Dissimilar Metal Bonding Using Molten Metal Jetting (MMJ)

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Abstract

Molten Metal Jetting (MMJ) is an economical method for producing components from a variety of metal alloys. This technology also enables the addition of metal alloy features to existing parts made from both similar and dissimilar materials. In this presentation, we will show the workflow that we have developed to evaluate and optimize the bonding between these metal materials. One major development of this workflow is the establishment of an efficient measurement system that can be used to evaluate the bonding quality between dissimilar materials. Utilizing this workflow, we have also demonstrated good bonding between several pairs of dissimilar metals. Although there is no universal parameter set (recipe) or guarantee for any metal pairs, the prospect of good bonding between dissimilar metals is very encouraging.

Introduction

There are many applications with parts made from different materials because of different functional requirements. Furthermore, even within a single part, there is a desire to use different materials to satisfy challenging situations where a single material cannot meet all the performance metrics. Creating a part with multiple materials[1] has become not only a possibility with 3D printing, but also a huge opportunity for hybrid approaches with subtractive and multiple additive manufacturing methods. Coming along with multiple materials, there is a natural need to address the bonding between these distinctly different materials or the materials manufactured with different technologies.

Multi-material printing can implement a single 3D technology, for example FDM. The compatibility between different materials is usually not very difficult. Hybrid additive printing can potentially cover a much broader range of materials and the bonding between different materials could be very challenging. For example, in a hybrid system consisting of laser DED and MMJ (Molten Metal Jetting), laser DED can be used for titanium, while MMJ is used to print aluminum.

Some 3D printing technologies (such as laser DED, MMJ and etc.) can build on pre-fabricated base structures. These base structures can be created with traditional subtractive machine tools or other manufacturing methods, and the materials selections are even broader. If these base structures are broken parts, the application turns into part repairing, another great opportunity for these 3D technologies.

MMJ (molten Metal Jetting) is an emerging metal 3D printing technology[2]. It converts solid feedstock into molten form and ejects small droplets of molten metal. These molten droplets are deposited and solidified to form a 3D part. Due to the liquid nature of the molten metal droplet, it spreads and wets the surface of the base structure upon impact and intimate contact is formed immediately at the interface. These instant spreading and wetting characteristics make MMJ one of the top candidates for applications associated with multi-material bonding. In addition, MMJ offers high resolution (~250um droplet) for precision delivery, large standoff distance (~20mm) for complicated prefabricated structures or parts repair, small thermal pulse (small amount of heat carried by a droplet) for printing on thermal sensitive substrates.

MMJ has demonstrated its capability to print on a wide range of base materials with a number of molten metal/alloy compositions. 1) MMJ onto similar metals (examples: Al alloys on Al alloys); 2) MMJ onto dissimilar metals (examples: Al alloys on Ti, stainless steel and etc.); 3) MMJ onto non-metals/ceramics (examples: Copper/Aluminum on glass); 4) MMJ onto plastics (example: aluminum on Kapton[3]); 5) MMJ onto composite materials (examples: copper or aluminum onto 3D printed fiber glass surfaces).

Bonding between two materials is usually very specific to the nature of the two materials and how they interact with each other. Many unique pair-wise situations can arise, and they are beyond the scope of this presentation. This paper will focus on the general considerations for bonding between two dissimilar metals/alloys, with one of them being printed with MMJ technology.

Bonding Recipe Development Workflow

Figure 1 illustrates the general workflow of the development of the process setpoints for an optimal bonding between two dissimilar metals. Starting with a customer's application, the functional requirements will determine the selection of the pair of metals/alloys. If one of them is suitable for MMJ, we proceed to the optimization-evaluation cycle, where many parameters and parameter combinations are going to be tested, and the bonding performances are going to be evaluated. When an optimal or satisfactory result is achieved, a final set of setpoints (recipe) is recorded.

Without loss of generality, we use MMJ to print one metal/alloy onto a flat blank sheet stock of a second metal/alloy for bonding investigation.

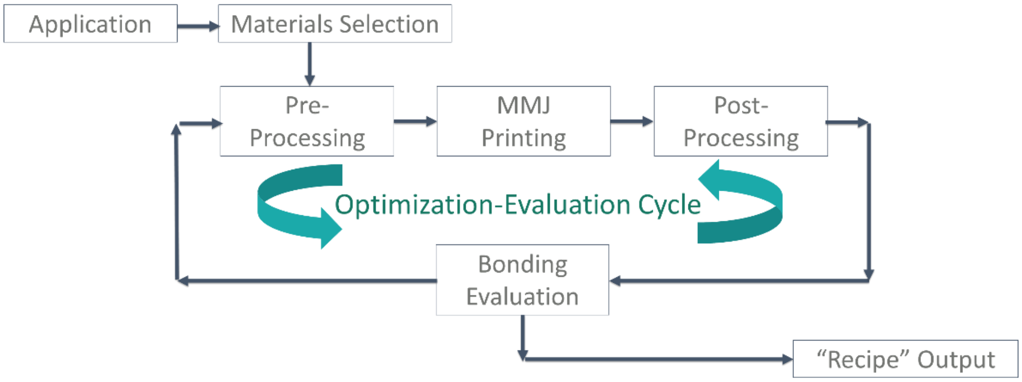

Figure 1: Bonding "recipe" development workflow

The optimization-evaluation cycle consists of four steps: 1) The first step is pre-processing of the base material. It is mostly cleaning with conventional preparations. It may involve physical cleaning such as sanding, brushing and abrasion. It may also involve chemical cleaning such as washing with solvent IPA, Acetone and etc. 2) The second step is the MMJ printing of a test pattern/part. Process control parameters or setpoints are mostly related to temperature and oxidation control. Temperature and temperature gradient greatly influence the MMJ solidification process including spreading and wetting. Base material temperature and jetting material temperature are the most important variables. Other setpoints such as jetting frequencies, drop spacing, line spacing etc.

play relatively minor roles. Oxidation can not only affect the dynamics of solidification, but also change the interface chemistry. Keeping oxidation to a minimum is always desired and the setpoints will depend on the details of the implementation of oxidation prevention. 3) The third step is post-processing of the printed part. For metals, especially some alloys, heat treatment is a way to improve the materials property significantly. This step is optional as some material pairs do not require heat treatment or cannot be subjected to post processing conditions. 4) The final step of the optimization-evaluation cycle is the bonding evaluation step. There are many standard measurements that are suitable for this purpose. For some measurements (for example, pull tensile tests), part machining is required to turn the 3D built part into a standard test specimen.

The optimization of bonding between two dissimilar metals could be a very complicated process. It is a co-optimization involving three parties, namely the base structure, the MMJ printed structure and the bonding structure. Compromises are typically made at the sub-component level in order to maximize system performance. During the pre-processing step, the situation is simple because it involves only the base structure. In the MMJ printing step, all three structures are affected simultaneously, but the temperature of the base structure and the MMJ printed structure have some degree of freedom for independent temperature controls. In the post-processing step, all three structures are subjected to the same thermal processes, including heating, cooling (includes quenching) and aging. During these coupled processes, the strength at the sub-system level (namely the base structure, the MMJ printed structure and the bonding structure) can strengthen or weaken, but as a whole system, the part strength should reach an optimal level.

A typical "recipe" development takes numerous optimization/evaluation iterations. An efficient bonding evaluation/measurement system is critical for the development cycle.

Quick-response Bonding Evaluation System Development

To obtain one bonding strength data, we need to print at least one part and measure one part. With some industrial standard measurements, the rate of the optimization-evaluation cycle is exceedingly slow. Let's take the tensile bar test as an example, the printing will take about 30min, part machining and the pulling test may involve different shops and services, and the final result may take several days to obtain.

To speed up the process, a quick-response bonding evaluation system is required. Let's point out that for internal use and for bonding optimization, a screening measurement system does not need to be compliant to the industrial standard, as long as the screen measurement is sufficiently quantitative and show good correlation to the intended metric.

Figure 2: Printed socket heads for torque measurements

We have developed a bonding strength evaluation system using socket head structures. The bonding strength is measured by a torque wrench. Socket heads are printed at various sizes (4mm, 5mm and 6mm). A socket wrench is used to record the maximum torque for each socked head before part failure. The result is sufficiently accurate and quantitative to allow DOE (design of experiments) and process optimization.

Structure/material failures[4], even for a single material, are complicated phenomena. Failure criteria (such as von Mises criterion[5] or Tresca criterion[6]) for various material properties, stress strain conditions are still under intensive research. The failure criterion of the composite structure we are investigating here is no exception. The torque experiment represents one particular type of failure and measures one metric of material strength. In principle, it should be strongly correlated to other failures or metrics of material strength such as tensile strength. The exact values of the tensile strength or the exact form of the correlation will be determined experimentally in the future.

The printing times of these small test parts are very short (a few minutes). In addition, a full set of test parts with a range of printing conditions (for example, base substrate temperatures) can be printed in a single session within one or two hours. After optional heat treatment, the parts do not need extra machining before the measurements. The torque values can be obtained almost instantaneously. Excluding the post-processing (heat treatment), the cycle time of the optimization-evaluation loop is reduced from days to hours or even within an hour for a single point test. This much improved screening efficiency also allows us to explore much larger parameter space or investigate the parameter space with greater details.

To develop a screening measurement procedure, we first print bolt heads of varying sizes on substrate under different printing or processing conditions. Then, we measure torques required to remove or strip bolt heads using torque wrench.

Figure 3 shows the torque measurements for three head sizes (4mm, 5mm and 6mm) printed and treated under various process conditions. In principle, the torque vs. size curve should be highly non-linear. However, numerous tests have shown that within the range of sizes from 4mm to 6mm, a linear approximation is valid. In addition, the cluster of lines from linear fits seem to have a common x-axis intercept. Therefore, the slope of this linear approximation becomes an excellent indicator of the bonding strength.

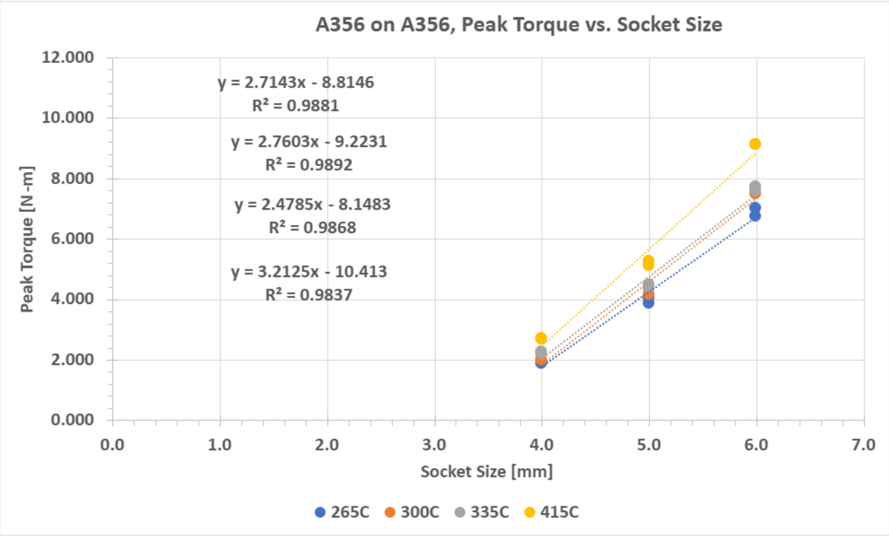

Figure 3: Torque measurements for three head sizes printed/bonded under different conditions

Alternatively, for simplicity, torque at a fixed size (for example 5mm) can be used as the figure of merit.

Examples of Bonding “Recipe” Development for Dissimilar Metals

Now, we are going to use aluminum A356/4008 and stainless steel SS410 as a material pair to illustrate how to develop a printing and processing “recipe” to achieve the optimal bonding. The SS410 sheet stock is used as the base substrate. A356/4008 wire is fed into an ADDiTEC ELEM X molten metal jetting system.

The surface of the SS401 stock is machined and first cleaned with IPA followed by acetone. Then it is scrubbed by Scotch Brite. Finally, it is wiped twice with acetone-soaked pad.

The jetting/printing condition is mostly standard (pulse shape, frequency, drop spacing, line spacing , shield Ar gas and etc.) with two exceptions: 1) the molten metal reservoir is operating at the higher end of its temperature range (with the reservoir set point of 825°C, the actual droplet temperature ranges from 650°C to 800°C, with lower temperatures at startup). 2) the base temperature varied throughout the investigation. Based on past learnings, the base temperature is a critical parameter for the bonding.

The post-processing (heat treatment) is performed at various setpoints. For this pair of materials, this heat treatment investigation has been the most challenging and time-consuming process step. The full heat treatment exploration is beyond the scope of this presentation, and we present only the final procedure here. The optimal heat treatment includes steps: solution treat at 490°C for four hours, followed by an age hardening process at 155°C for three hours.

Figure 4 shows the test results for two heat treatment configurations (as printed vs. optimal heat treatment) under a range of base temperatures during printing. With no heat treatment (as printed), the composite part is very weak. After heat treatment, the system performance improved significantly across all printing temperatures, with the best results at 400°C ~450°C. Temperatures higher than 450°C were not tested due to limitations set by MMJ printing of A356.

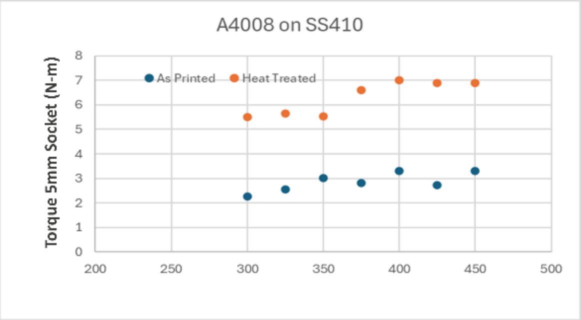

Figure 4: Torque measurements for various printing & processing conditions

The huge performance improvement through heat treatment is interesting and the underlying mechanism is investigated. The torque measurement is measuring the strength of the whole bolt head system against the twisting of the torque wrench. The system fails at the weakest link, and this link is not necessarily the bonding between the two dissimilar metals. Figure 5 illustrates the relative strength of the sub-structures of the bolt head system and the images of the fractured surfaces under two failure conditions. For SS401 (the base material), the printing and the post-processing conditions are not likely to cause much mechanical degradation. Therefore, it is the strongest sub-structure throughout. For A356/4008 (the build material), it is well-known that it is very soft as printed (no heat treatment). Therefore, the A356 bolt head itself could be the weakest link (weaker than the bonding) as printed. The image at the top right of figure 5 clearly shows the fracture occurred within the body of the bolt head.

After proper heat treatment, the strength of the A356 increases significantly and becomes stronger than the bonding. Now, the bonding is the weakest link, and failure should occur at the interface. The image at the bottom right of figure 5 confirmed this expectation.

What happened to the strength of the bonding during this optimal heat treatment is not well understood. However, when we raise the solution treatment temperature of the heat treatment, the bonding fails at a much lower torque.

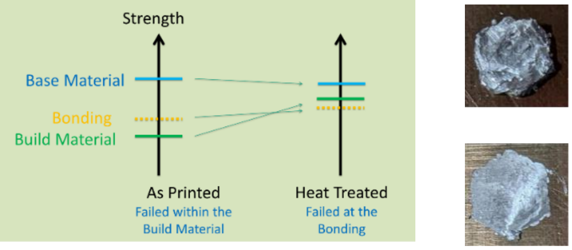

Figure 5: Illustrations of part strength throughout the printing & processing steps

As we have pointed out earlier, the optimal heat treatment for the composite bolt head system is a result of compromises among subsystems. This heat treatment procedure is significantly different from the standard heat treatment for A356/4008 alone. The baseline heat treatment process for Additec's A356 parts is solution treat at 538°C for four hours, followed by an age hardening process at 155°C for three hours. In comparison, the solution treat temperature for optimal performance of this composite bonding structure is much lower, at 490°C. As a result, the bolt head is also not as strong as it would have been if it were treated separately.

	A356/4008 on SS410	A356/4008 on Ti
Pre-Processing	• IPA + Acetone after machining • Scotch Brite surface • Wipe with Acetone 2 times	• IPA after machining Ti plate • Scotch Brite Ti surface • Clean surface with Acetone 2 times
Printing Condition	• Surface Temp = 400°C ~ 450°C • Use high drop temperature • Good oxidation prevention	• Ti64 surface Temp = 415°C • Use high drop temperature • Good oxidation prevention
Post-Processing	• Solution treatment 490°C @ 4 hrs • Water Quench within 10 Seconds from removal from furnace • Age 155°C @ 3 hrs	• Solution treatment 538°C @ 4 hrs • Water Quench within 10 Seconds from removal from furnace • Age 155°C @ 3 hrs
Torque 5mm Socket	• 6.9 N.m	• 5.9 N.m
Ultimate Shear Strength	• 262 MPa	• 224 MPa

Table 1: Bonding "recipes" for two pairs of dissimilar metals

We have shown how we have developed the "recipe" for the A356/4008 and SS410 pair. With similar methodology, we also evaluated the A356/4008 and Ti bonding. For comparison, the parameters and performances are listed in table 1.

The most noticeable difference between the two recipes is the solution treatment temperature. It might indicate that the bonding mechanisms for the two pairs of metals are different.

Conclusions

MMJ has been expected to perform well for multi-metal printing and hybrid fabrication. One key aspect of this multi-materials printing is the bonding between two different materials. We have developed a workflow to evaluate and optimize this bonding. Utilizing this workflow, we have also demonstrated good bonding between several pairs of dissimilar metals. Although there is no universal parameter set (recipe) or guarantee for any metal pairs, the prospect of good bonding is very encouraging. Further investigations into various bonding mechanisms between metals using MMJ are important for understanding and generalization of design rules for applications involving bonding between dissimilar metals.

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