Final Technical Report

Project Title: Energy-Saving Melting and Revert Reduction Technology (E-SMARRT): Use of Laser Engineered Net Shaping for Rapid Manufacturing of Dies with Protective Coatings and Improved Thermal Management

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List of Acronyms

LENS™ = Laser Engineered Net Shape (registered trade mark)

NADCA = North American Die Casting Association

NIU = Northern Illinois University

OSU = The Ohio State University

POM = Powder on Metal process

SME = Society of Manufacturing Engineers

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Executive Summary

In the high pressure die casting process, molten metal is introduced into a die cavity at high pressure and velocity, enabling castings of thin wall section and complex geometry to be obtained. Traditional die materials have been hot work die steels, commonly H13. Manufacture of the dies involves machining the desired geometry from monolithic blocks of annealed tool steel, heat treating to desired hardness and toughness, and final machining, grinding and polishing. The die is fabricated with internal water cooling passages created by drilling.

These materials and fabrication methods have been used for many years, however, there are limitations. Tool steels have relatively low thermal conductivity, and as a result, it takes time to remove the heat from the tool steel via the drilled internal water cooling passages. Furthermore, the low thermal conductivity generates large thermal gradients at the die cavity surfaces, which ultimately leads to thermal fatigue cracking on the surfaces of the die steel. The high die surface temperatures also promote the metallurgical bonding of the aluminum casting alloy to the surface of the die steel (soldering). In terms of process efficiency, these tooling limitations reduce the number of die castings that can be made per unit time by increasing cycle time required for cooling, and increasing downtime and cost to replace tooling which has failed either by soldering or by thermal fatigue cracking (heat checking).

The objective of this research was to evaluate the feasibility of designing, fabricating, and testing high pressure die casting tooling having properties equivalent to H13 on the surface in contact with molten casting alloy - for high temperature and high velocity molten metal erosion resistance – but with the ability to conduct heat rapidly to interior water cooling passages. A layered bimetallic tool design was selected, and the design evaluated for thermal and mechanical performance via finite element analysis. H13 was retained as the exterior layer of the tooling, while commercially pure copper was chosen for the interior structure of the tooling. The tooling was fabricated by traditional machining of the copper substrate, and H13 powder was deposited on the copper via the Laser Engineered Net Shape (LENS™) process. The H13 deposition layer was then final machined by traditional methods.

Two tooling components were designed and fabricated; a thermal fatigue test specimen, and a core for a commercial aluminum high pressure die casting tool. The bimetallic thermal fatigue specimen demonstrated promising performance during testing, and the test results were used to improve the design and LENS ™ deposition methods for subsequent manufacture of the commercial core. Results of the thermal finite element analysis for the thermal fatigue test specimen indicate that it has the ability to lose heat to the internal water cooling passages, and to external spray cooling, significantly faster than a monolithic H13 thermal fatigue sample. The commercial core is currently in the final stages of fabrication, and will be evaluated in an actual production environment at Shiloh Die casting.

In this research, the feasibility of designing and fabricating copper/H13 bimetallic die casting tooling via LENS ™ processing, for the purpose of improving die casting process efficiency, is demonstrated.

Introduction and Background

Most die casting industry tooling is machined from premium grade H-13 tool steel. While these dies generally provide excellent performance in terms of service life, they have some inherent limitations because the thermal conductivity of H13 is relatively low. The primary problems are prolonged cycle times required for cooling the die steel, soldering of the casting alloy onto the overheated die steel surfaces, and thermal fatigue cracking of the tooling.

The overall objective of this research is to demonstrate the feasibility of designing and fabricating bimetallic die casting tooling for the purpose of improved thermal management to reduce casting cycle time, reduce die spray requirements (time and volume applied), reduce the tendency of the tooling to solder, and improve thermal fatigue life. Reduced casting scrap and improved up-time will increase the overall energy efficiency of the die casting process.

Laser Engineered Net Shaping (LENS^{TM}) is a relatively new solid freeform fabrication process that is capable of rapidly producing complex geometry, dense parts directly from a CAD model without the need for molds or ancillary tooling. In addition, the process can produce parts with localized variation in composition, and can be used to apply cladding layers on substrate materials. With this unique process, it becomes possible to fabricate dies with a bimetallic structure, internal passages having complex geometry, or localized variation in composition, for improved thermal management. To this point, there has been limited work conducted on the use of LENS^{TM} for bimetallic tooling designs for high pressure die casting applications.

The approach taken in this research is summarized in the work breakdown structure shown in Table 1. The first tasks (5.9.1 through 5.9.3) were accomplished at Lehigh University in the early years of this project (2004-2005). Early in the project, the concept was to create a H13 geometry by traditional methods to act as the face of the tool in contact with molten aluminum during the casting process, and then LENS^{TM} deposit copper to back-up the face and provide for conformal cooling passages in a high thermal conductivity material.

Professor John Dupont at Lehigh University developed the methods and procedures for successfully depositing copper powder on an H13 substrate. A nickel base interlayer alloy was successfully used by Lehigh to generate LENS fabricated dual layer coatings. The layered coating was required to minimize cracking that was experienced at the copper/H13 interface. The Technical Report from Lehigh University summarizing their work is included in Appendix 1.

Subsequent to the Lehigh work, the project experienced an interruption in funding, and was restarted in September 2012. The goals of the research were reviewed and updated, and Task 5.9.4 became the first objective after the project re-start. The idea was to design and fabricate a thermal fatigue specimen of the geometry used by the die casting industry for many years to evaluate the performance of die steels. The test is conducted at Case Western University, and is commonly called the “Dunk Test”, because it consists of immersing an internally cooled tooling specimen of standard geometry in molten aluminum, and then removing it and allowing it to cool. This process is repeated in a cyclic fashion until cracks are observed forming on the surface of the test specimen.

The bimetallic thermal fatigue specimen for this project was designed to have a commercially pure copper core, with a LENS deposited H13 skin on the exterior. This approach was the opposite of that investigated by Lehigh University, and furthermore, the LENS^{TM} machine at Lehigh was indefinitely out of service when the project restarted. After an extensive search, Professor Federico Sciamarella at Northern Illinois University was contracted to do the H13 deposition on a copper substrate.

Table 1: Work Breakdown Structure of the Project

Task	Task Description
5.9.1	**Selection of commercial Ni base interlayer alloy**
5.9.2	**Fabrication of dual layer coating**
5.9.3	**Characterization of coatings**
5.9.4	**Fabrication of Thermal Fatigue Specimen**
5.9.5	**Evaluation of Thermal Fatigue Specimen**
5.9.6	**Study of Die Spray Amount and Spray Time**
5.9.7	**Fabrication of Die Insert with Bimetallic or Conformal Cooling**
5.9.8	**Demonstration of Die Insert with Bimetallic or Conformal Cooling**

Wallace (Benedyk, Moracz, and Wallace, 1970) conducted laboratory thermal fatigue studies to simulate the temperature cycles encountered in die casting dies. He developed a “dunk-test”, which was calibrated such that the temperature fluctuations in test pieces measured during testing were similar to those measured in production H-13 die casting dies. With the Wallace “dunk test model” as the base line, a computational model was used to determine optimum level of copper substrate for the fabrication of the thermal fatigue specimen. A finite element analysis was conducted to estimate the relative thickness of H13 on Cu that would maximize the thermal and cyclic thermo-mechanical (fatigue) performance of a bimetallic H13/Cu thermal fatigue test specimen. Four different geometries were studied: pure H13; 25% Cu Model; 50% Cu Model; and 75% Cu Model. Results of the finite element analysis are shown in Figure 1. A schematic of the thermal fatigue test is shown in Figure 2.

As shown in Figure 1, the maximum attained temperature decreases with increase in % copper. The maximum temperatures attained by 100% H13, 25% copper and 50% copper samples are 848°K (575°C), 813°K (540°C), and 791°K (518°C), respectively (at exterior corner of specimen).

The thermal fatigue life was estimated using the method of universal slopes (Manson, 1966) which relates the calculated cyclic strain ranges to the number of cycles to fatigue crack initiation. The following table gives the calculated cycles to failure in H13 region when subjected to dunk test. The results of the thermal fatigue predictions are shown in Table 2. A H13 deposition of 0.100” inches (50% Cu Model) was found to provide the best balance between thermal performance and fatigue life (lowest stresses and strains).

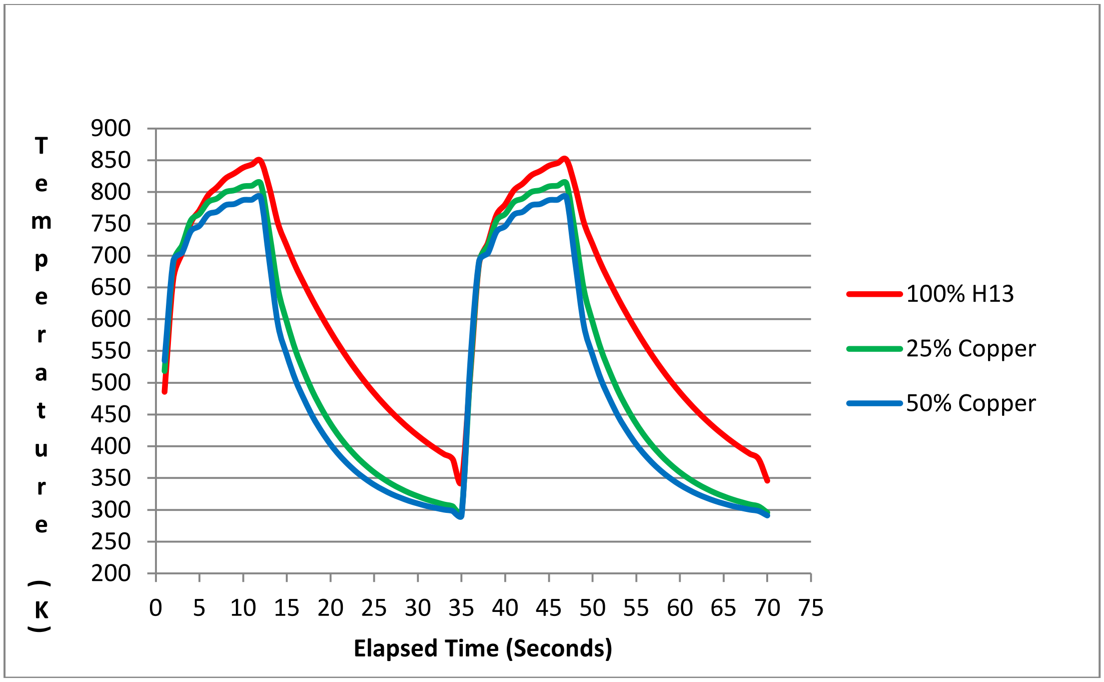

Figure 1. Thermal performance of 100% H13 versus 25% Cu versus 50% Cu, via finite element model (FEM).

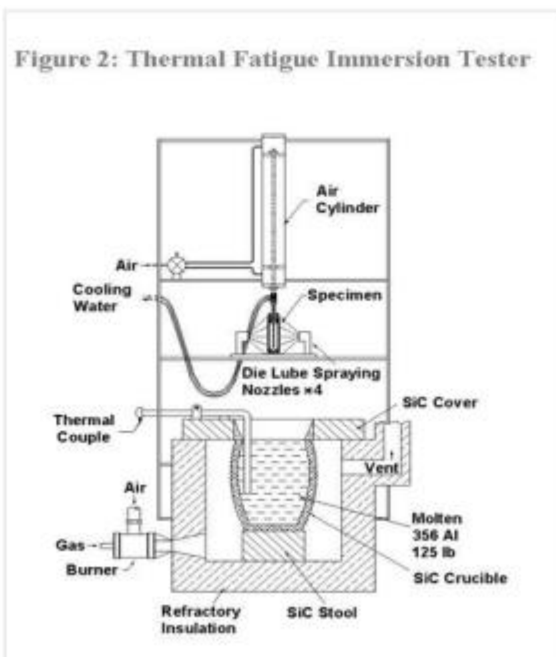

Figure 2. Schematic of "dunk test" apparatus (Case Western University website).

Table 2: Thermal Fatigue Life Estimation of 100% H13, 25%, 50% and 75% Cu

Geometry	Calculated cycles to failure (N_f) for H13 region	Calculated cycles to failure (N_f) for Copper region
pure H13	5827	-
25% Cu	6036	12696
50% Cu	8503	8680
75% Cu	31026	6284

Upon completion of the design phase for the thermal fatigue specimen, copper was then machined undersized by 0.100" per side, to accommodate the LENS™ deposition of H13. The substrate material procured was 2" square C11000 copper. The copper was cut to a length of 7", then milled to 1.825" x 1.825" and drilled in the center with a 1.5" diameter hole for the cooling channel. The copper substrate was then shipped to Northern Illinois University, where the LENS™ deposition and final machining of the H13 were performed. Figure 3 shows the University of Northern Illinois (NIU) LENS™ machine.

The H13 powder used for the LENS™ deposition was spherical Micro-Melt (-80+270M) H13 CPP was provided by Carpenter Technologies. Table 3 shows the chemical analysis of the powder in weight %. The copper substrate was mounted on a heated work table in the LENS™ fabrication chamber (Figure 3), and mounted on a slight angle. As copper is a very reflective substrate material, it can damage the laser via back reflection. This can lead to burning out the cover slide, or the laser fiber optics in the LENS™ machine. As a method to circumvent this issue the substrate was tilted by few degrees.

Table 3: Chemical Analysis of H13 Powder (weight %)

C	Si	Mn	Cr	Mo	V	P	S
0.41	0.91	0.49	5.20	1.51	1.04	0.003	0.015

A 0.15" thick layer of H13 was deposited onto the copper, then subsequently milled to the final 2" x 2" x 7" dimensions, then a pipe thread was tapped into the cooling hole. Figure 4 shows the final thermal fatigue specimen that was fabricated. The as-deposited hardness of the H13 was HRC 58.

The thermal fatigue specimen was then shipped to Professor David Schwam at Case Western University for testing, which was the primary goal of Task 5.9.5, Evaluation of Thermal Fatigue Specimen. The results of thermal fatigue testing are described in the Results and Discussion section of this report.

Figure 3. Northern Illinois University LENS™ machine (left) and heated work table with copper substrate mounted in the chamber (right).

Figure 4. Completed thermal fatigue specimen with 0.100" thick H13 on C1100 copper.

The objective of Task 5.9.6, Study of Die Spray Amount and Spray Time was to investigate the potential die casting process efficiencies, in terms of spray time/cycle time and volume of spray lubricant required, which might be possible with bimetallic Cu/H13 tooling. Starting with the finite element model developed for the design of the bimetallic thermal fatigue test specimen, enhancements to the model were made to emulate the heat transfer of external spray cooling. As shown in Figure 5, the modeling approach was to use the same thermal fatigue specimen bimetallic structures previously evaluated during the design phase, subject the specimen to the dunk test thermal cycle, and then use the model results to track the maximum temperature in the specimen as a function of time.

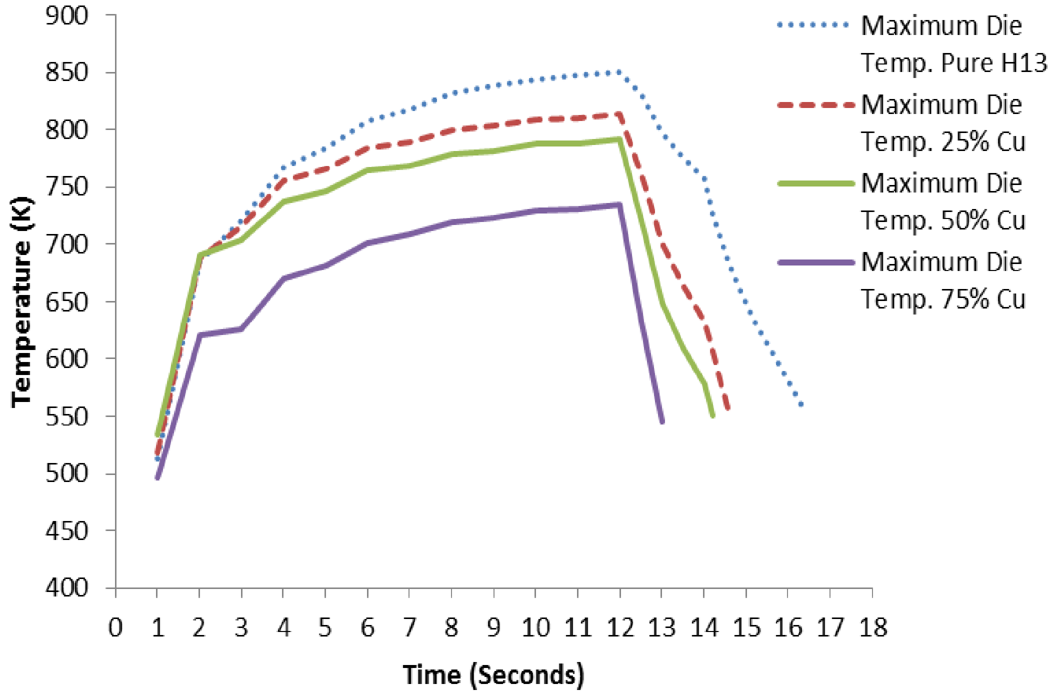

Figure 5. Finite element model of spray time required to cool thermal fatigue test specimen below typical die operating temperature (561°K) for pure H13, 25% Cu, 50% Cu, and 75% Cu (same Cu/H13 bimetallic ratios shown in Figure 1).

The results clearly show that as the relative amount of copper in the cross section of the test specimen increases, the maximum temperature decreases significantly. The 50% Cu model represents the design of the bimetallic Cu/H13 thermal fatigue specimen in this study. Also, in this evaluation, the heat flux assigned to the spray in the finite element model, and 561°K (288°C) typical die operating temperature after spray, were based on previously acquired data from spray lubricant testing at OSU.

Another method to evaluate the influence of the bimetallic structure was to evaluate the spray time, and corresponding spray volume (at a given flow rate associated with the heat flux used in the model), to reach the typical die operating temperature after spray. Table 4 shows these data from the finite element model as related to the amount of copper in the cross section of the thermal fatigue test specimen. The percentage copper in the bimetallic structure clearly has a significant influence in reducing spray time and volume. It should be noted that these percentages are definitely geometry dependent, and each bimetallic tool component would need to be evaluated individually in terms of cooling performance in comparison to an equivalent monolithic H13 tool.

Based on lessons learned from the design and fabrication of the bimetallic Cu/H13 thermal fatigue specimen, the next project objective was Task 5.9.7, Fabrication of Die Insert with Bimetallic or Conformal Cooling. The first goal of this task was to identify a high pressure die casting tool component in commercial use that was prone to early failure due to soldering, thermal fatigue, needed frequent refurbishment or replacement, or required additional cycle time or spray cooling volume to bring down to desired operating temperature each casting cycle. Steve Udvardy of NADCA identified a cylindrical core with these problems in current production at Shiloh Die Casting. Shiloh agreed to put a LENS™ fabricated bimetallic core in their production tool for evaluation. This core had also been previously studied for alternative die materials constructed using the Powder on Metal (POM) process, which made it additionally useful as a point of comparison with a bimetallic LENS™ fabricated core of the same geometry. Figure 6 is an engineering drawing of the core selected for this project.

Table 4: Spray Cooling Time and Relative Spray Volume Required For Monolithic H13, 25% Cu, and 50% Cu Thermal Fatigue Test Specimens

Thermal Fatigue Test Specimen	Lubricant Spray time in seconds for maximum die temperature to drop below 561 K	Percentage reduction in spray time and lubricant volume as compared to monolithic H13
Monolithic H13	2.4	-
25% Copper	0.6	75%
50% Copper	0.2	91.6%

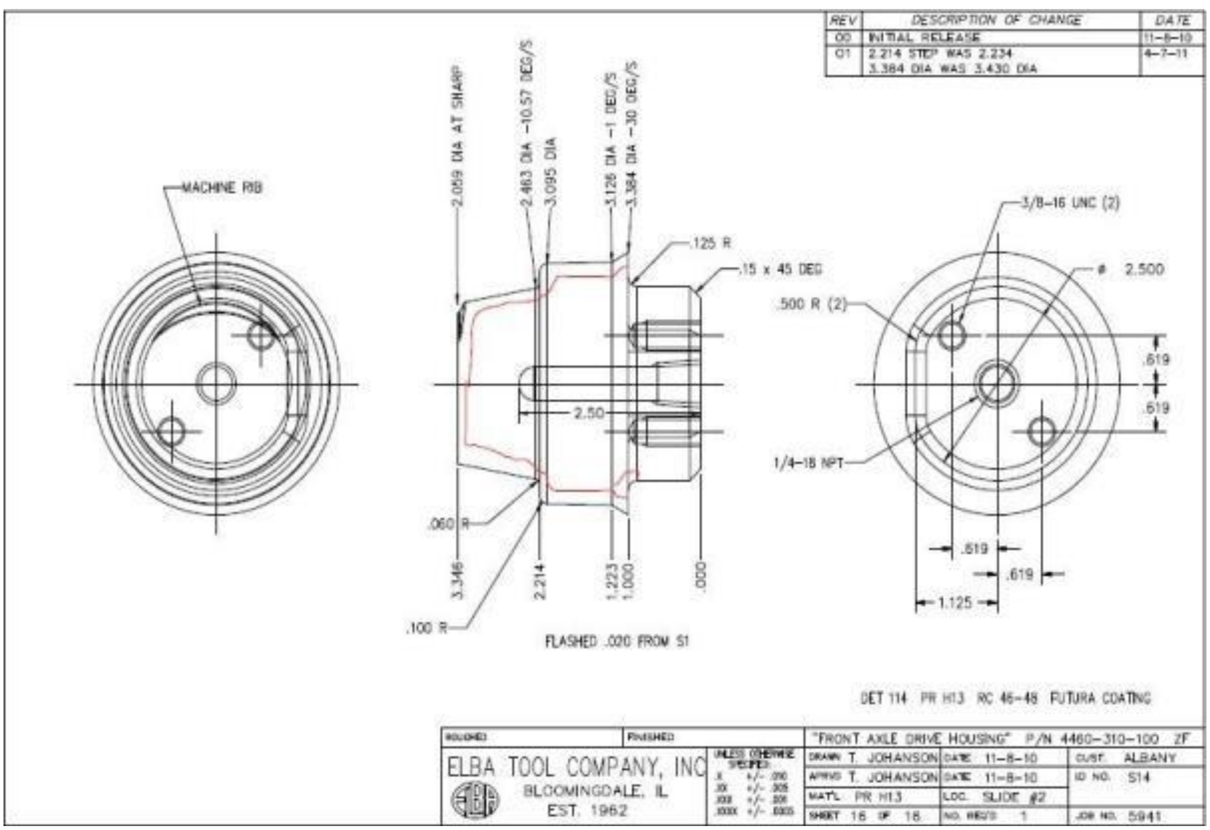

Figure 6. Shiloh core drawing as provided by NADCA. The red hand-drawn line represents the 0.100 inch cladding of H13 on the copper core.

The raw C1100 copper stock was ordered and drop shipped to Dave Rawlings at Mo-Tech, who machined the geometry undersized 0.100 inches to accommodate the LENS^{TM} deposition of the H13. The machined copper was shipped to Federico Sciamarella at Northern Illinois University (NIU) for LENS^{TM} deposition, and then back to Mo-Tech for final machining.

Results and Discussion

The results of the thermal fatigue test at Case Western University were that after the bimetallic specimen had accumulated 2,890 cycles, cracks were noticed on the surfaces of the specimen. The test was stopped, because it was not known how deep the cracks were, and there was the potential of the internal water in the specimen leaking out through the cracks to interact with the molten aluminum to cause a safety hazard. Figure 7 shows the actual dunk test apparatus at Case Western University, and Figure 8 shows the dimensions of their standard thermal fatigue specimen.

Figure 7. Thermal fatigue apparatus used to evaluate the performance of the bimetallic test specimen at Case Western University (Case Western University Website).

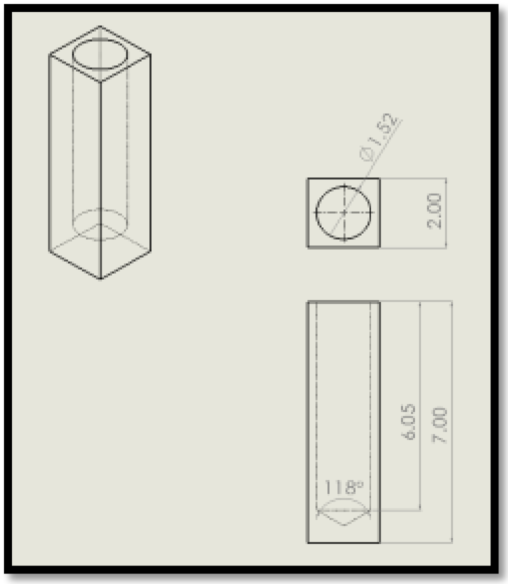

Figure 8. Standard thermal fatigue test specimen geometry (dimensions are inches).

During the LENS™ deposition at NIU, they used a reference system for the four sides of the bimetallic specimen, and the cracks are shown in Figure 9 according to this system. The cracks were observed between 1 to 2 inches from the bottom of the specimen, and were perpendicular to the length of the specimen. It was noted that the cracks are located close to the bottom of the internal cooling channel. Side 3 does not show any signs of cracking, whereas side 1 has the largest cracks. The cracks on side 1 appear to have initiated on the corners of side 1, and propagated to sides 2 and 4. According to the predictions based on the finite element model, the bimetallic specimen should have endured approximately 8000 cycles before failure. However, since the cracks were formed in less than 3000 cycles, an investigation was conducted to determine the causes for the premature cracking.

Figure 9 illustrates examples of the typical crack patterns that develop in H13 during the thermal fatigue test. These cracks are small and numerous, and initiate at all four corners of the specimen. The cracks that developed in the bimetallic specimen were very few, and propagated out onto just three faces of the specimen, on sides 1, 2, and 4. The first evaluation conducted was checking the hardness of the H13 cladding. The Rockwell C hardness, based on 30 readings taken along length of H13 on specimen exterior was 50±2 HRC. This level of hardness is reasonable based on the amount of accumulated time it had spent being tempered immersed in molten aluminum (the as-deposited hardness was 58 HRC).

Subsequent to the cracking of the specimen during the thermal fatigue test, NIU provided additional input about some issues that developed during the deposition of the specimen. Figure 11 is a schematic of the LENS™ process showing the powder being fed through the laser focal point, being melted and deposited in a linear fashion on a substrate material. One of the problems with copper is that it is highly reflective to the laser beam, and reflected light can damage components of the laser optics of the machine. This happened during the deposition process of the thermal fatigue specimen on side 1, and melted the NIU LENS™ machine focusing lens. This resulted in poor fusion between the copper and the H13.

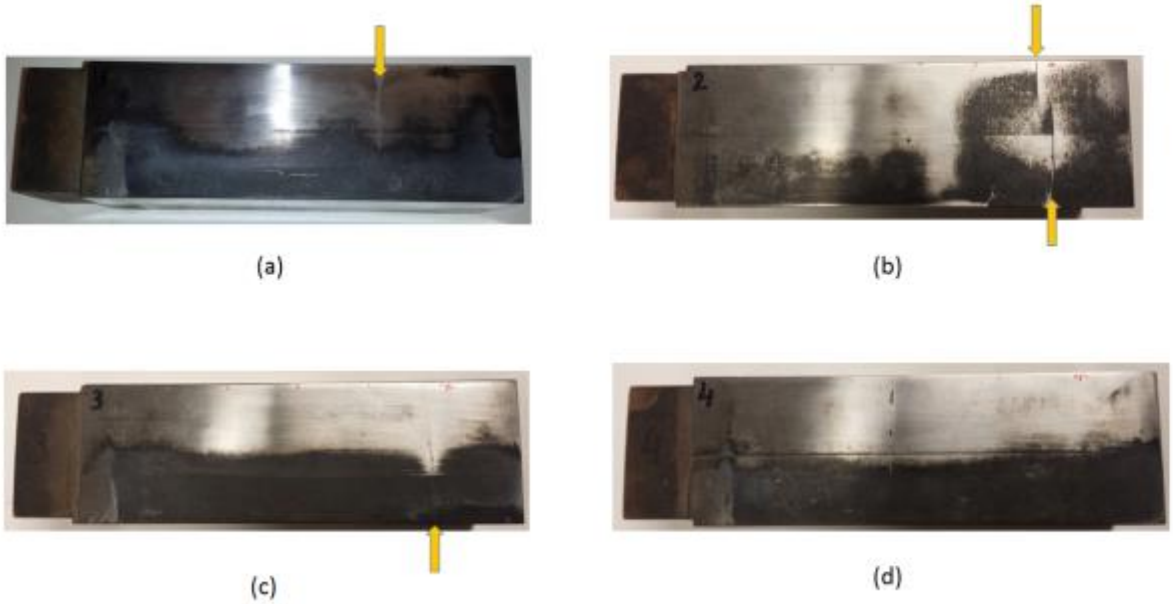

Figure 9. Bimetallic thermal fatigue test specimen subsequent to testing, showing cracks that developed: (a) NIU Side 4, (b) NIU Side 1, (c) NIU Side 2, (d) NIU Side 3.

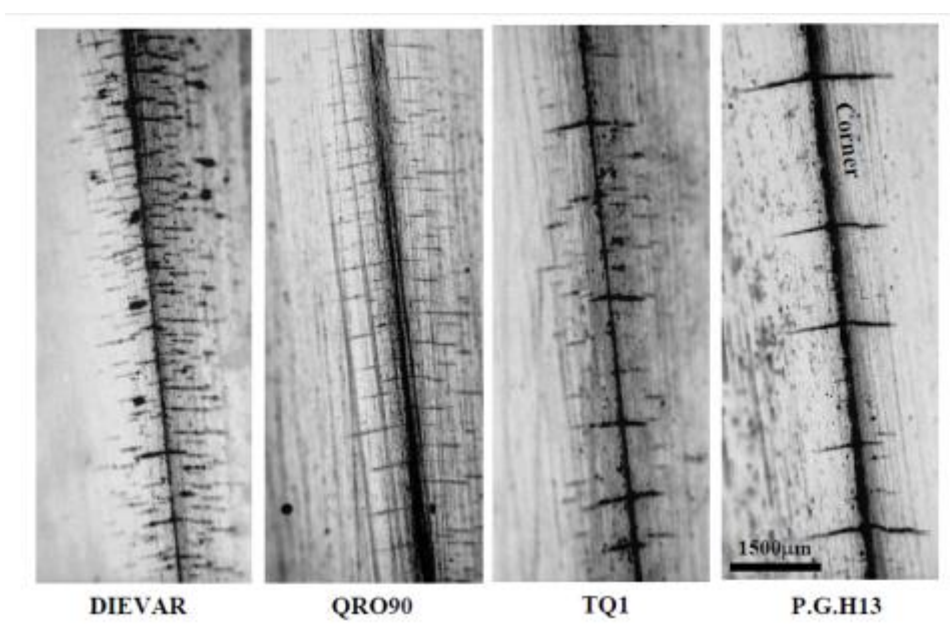

Figure 10. Typical thermal fatigue test corner cracking on various commercial monolithic H13 tool steel specimens.

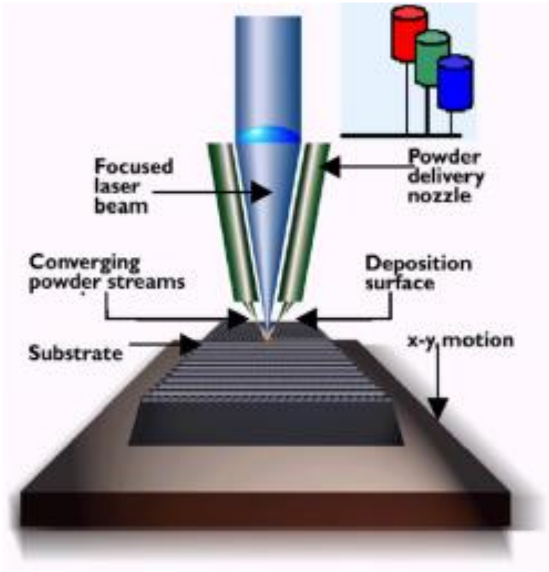

Figure 11. Wald, Nicholas R., and Robert P. Mudge. "Laser Engineered Net Shaping Advances Additive Manufacturing and Repair." (*Http://www.rpmandassociates.com*. N.p., n.d. Web. 06 June 2013).

The crack locations on side 1 correspond well with the general location of where there was a major issue with the initial deposit (Figure 12). This side had initially zero fusion between the copper block and the deposited steel creating a cavern between the steel and copper. This trouble area was machined off down to the base copper and H13 was re-deposited onto the trouble area (Figure 14). Although this area was "fixed", NIU suggested that there could be a difference between the repaired area and those immediately adjacent (with sides 2 and 4).

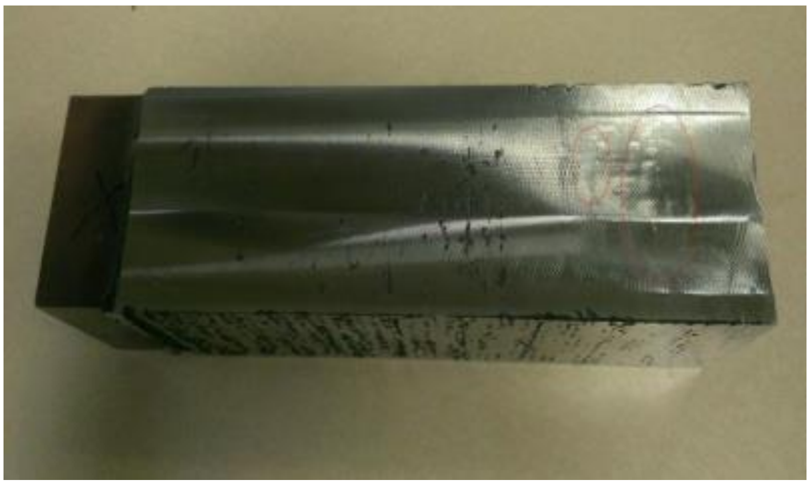

Figure 12. Circled in red are the cracks formed during deposition from the focusing lens melting.

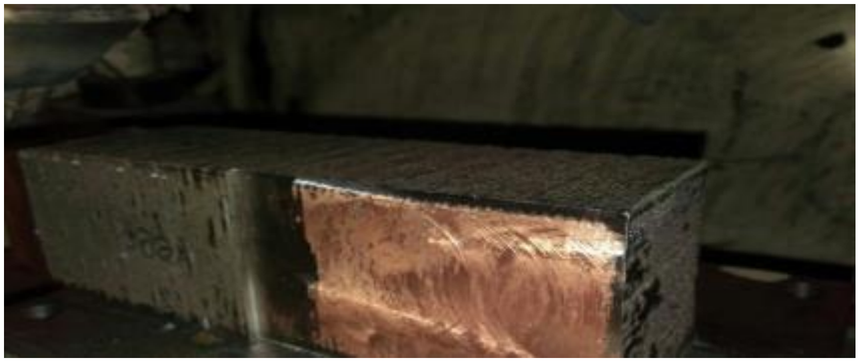

Figure 13. Cracked region machined back down to copper for re-deposition.

In addition, NIU reported that there was an unexpected depth of penetration into the copper substrate for layer 2 of the deposition on all sides. The first layer had extremely low depth of penetration, but the second layer and beyond had extremely deep penetration due to the laser having an much better absorptivity in to the deposited steel, translating in to a melt pool deep in to the copper below. This created a saw toothed pattern in the cross section as seen in Figure 14. This may have led to an unusually high transitional layer between the two materials on top of stress concentrations during thermal cycling. NIU suggested that they would be using lower laser power on layers 2+ to avoid this saw toothed pattern in the future.

Figure 14. "Sawtooth" pattern formed on second layer of H13 deposition.

Also, NIU indicated that the hotplate shown in Figure 3 also had limitations. The dimensions of the hot plate were not sufficient to hold the entire copper thermal fatigue sample substrate. The closed end of the specimen was over-hanging the hot plate, and created a lack of preheat in this portion of the copper. This may have reduced the laser absorption in the 1064 nm range of the YAG laser towards the end of the block.

Based on the information provided by NIU, the thermal fatigue specimen was sectioned on the diagonal of the corner of side 1 and side 4 via wire EDM at OSU. Figure 15 shows the specimen with the corner removed, and the cut surfaces exposed. A close-in view of the cut surface on the main specimen (Figure 16) shows that the H13 did not adhere to the copper substrate on side 1 – the same side that was repaired due to lack of fusion during the build at NIU. There is a clear sawtooth pattern of penetration into the copper that is visible on the end of the specimen, and on side 4. This sawtooth pattern can also be seen in Figure 16, which is a closer view of the corresponding cut corner section. However, there is not a sawtooth pattern visible on side 1, but rather a visible gap exists between the copper substrate and the H13 cladding. It is also clear from both Figures 15 and 16 that the cracks in the H13 cladding did not penetrate into the copper substrate.

Figure 15. Thermal fatigue specimen with the sides 1-4 corner removed via wire EDM.

The large surface cracks that developed prematurely during the thermal fatigue testing were clearly the result of problems that occurred during LENS™ deposition at NIU. The outside corners of the thermal fatigue specimen that normally develop small thermal fatigue cracks had not yet shown any cracking at 2,890 cycles. Had the gross cracks on the surface faces not developed (due to deposition problems), it is very possible that the thermal fatigue specimen would have survived thousands of more cycles before corner cracks developed in the anticipated manner.

Additionally, small cracks were observed in the copper substrate (Figure 17, white arrow) just at the base of the sawtooth pattern on the closed corner of the specimen, and along the bottom surface, and vertical surface of side 4 of the specimen. The cause of these cracks was suspected to be the complex 3-dimensional strains induced by the Case Western thermal fatigue cycling test. However, the 2-dimensional finite element model created previously was not sufficient to evaluate these corner stresses and strains. Therefore, a 3D finite element model was created in ANSYS to better simulate the actual conditions in the cracked copper areas during the thermal fatigue test cycling.

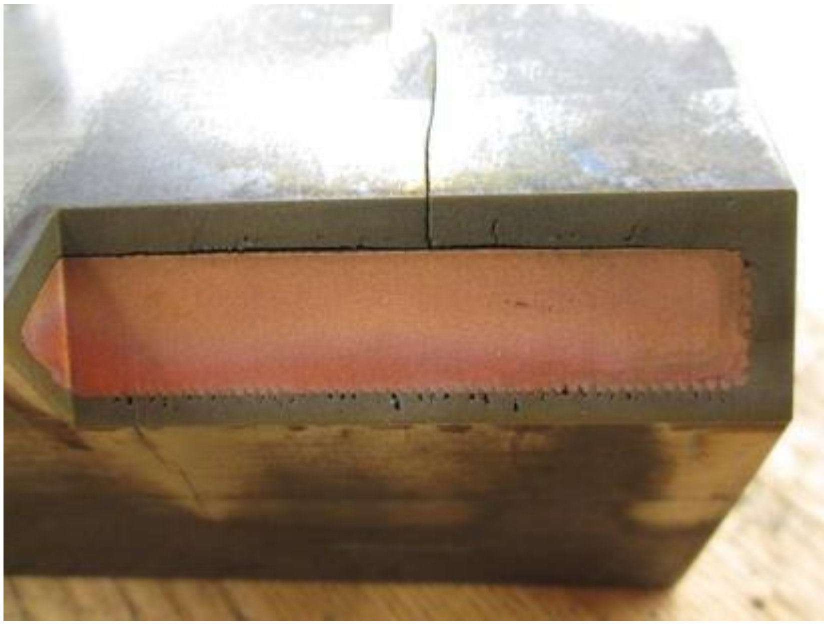

Figure 16. Close-in view of the cut surface on the main specimen. Side 1 is the top horizontal surface in the photo, and side 4 is the vertical surface.

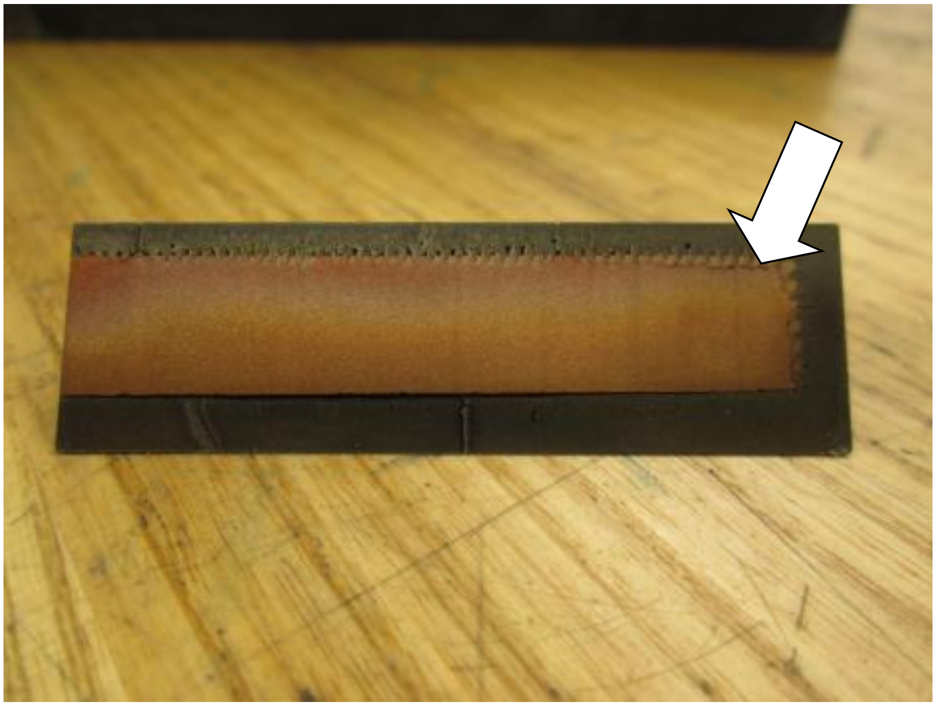

Figure 17. Close-in view of the cut corner surface. Side 1 is the H13 clad surface under the copper in the photo, and side 4 is on the top of the copper (sawtooth pattern visible).

As in the case of the previous 2D finite element simulations, steady state in the 3D model was achieved from the second thermal fatigue cycle onward. The maximum stress (von-Mises) observed at the end of t_1 for the second cycle, was 923Mpa in the corner region at the Cu- H13 interface. Therefore, the 3D model verified that the small internal longitudinal cracks observed in the copper initiated in the highest stress regions of the thermal fatigue sample; at the hot (molten aluminum) end of the sample, near the corners, at the Cu- H13 interface.

Lessons learned from the fabrication and testing of the Case Western thermal fatigue specimen were applied to the design and fabrication of the commercial core for the Shiloh die casing tool. To accommodate for H13 LENS^{TM} deposition, the core geometry was machined 0.100" undersized in C1100 copper by Mo-Tech. The machined core was then shipped to NIU for H13 LENS^{TM} deposition. Figure 18 shows the copper substrate machined, and on the heated table in the LENS^{TM} machine.

Figure 18. Machined copper substrate for Shiloh commercial core on the heated table in the LENS^{TM} machine at NIU.

Being a circular geometry with a taper, the commercial core posed much greater technological challenges for the LENS^{TM} deposition at NIU, in comparison with the rectangular Case Western thermal fatigue specimen geometry. Since LENS^{TM} deposition is a "line–of-sight" process, the copper core had to be further machined to allow the deposition of H13 on all surfaced to be accomplished. Also, fixtures had to be designed and constructed to hold and rotate the core on the heated table in the LENS^{TM} machine. The deposition was accomplished, but several problem areas developed, specifically, at the transition from the cylindrical diameter of the core and the flat top. Figure 19 shows the as-deposited core after it was received at Mo-Tech for machining of the H13 to final dimensions. Several pockets or cavities are visible near the top of the core. Figure 20 shows these areas after rough machining at Mo-Tech. The core will require additional

LENS^{TM} deposition at NIU, and then final machining to size at Mo-Tech before it is ready for testing at Shiloh in their commercial die casting process. This activity will continue, and the performance of the bi-metal core evaluated. However, this project is ended, and so those results cannot be reported at this time.

Figure 19. Commercial core subsequent to LENS^{TM} deposition with H13.

Figure 20. Commercial core subsequent to LENS^{TM} deposition with H13 and rough machining at Mo-Tech.

Benefits Assessment

Potential energy savings from this research could be realized due to more efficient manufacturing processes in the fabrication of tooling components for die casting, and also from greater efficiency of the die casting process where bi-metallic tooling is employed. The copper in the Cu/H13 bi-metallic tooling requires less energy to machine than does monolithic H13. Furthermore, the LENS^{TM} deposited H13 does not require the same heat treatment as monolithic H13 tooling components (hardening to martensite, and then triple tempering). This H13 heat treatment is a very energy-intensive process.

Considering the die casting process, this research has shown that the Cu/H13 bi-metallic tooling removes heat from the casting more quickly than does monolithic H13. This can increase the number of castings produced per unit time (reduced cycle time). Furthermore, the increased cooling efficiency of the Cu/H13 bi-metallic tooling reduces the amount of external spray lubricant application. This reduces the environmental emissions (aerosol and water) generated by the die casting process.

Therefore, it is anticipated that commercial implementation of LENS^{TM} fabricated Cu/H13 bi-metallic tooling technology would reduce overall energy consumption, along with its affiliated greenhouse gas emissions, and also reduce other aerosol emissions and effluent water quality from die casting operations.

Commercialization

Although this research demonstrated the its potential, additional technological development is required for commercialization of the LENS^{TM} fabricated Cu/H13 bi-metallic tooling. Specifically, the technology of depositing H13 on copper substrates via the LENS^{TM} process is not sufficiently robust to support commercialization. The evidence of this is shown in Figures 13, 15, 16 and 19.

The fundamental barrier is that copper and iron (H13 tool steel) are metals having very different physical and mechanical properties, and very limited metallurgical affinity for one-another. Locally melting, mixing, and solidifying these metals together to create a bi-metallic structure is difficult, and is not always successful. If bonding is successful, high stresses result, and local cracking is observed.

Two approaches to these fundamental issues were investigated in this research. The approach of John Dupont at Lehigh was to include an intermediate layer of nickel between the copper and H13. Nickel has good metallurgical affinity for both copper and iron (H13), and this approach was demonstrated to eliminate bonding and cracking problems during LENS^{TM} deposition for Cu/H13 bi-metallic structures. However, the drawbacks to this approach are that nickel is expensive, and that the extra nickel layer represents significant additional time for fabrication via LENS^{TM} deposition.

The approach taken by Federico Sciammarella at NIU, was to raise the temperature of the copper substrate during LENS^{TM} deposition of H13 via a heated work table. The concept is that the elevated temperature facilitates diffusion between the copper and iron to create a better bonding region (eliminating the need for a nickel layer between the copper and iron), and decreases the cooling rate of the melt pool (smaller delta in temperature leads to lower cooling rates) leading to a lesser chance to generate cracks.

Further development of these two approaches to LENS™ fabricated Cu/H13 bi-metallic tooling is necessary to enable commercialization of this technology.

Accomplishments

Specific project accomplishments include the development and evaluation of two approaches to the fabrication of bi-metallic Cu/H13 die casting tooling via the LENS™ process. These processes were developed at Lehigh University and Northern Illinois University. Computer modeling via finite element analysis was used to aid in the design of the bi-metallic Cu/H13 die casting tooling, and to evaluate and establish the thermal fatigue life and cooling proficiency benefits of bi-metallic tooling in the die casting process. In addition, a bi-metallic Cu/H13 thermal fatigue specimen was fabricated and evaluated via the Case Western University die casting industry standard accelerated thermal fatigue (dunk) test. Subsequent to the testing, the thermal fatigue specimen was evaluated to identify reasons for the development of cracks. Finally, a core having propensity for early failure by overheating, soldering and thermal fatigue was fabricated for commercial testing in a NADCA corporate member's die casting facility.

Project accomplishments were communicated, and technology transfer occurred via meetings with the die casting technical community at NADCA, a graduate student thesis based on the project work, and presentations/publications including:

1. Presentations and discussions of project progress and accomplishments took place in June, 2013 and February, 2014 at NADCA Research and Development Committee and Die Materials Committee meetings.
2. Jain, A., Design and LENS® Fabrication of Bi-metallic Cu-H13 Tooling for Die Casting, Master of Science Thesis, Industrial and Systems Engineering, The Ohio State University, 2013.
3. Brevick, J., Jain, A., "Investigation of Cu/H13 Bimetallic Tooling for Die Casting", abstract submitted for presentation/publication at the 2014 NADCA Casting Congress, September, 2014.
4. Sciammarella, F.M., Gonser, M., Styrcula, M., "Laser Additive Manufacturing of Copper", SME RAPID conference on Additive Manufacturing, June 9-12, 2014.

Conclusions

The processes for LENS™ fabricated Cu/H13 bi-metallic tooling developed at Lehigh University and Northern Illinois University represent creative and novel approaches to a difficult technical problem. Both show promise, but further development of these two approaches is necessary to enable commercialization of this technology.

Recommendations

The logical follow-on to this research project would be to investigate the viability of using the heated substrate method employed by NIU, along with the nickel interfacial layer demonstrated by Lehigh University for LENS™ fabricated Cu/H13 bi-metallic die casting tooling. Tooling fabricated successfully by this method should be evaluated for its longevity in service and cooling proficiency in a commercial die casting demonstration.

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Appendix

The Use of Laser Engineered Net Shaping for Rapid Manufacturing of Dies with Improved Thermal Management

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July 6, 2007

Abstract:

Nickel-based alloys Inconel 625 and Monel 400 were deposited by the laser engineered net shaping (LENS) process between H13 tool steel and pure copper. A nickel-based interlayer material was employed to (1) prevent the occurrence of solidification cracking when copper is deposited onto steel and (2) to minimize thermal stresses that develop at joints between dissimilar metals that have very different thermal expansion properties. Light optical microscopy techniques were used to observe the solidification cracking behavior of the deposits and microhardness measurements were used to characterize mechanical behavior of the deposits.

This work determined that Monel 400 contained a copper content too high to prevent solidification cracking and was not considered further for testing. Inconel 625 showed a much lower occurrence of solidification cracking. It was observed that as little as one layer of Inconel 625 could be used to prevent solidification cracking. In addition, microhardness measurements across several deposited layers revealed that the deposition of Inconel 625 onto H13 tool steel causes a layer of martensite to form in the heat affected zone of the tool steel substrate. Additionally, it was observed that several layers of copper are required for pure copper to be deposited, as observed in the decreasing microhardness values within subsequently deposited copper layers.

Since Inconel 625 is commercially available and does not introduce solidification cracks, it is a viable material to use as an interlayer between H13 tool steel and copper for producing casting dies that contain copper cooling channels.

Introduction:

Die casting is a widely used process for large production quantities of a particular part, usually used in casting light / low melting point metals. Tool steels, such as H13, are typically used as a die material since they have sufficient hardness, but unfortunately also have rather low thermal conductivities which do not allow a die-cast part to cool quickly. Copper, on the other hand, has a comparatively larger thermal conductivity than H13. The interest in bringing these two materials together in die fabrication arises from the potential decrease in cycle time during production if the castings can cool faster, i.e. allowing for less time between subsequent pours. In order to introduce complex shaped copper cooling channels in tool steel dies, the Laser Engineered Net Shaping (LENS) process is attractive since it can build components by an additive process that creates parts according to a computer-aided design drawing. This is accomplished by injecting metal powders into a laser-induced molten weld pool, causing the injected powders to melt, subsequently solidify, and become incorporated into the material it was deposited upon. The expectation is that the copper cooling channels will be built directly into the steel without the need to drill holes into dies and insert copper pieces, which does not allow for complex or conformal cooling channel designs.

The objective of this research is to identify candidate Ni base alloys, which are commercially available, as potential inter-layers between tool steel and copper coatings. Selection of candidate alloys will be based on their known resistance to thermal fatigue and metallurgical compatibility with both the tool steel substrate and copper coating. Information from preliminary research sponsored by the National Science Foundation (NSF) on direct deposition of copper onto steel was leveraged in this work.

Solidification Cracking:

Unfortunately, weld deposits of copper onto steel are very prone to solidification cracking. Previous work [1, 2] was conducted to assess the cause of solidification cracking in copper deposits on H13 tool steel. It was observed that solidification cracking occurred within a fusion zone composition range of 5.4 to 43.3 wt% Cu. On the other hand, compositions greater than 51.5 and less than 4.7 wt% Cu were observed to be crack-free. The underlying mechanism for solidification cracking in the Fe (H13) - Cu system was observed to be a function of the temperature range over which solidification occurs. Larger solidification temperature ranges were found to promote solidification cracking due to excessive amounts of terminal liquid between solidified dendrites. Terminal liquid does not have the strength to withstand shrinkage stresses and strains that are imposed on the deposit zone during cooling. In addition, pure nickel was deposited onto H13 tool steel whereupon copper was deposited using gas tungsten arc welding (GTAW), see Figure 1. Fusion zone compositions up to 75 wt% Ni exhibited solidification cracking, whereas binary Fe-Ni and Ni-Cu weld deposits did not. The fact that binary Fe-Ni and Ni-Cu weld deposits did not exhibit solidification cracking shows promise for the use of nickel or nickel-based alloys as an interlayer material. However, the composition of the nickel layer must be nickel-rich after dilution of the base metal to overcome solidification cracking as observed in the multilayer weld deposits. Figure 2 shows the solidification cracking results for the multilayer weld deposits, where green triangles indicate compositions that were crack-free and red squares indicate compositions that produced cracks.

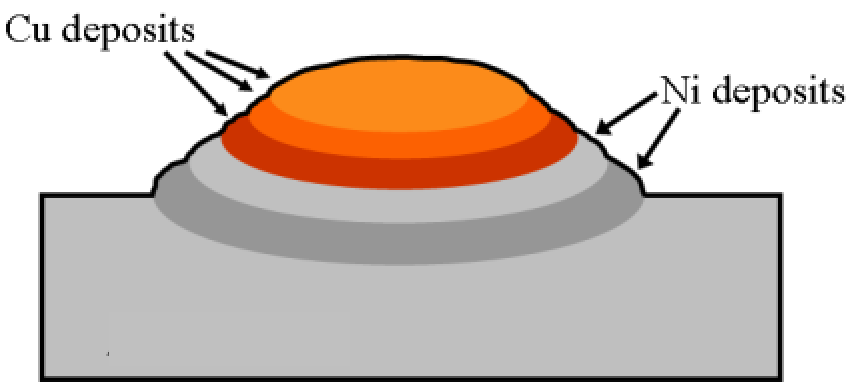


Figure 1: Schematic representation of multi-layer steel-Ni-Cu GTAW deposits [2].

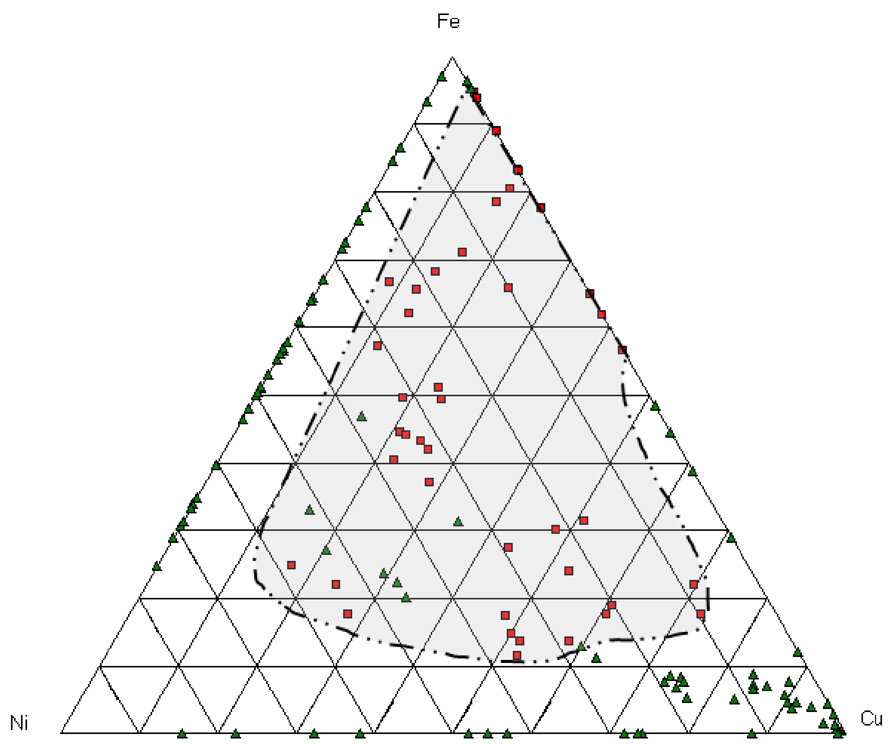


Figure 2: Solidification Cracking Results. Squares and triangles represent cracked and crack free compositions respectively. Dotted line defines crack susceptible composition range [2].

From the results of the previous work, it is apparent that the use of an interlayer material requires a high nickel content of the material upon which the copper will be deposited. To achieve this goal, several layers of interlayer material may need to be deposited due to dilution by the base metal. Determining this is one of the primary goals of this work.

Ni-Interlayer Selection:

Expanding upon the previous work, nickel-based alloy selection for eliminating solidification cracks and optimizing overall performance of the multilayer setup is the main objective. To start, several candidate alloys were chosen and are listed with corresponding compositions in Table 1.

Table 1: Several candidate nickel based alloys with selected compositions of elements

Material	Ni (wt%)	Fe (wt%)	Cr (wt%)	Cu (wt%)	Mn (wt%)	Mo (wt%)	Nb + Ta (wt%)
Ni 200	99.0 min	-	-	-	-	-	-
Monel 400	63.0 min	2.5 max	-	28.0-34.0	2.0 max	-	-
IN 600	72.0 min	6.0 -10.0	14.0-17.0	0.5 max	1.0 max	-	-
IN 625	58.0 min	5.0 max	20.0-23.0	-	0.5 max	8.0-10.0	3.2-4.2

From the list of alloys, several material properties were identified that will affect the performance of the material as an interlayer component of a complex part, such as a casting die. Factors under consideration include thermal stresses and thermal conductivity. Managing thermal stresses in a dissimilar material multilayer component is important because stress would be generated during thermal cycling as a result of thermal expansion and modulus of elasticity mismatch between the different materials. The thermal conductivity of the interlayer material is important to the current application since the objective of using copper is to increase the rate of heat extraction from the H13 tool steel used in dies for casting. Here, an alloy with a higher thermal conductivity than H13 would be preferred so that the use of a nickel interlayer will not effectively insulate the copper from the H13.

The thermal expansion coefficients of steel and copper are very different and could lead to large thermal stresses in the copper and steel layers. In the case of multi-layer (dissimilar) materials, the mismatch of the coefficient of thermal expansion (CTE) and the modulus of elasticity (E) between two materials are the major contributors to thermal stresses in high temperature applications [3,4], even for an unrestrained component.

Figure 3 shows the respective moduli of elasticity for H13 tool steel, the candidate nickel-based alloys, and copper as they vary with temperature. The modulus of elasticity and the coefficient of thermal expansion are the two most influential variables in thermal stress of layered components. However, the elastic moduli for the Ni-based alloys fall in a close range of values and should not play a large role in the calculation of thermal stresses for the comparison of different interlayer materials. The only possible exception to that being Monel 400.

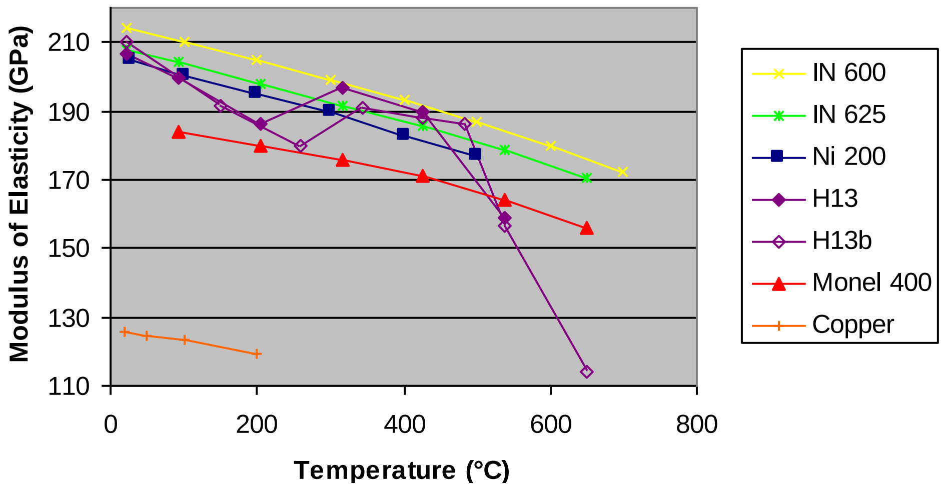


Figure 3: Variation in the modulus of elasticity of several materials

The CTE is shown for several alloys as it varies with temperature in Figure 4. Alloys 200 and 600 have nearly identical CTE behavior with changes in temperature. Their CTE behaviors, however, lie slightly closer to the CTE behavior of H13 rather than half way in between copper and H13. The CTE behavior of Alloy 625 lies even closer to that of H13 than 200 and 600, and this may be due to the lower Ni content and addition of 10 wt% Mo. Alloy 400 has a CTE almost exactly between that of copper and H13.

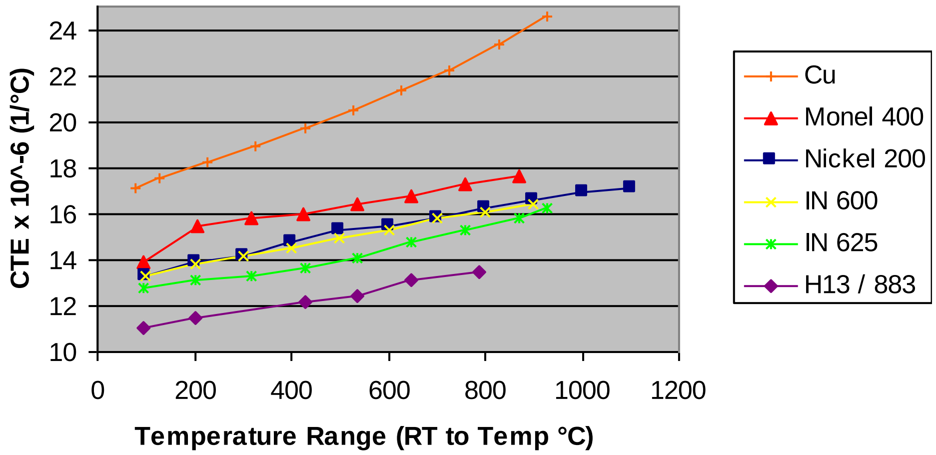
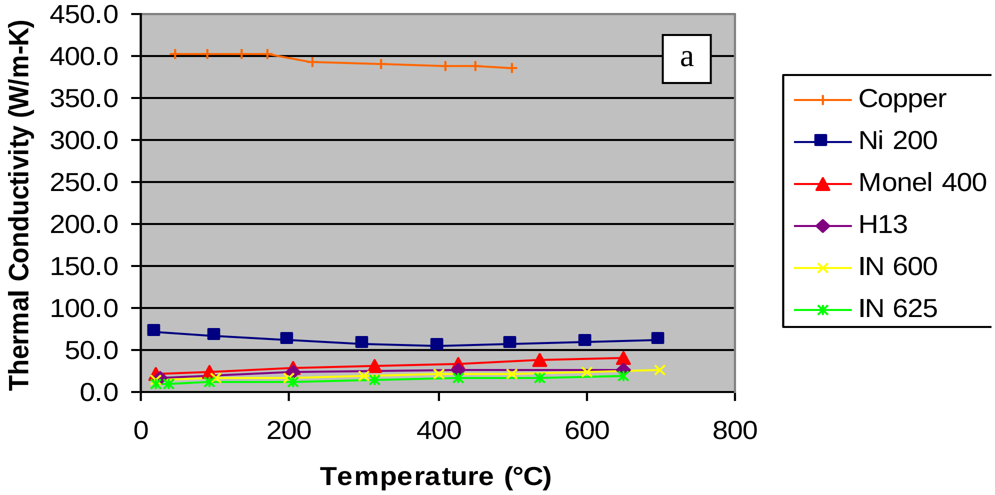


Figure 4: CTE data for various materials

As mentioned earlier, the thermal conductivity of the various materials is also a major factor in selecting a nickel-based material. Figure 5 shows the variation in the thermal conductivity of several materials with temperature. From this perspective, Ni 200 is the only nickel based alloy that can be said to have a slight advantage over the others, which all have similar values. Based on these considerations, alloys 400 and 625 were selected for experimental work. Alloy 400 was selected because of its potential advantages in terms of modulus and thermal expansion match to copper and H13, while Alloy 625 was selected due its well known resistance to thermal fatigue and use as a material in dissimilar weld applications.



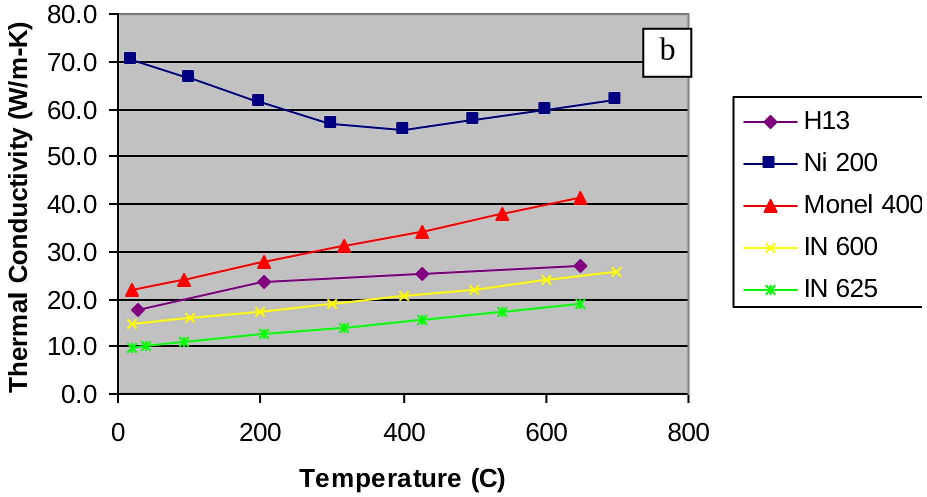


Figure 5: Variation in thermal conductivity with temperature, (a) for all materials and (b) for all materials except copper to show changes clearly

Experimental Procedure:

Using a Nd:YAG laser, with a measured power rating of approximately 350W, various metal powders were deposited onto wrought H13 tool steel. Layers, approximately 0.25mm x 12.7mm x 12.7mm, were produced by rastering the laser induced weld pool on the sample while spraying powders into the molten pool. Layers were deposited on top of one another as needed. Samples with one, three, or five layers of a nickel-based alloy, either IN 625 or Monel 400, were produced on top of the H13 substrate. Layers of pure copper were deposited on top of the nickel-based alloy layer(s) as needed, ranging from 0 – 11 layers. After six to eight layers of copper were deposited, the weld pool started to decrease in size due to a low absorptivity of the laser wavelength (1064nm) in copper.

Microstructural characterization was performed by employing standard metallographic sample preparation procedures, followed by electrolytic etching in equal parts of sulfuric acid, phosphoric acid, and water for 3s at 3V, and observed using light optical microscopy (LOM). Microhardness testing was conducted using Vickers scale to observe the hardness values within each layer of the sample.

Results and Discussion:

Layered Deposits:

Figure 6 shows increasing magnification views of a layer of pure copper that was laser deposited onto H13 tool steel. The most important feature is the presence of cracks in the microstructure. This result confirms previous results [1] that solidification cracking occurs in copper / steel dissimilar metal welds.

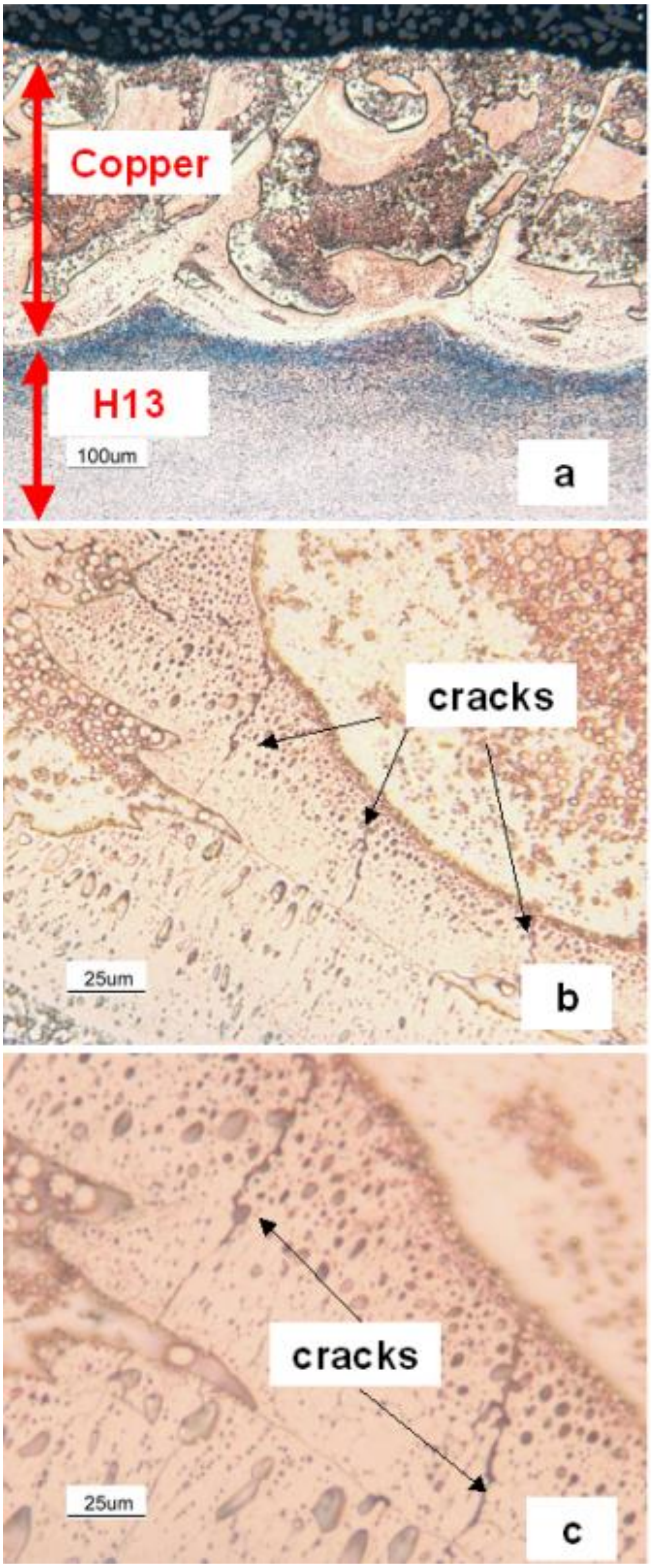
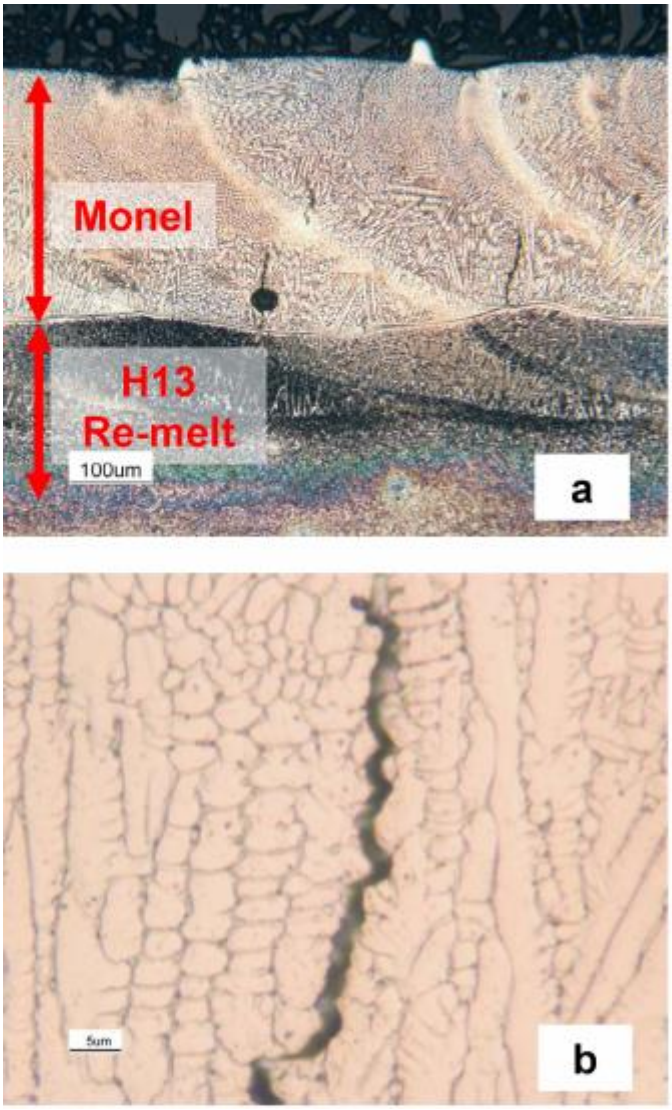


Figure 6: (a) Low, (b) medium, and (c) higher magnification views of a layer of pure copper that was laser deposited onto H13 tool steel.

Figure 7 shows increasing magnification views of one layer of Monel 400, a Nickel – 30wt% Copper alloy, which was laser deposited onto H13 tool steel. Solidification cracks using this alloy were abundant in all samples and it was not considered further for use as an interlayer material. It is expected that the large copper content in Monel 400 is the cause for the solidification cracking.



5μm

Figure 7: (a) Low magnification image of one laser deposited layer of Monel 400 onto H13 tool steel substrate, exhibiting solidification cracks, shown at higher magnification (b).

As a result of dilution during welding, the first and subsequent layers of IN 625 will contain Fe from the H13 tool steel substrate. To confirm that IN 625 is suitable as a substrate for depositing copper, a wrought IN 625 bar was used to avoid the issue of dilution. Figures 8a and 8b show that solidification cracks do not form when one or two layers of pure copper, respectively, are deposited onto "pure" alloy 625.

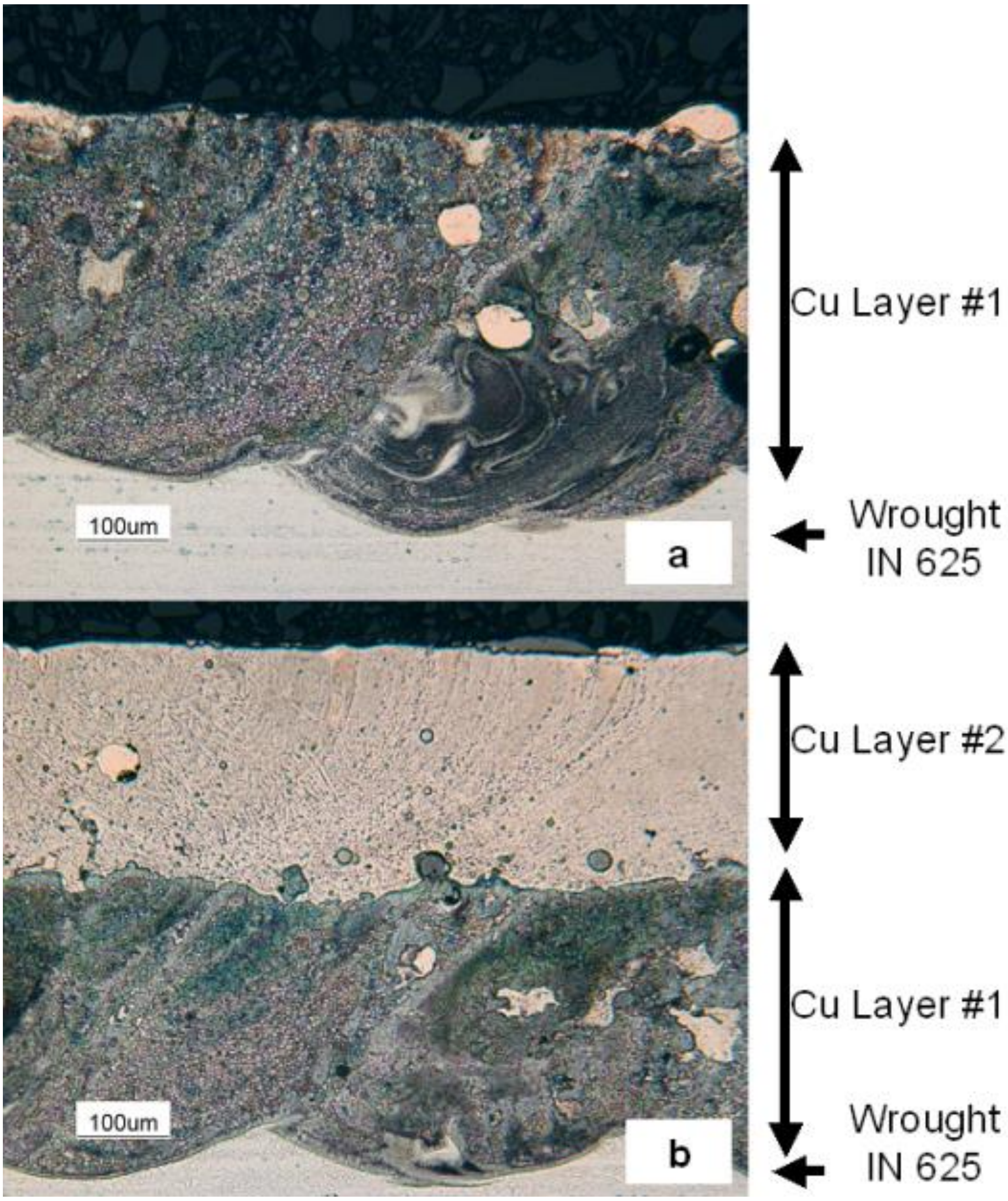


Figure 8: (a) One and (b) two layers of laser deposited copper onto a wrought Inconel 625 substrate, exhibiting no solidification cracks.

The samples shown in Figures 9-11 were produced to observe the effect of the number of layers of alloy 625 on reducing the iron content (through dilution) such that deposition of copper could occur without solidification cracking. Figure 9a shows the reduction in solidification cracking when one layer of Inconel 625 was deposited onto H13 tool steel as opposed to Monel 400. This is expected from the lack of copper in IN 625. Figure 9b shows the lack of solidification cracking when one layer of pure copper was deposited onto one layer of alloy 625. Very few solidification cracks were observed. This may indicate that dilution of the H13 base metal was very low in these samples and would therefore imply that very little Fe was present in the 625 layer when the copper was deposited. Figure 10 contains an H13 tool steel substrate, three layers of alloy 625, and one layer of pure copper. Very few solidification cracks were observed. Figure 11 contains an H13 tool steel substrate, five layers of alloy 625, and one layer of pure copper. Very few solidification cracks were observed.

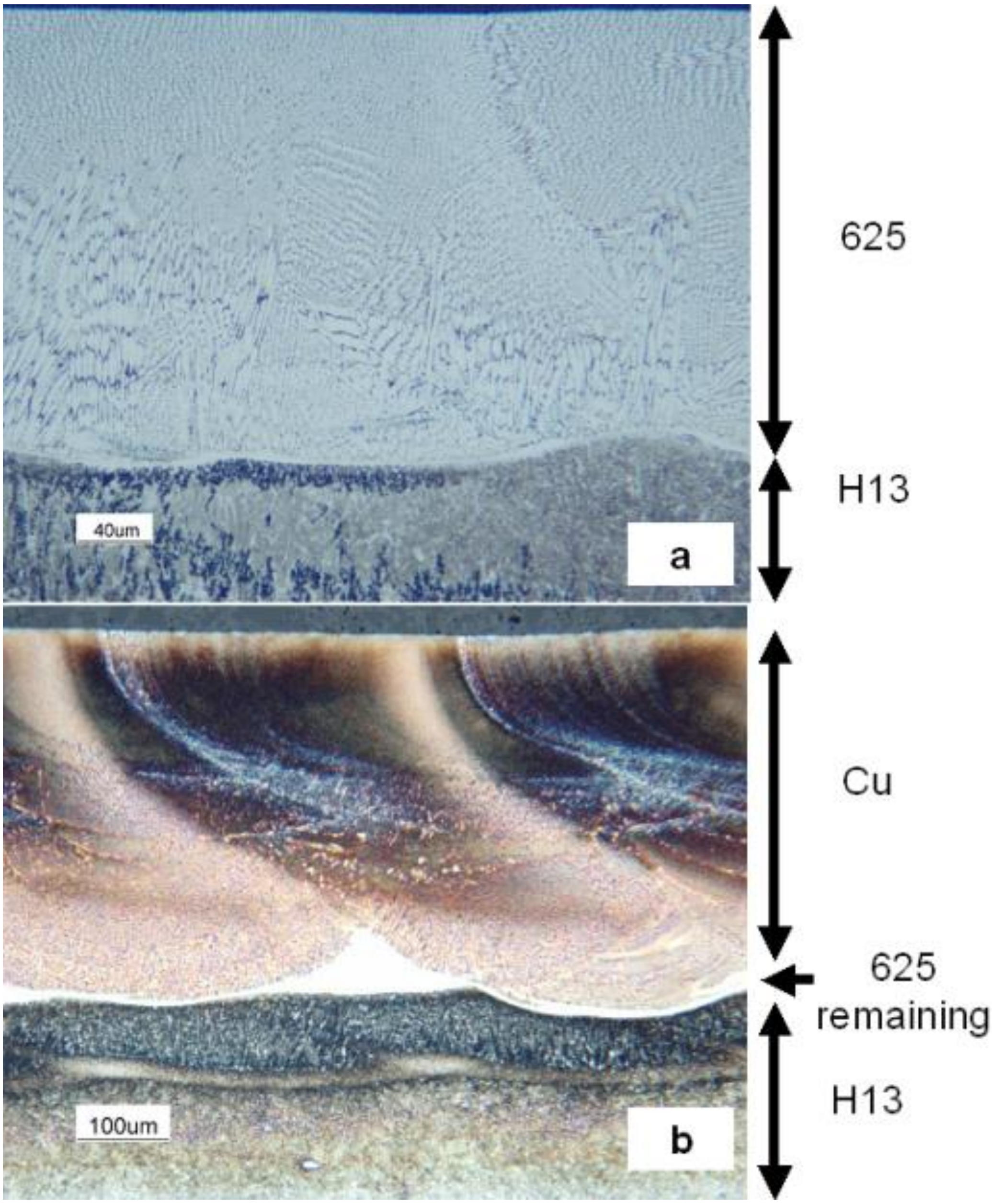


Figure 9: (a) One layer of Inconel 625 on H13 substrate and (b) one layer of laser deposited copper on one layer of Inconel 625 on H13 substrate, exhibiting no solidification cracks in the micrograph.

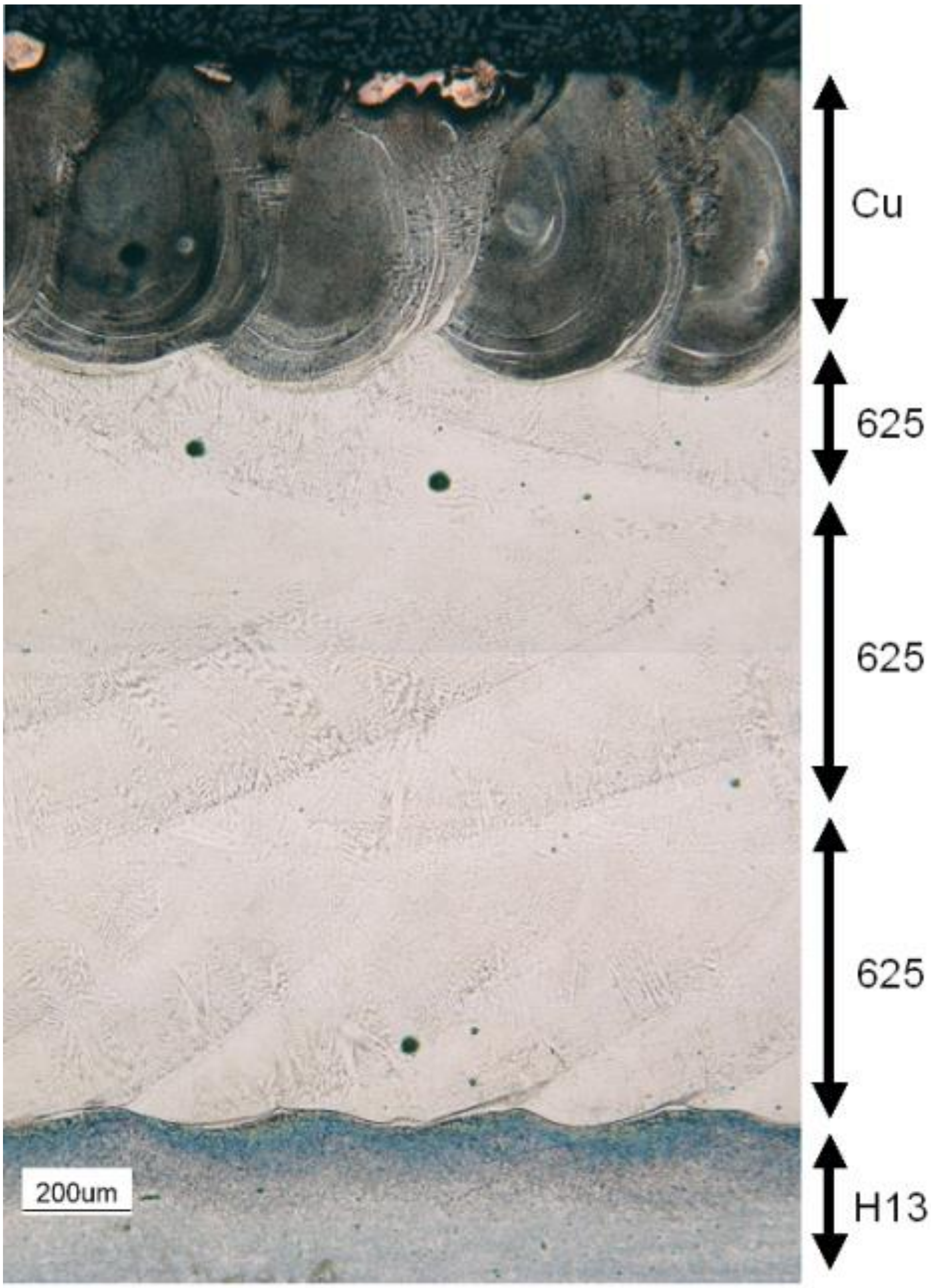


Figure 10: One layer of laser deposited copper on three layers of Inconel 625 on H13 substrate, exhibiting no solidification cracks in the micrograph.

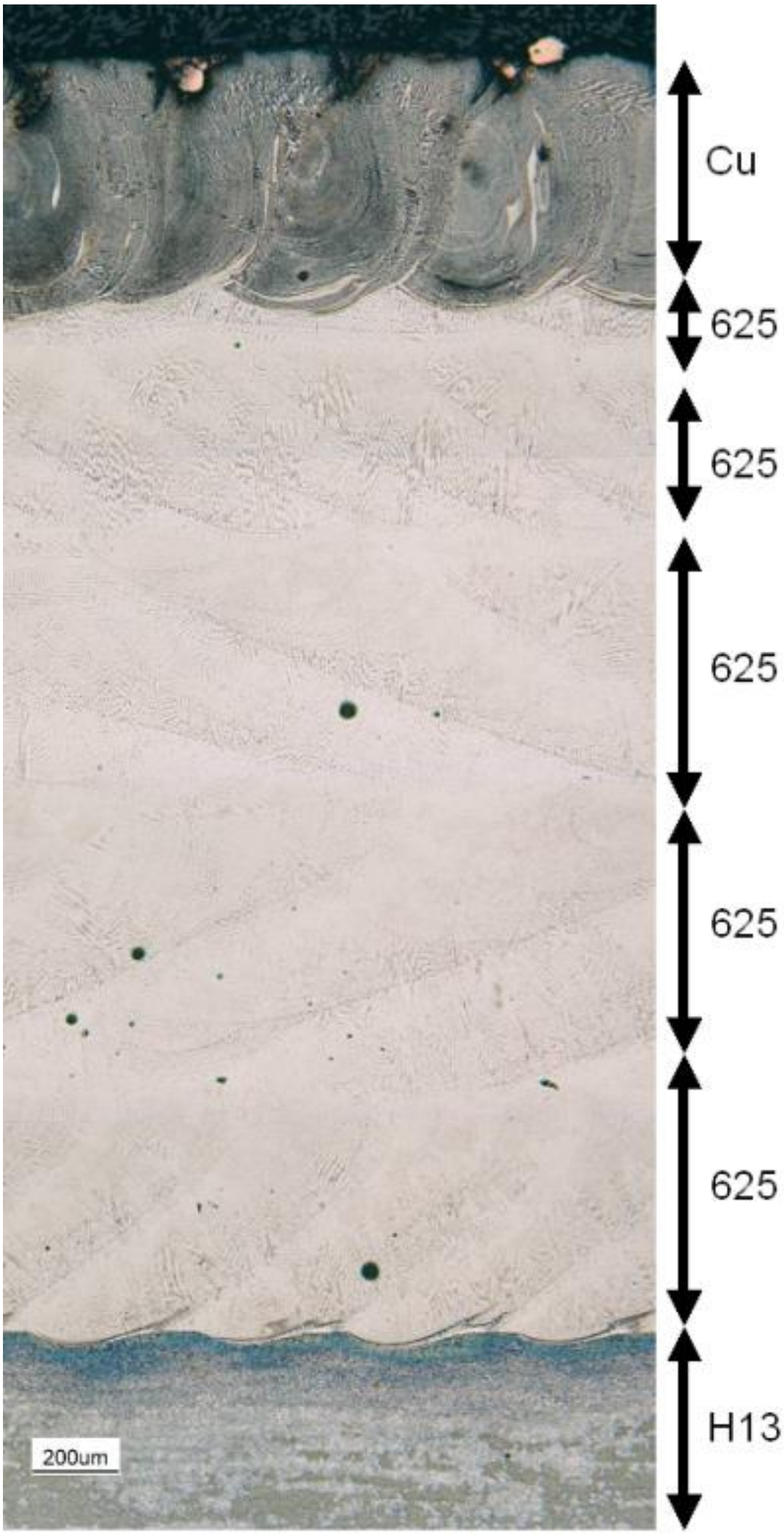


Figure 11: One layer of laser deposited copper on five layers of Inconel 625 on H13 substrate, exhibiting no solidification cracks in the micrograph.

Microhardness:

Figure 12 shows a trace of microhardness measurements that were taken across several layers of a sample that contained H13 tool steel substrate material, three laser deposited layers of Inconel 625, and two layers of laser deposited pure copper, as shown from left to right on the figure. The H13 exhibits increasing hardness as the interface with the first layer of IN 625 is approached. This increase in hardness is due to a layer of martensite that forms as a result of a steep concentration gradient in the partially mixed zone, leading to an increased M_S temperature leading up to the fusion line [5]. The hardness values of the three layers of IN 625 are fairly constant. This may be an indication that dilution of the H13 substrate by the first layer of IN 625 that was deposited was low. The same argument may hold for the subsequent layers of IN 625. This does not appear to hold for the first copper layer, since the hardness of the first copper layer was approximately that of the IN 625 layers. This would indicate that dilution of the last IN 625 layer by the first copper layer had occurred. The subsequent layer of copper must have had a moderate amount of dilution as the hardness decreased. This would be expected as was seen in a separate sample that had many copper layers deposited. For this sample, copper was continually laser deposited with the same process parameters until the laser would no longer melt the base material as a result of copper's inability to absorb the wavelength of the laser (Nd:YAG = 1064 nm). Several microhardness measurements were taken from the upper portion of the many-layered copper specimen, in an effort to measure the hardness of deposited copper that was pure. The average hardness values were approximately 72 HV, which is lower than the copper layers in the sample in Figure 12. This indicates that two layers of copper are insufficient to reach a pure copper composition.

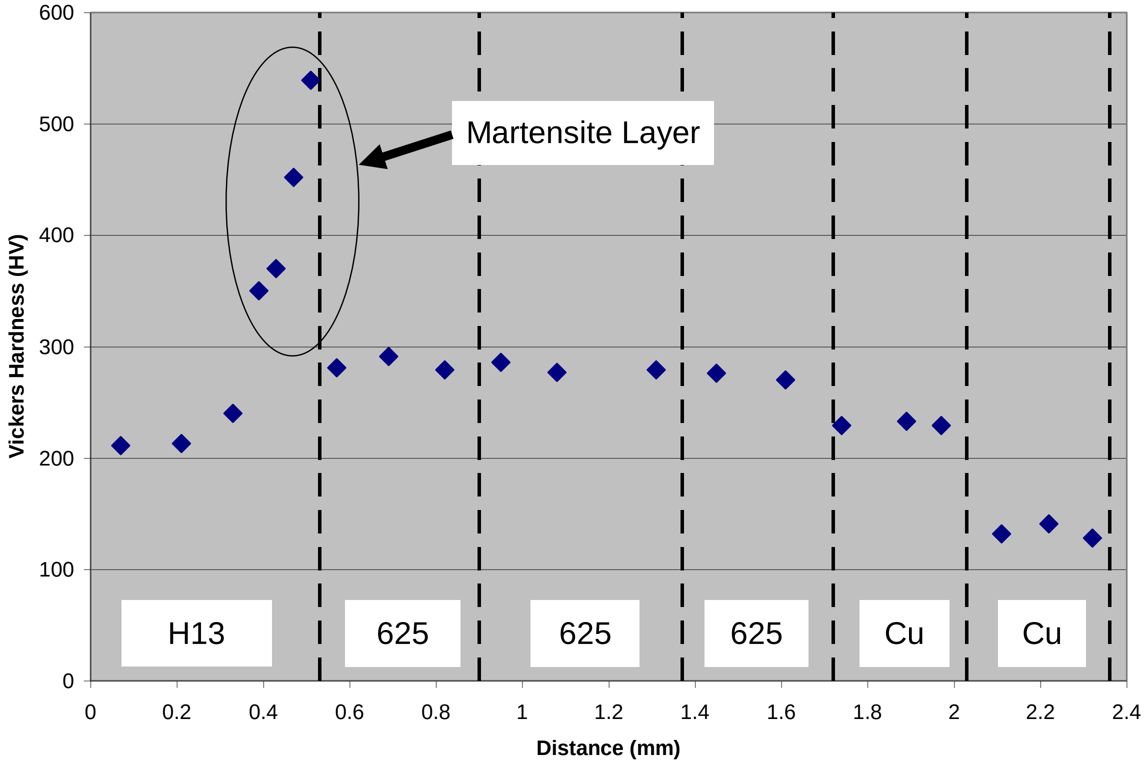


Figure 12: Results of a microhardness trace on a multi-layer LENS deposited sample, containing a H13 tool steel substrate, three deposited layers of Inconel alloy 625, and two deposited layers of pure copper.

Summary and Recommendations:

In the case of a die, solidification cracks can compromise the mechanical integrity of the part. Therefore, a nickel-based interlayer material is sought after that: (1) is soluble in both copper and H13 tool steel in order to circumvent the solidification cracking issue, (2) can provide an intermediate coefficient of thermal expansion and modulus of elasticity between that of copper and tool steel to minimize the thermally induced stresses between the different materials, and (3) has a thermal conductivity greater than that of H13 tool steel so the interlayer does not effectively insulated the copper from the tool steel.

This work identified that Monel 400 contained a copper content that was too high to prevent solidification cracking when depositing onto H13 tool steel. Inconel 625, on the other hand, showed a much lower occurrence of solidification cracking. In addition, copper was successfully deposited onto Inconel 625 with similarly few observed solidification cracks.

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