. In reality, there is no definitive data available through this research or other publications which can give a finite value to the temperature difference required to cause a hot tear. In such small geometry and in a material prone to cracks, however, it is possible that 0.15 K may be enough to produce a defect.

It is interesting to note that the results for the cylindrical mold analysis show a hot spot in the exact region in which the defect occurred in the original copper casting. In this original casting, however, the actuation pin hole was not cast into the part, so the first land was not completely hollow. This most likely would have created a larger temperature difference than the 0.15 K seen in this analysis.

In addition, the temperature plot for this mold geometry indicates another hot spot in the rods of the lattice furthest from the metal feed. Again, the hot spot in this area is only 0.15 K hotter than the surrounding regions, but it could still be considered a possible defect area.

4.2. conical mold

The second transient thermal analysis was performed with a longitudinal slice of a conical ceramic mold, as shown in Figure 8. This mold was designed to provide insulation to the copper closest to the gating system. A temperature plot of the copper casting within this mold is shown just before solidification in Figure 9.

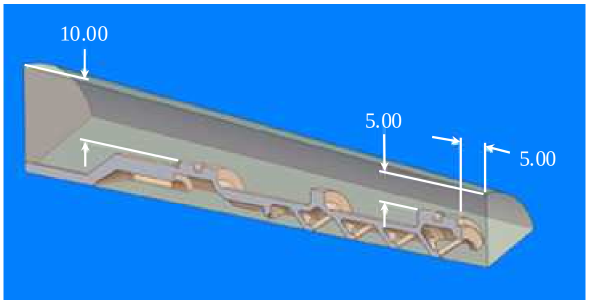

Figure 8 Longitudinal slice of conical ceramic mold (dimensions in mm).

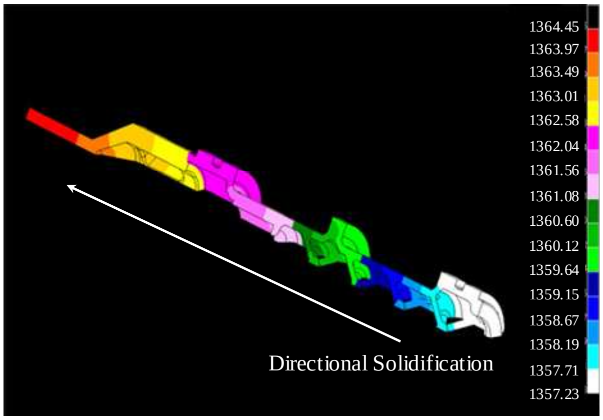

Figure 9 Temperature plot (in K) of copper just before solidification in the conical mold.

It can be seen from the temperature plot that the conical mold design has induced perfectly directional solidification toward the metal feed. These results indicate no possible defect areas within the spool. Therefore, the use of this conical mold will theoretically produce a defect-free spool, although this hypothesis must be tested in the future with an experimental casting.

4.3. reverse conical mold

The final transient thermal analysis was performed on a longitudinal slice of a reverse conical mold, as shown in Figure 10. This mold was modeled in order to deliberately induce poor solidification. The temperature distribution within the copper for this mold iteration is shown just before solidification in Figure 11.

As expected, this mold geometry causes very poor solidification in the spool. The metal feed and gating system will solidify before any other region. Hence, a hot tear will most likely form in the last part of the spool to solidify – the region just past the second land.

This final iteration of ceramic mold geometry could be quite useful to test defect predictions experimentally. By casting an actual spool using mold geometry which theoretically produces poor results, it should be possible to match the location of an actual hot tear with the location predicted from the solidification model.

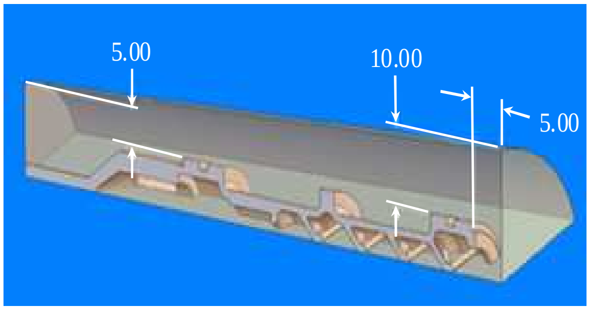

Figure 10 Longitudinal slice of reverse conical ceramic mold (dimensions in mm).

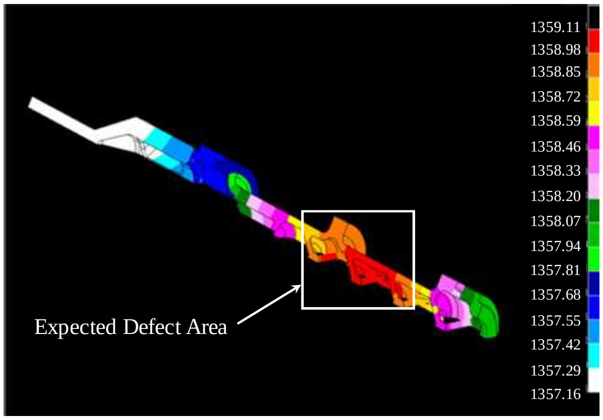

Figure 11 Temperature plot (in K) of copper just before solidification in the reverse conical mold.

5. Conclusions

This research shows that it is theoretically possible to move hot spots and, in turn, potential defect areas within a copper casting based on geometric alterations to the ceramic mold. However, the initial analysis for the cylindrical mold yielded a questionably small temperature difference in possible defect areas, so there is no definitive proof at this time that even the original mold geometry will cause a hot tear in the spool. Through experimental castings in the near future, though, it should be possible to verify the mode of defect occurrence for parts cast using all three mold iterations.

6. Recommendations for further research

While this research provides a basis for prediction of defects in copper spool castings via finite element analysis, there are a number of issues which merit further study. First, actual parts should be cast in order to prove the validity of defect predictions. Second, more reliable material properties should be formulated for the ceramic based on its powder and binder composition. Third, solidification models should be created and tested experimentally for materials other than copper; the process presented in this research can easily be altered to accommodate such analyses.

It should be noted, however, that if models are created for ferrous alloys, particularly 4140 steel, it will be necessary to investigate the effects of wide-range solidification. According to Dr. William T. Reynolds, Jr. of Virginia Tech, 4140 steel solidifies over a wide temperature range, and this range varies based on the cooling rate for a particular casting process [12].

Finally, an investigation of better solidification simulation software should be conducted. Prediction of hot tears through finite element modeling is still not a well-defined process, but current research is being conducted in various labs to establish more practical simulation tools. In particular, researchers in the Solidification Laboratory at the University of Iowa have been working toward further developments in this area [13].

7. Acknowledgements

The author would like to thank the National Science Foundation and the Rapid Prototyping Center (RPC) at MSOE for their funding and support of the Research Experience for Undergraduates (REU) program. He would also like to thank his advisor, Dr. Subha Kumpaty, for his constant support throughout the research process, Vito Gervasi and Adam McMillen for their ideas and assistance, Matt Ricker, Scott Kruepke, and MSC Software Technical Support for their aid with FE modeling, and Dr. William T. Reynolds, Jr. of Virginia Tech for sharing his knowledge of solidification. Finally, a special thanks goes to Ann Bloor and Betty Albrecht for their administration of the REU Program, and to all other REU advisors and participants for their continual support.

This material is based upon work supported by the National Science Foundation under Grant No. EEC-0139142. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author and do not necessarily reflect the views of the National Science Foundation.

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