A METHOD TO ELIMINATE ANCHORS/SUPPORTS FROM DIRECTLY LASER MELTED METAL POWDER BED PROCESSES

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Abstract

Metal powder bed AM processes have a significant drawback in that they require anchors/supports to hold overhanging features down during laser processing. This severely restricts the geometries that the processes can make, adds significant time and cost to production and reduces throughput as parts cannot be easily stacked in the build bed. A method to eliminate the need for these anchors/supports has been invented and will be described. Early parts made without anchors will be shown and next steps for research will be discussed.

1.1 Selective Laser Melting (SLM) and the requirement for anchors/supports

SLM is a powder bed process that begins with the deposition of a thin layer of powder (typically 20-100µm thick) onto a metal substrate. A high power laser raster scans the surface of the powder and the heat generated causes powder particles to melt and form a melt pool (Santos, Osakada et al. 2004). Once the layer has been scanned the melt pool solidifies and another layer of powder is deposited and again melted by the laser until the part is fully complete. Powder particles that are not processed by the laser remain loose and can be re-used at a later stage.

High heat intensities are generated by the laser source during processing, this is required to ensure complete melting of metal powder particles and minimise part porosity (Kruth, Mercelis et al. 2005; Li, Shi et al. 2009). However the rapid heating/melting of material is followed by a rapid solidification (Thijs, Verhaeghe et al. 2010) inducing thermal variations that cause areas of the part to expand/contract at different rates and subsequently create stress which can cause a part to warp (Kruth, Froyen et al. 2003; Morgan, Sutcliffe et al. 2004; Mercelis and Kruth 2006). An example of warpage can be seen in Figure 1(a), a SLM zinc part curls due to un-anchored geometry. This type of warpage can be controlled with the use of anchors. Anchors are metallurgical fused to the substrate and various locations across the part forcibly holding geometries in place. Figure 1(b). shows a SLM component (316L) made with an without anchors. Anchors are made from the same material as the SLM part and are also formed through the melting of powder on the powder bed. The number and location of anchors are dependent on the part geometry and build direction/orientation (Zaeh M. and Branner G. 2010). Typically large overhanging/unsupported geometries built parallel to the powder bed require the most anchors (Vandenbroucke B. and Kruth J.P. 2007). However the inclusion of anchors does not guarantee a component will be warp free, large stress prone geometries can rip anchors from the substrate during a build causing it to fail. Once a build is complete the task of removing anchors adds time and cost. In many cases the anchors cannot be accessed or removed. Parts can still warp even after anchor removal due to the remaining stress, this can be relieved through furnace heating cycles prior to anchor removal (Shiomi, Osakada et al. 2004).

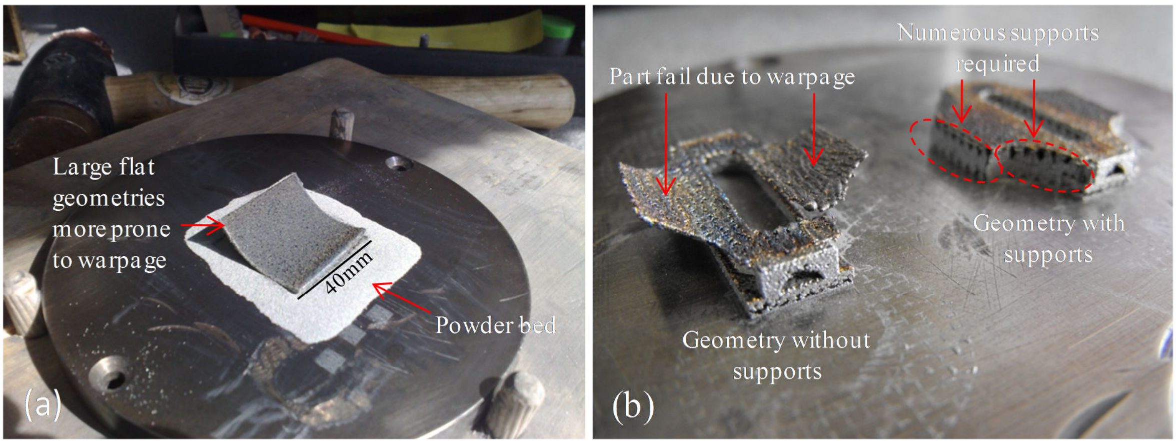

Figure 1 Warpage of un-anchored zinc part

1.2 Polymer based AM that does not require supports

The AM method Selective Laser Sintering (SLS) uses lasers to process polymer materials from a powder bed. SLS uses the same layer by layer method as SLM to produce parts but is able to do so without the requirement for anchors. SLS uses special 'supercooling cooling' polymers and careful processing temperature control to enable anchorless SLS parts to be made (Shi Y., Li Z. et al. 2004). SLS materials nylon 11 and 12 are supercooling polymers that have re-freezing temperatures (138-143°C) that are lower than their melting temperature (185-189°C)(Scholten H. and Christoph 2001). During SLS powder bed temperatures are maintained above the material's solidification temperature but below it's melting temperature (Scholten H. and Christoph 2001; Tontowi A. and Childs T. 2001), the laser scans regions of the powder bed causing the polymer to melt, more preheated powder is deposited and processed until the part is complete. Material that is not laser processed remains solid, whereas the bed temperature ensures the laser melted polymer remains liquid throughout the build and does not transition back into a solid until later. After building, the part is allowed to cool over several hours and completely solidify. Eliminating rapid material solidification during a build reduces a components tendency to warp and eliminates the requirement for anchors leading to greater geometry freedom and reduced post-processing.. Furthermore, SLS parts do not need to be physically attached to a substrate and therefore parts can be stacked on top of each other, improving productivity as the number of parts within each build increases.

1.3 Applying SLS material principles to SLM

The super cooling behavior of nylon 11 and 12 allows SLS to produce parts without anchors. However, there are no known 'super cooling metals' in existence today that have a melt temperature that is significantly higher than the re-freezing temperature. There are combinations of metals that, when combined in specific proportions, form an alloy that has a lower melting/freezing temperature than one or more of the individual materials prior to alloying. These alloys are known as ‘eutectic alloys’ with the lowest possible melting point forming the eutectic point (Askeland and Fulay 2009).

1.4 Eutectic Alloys

A simple binary eutectic system is typified by the metallic alloy of bismuth and zinc. Pure elemental bismuth exhibits an equilibrium freezing point of 270°C and pure elemental zinc exhibits an equilibrium freezing point of 420°C. When bismuth and zinc are fully alloyed in proportions of 97%Wt and 3%Wt respectively a melt point of 254°C is formed (Okamoto 1997), this is 16°C lower than the melting point of bismuth. A simple binary eutectic phase diagram is shown in Figure 2. Alpha, beta, solid and liquid phases are shown with respect to varying material compositions and temperature, T_E represents the eutectic melting point. Eutectic material proportions can vary from the exact eutectic point creating hypo or hyper eutectics (alloys containing a eutectic system) with variable solidification temperatures and material properties.

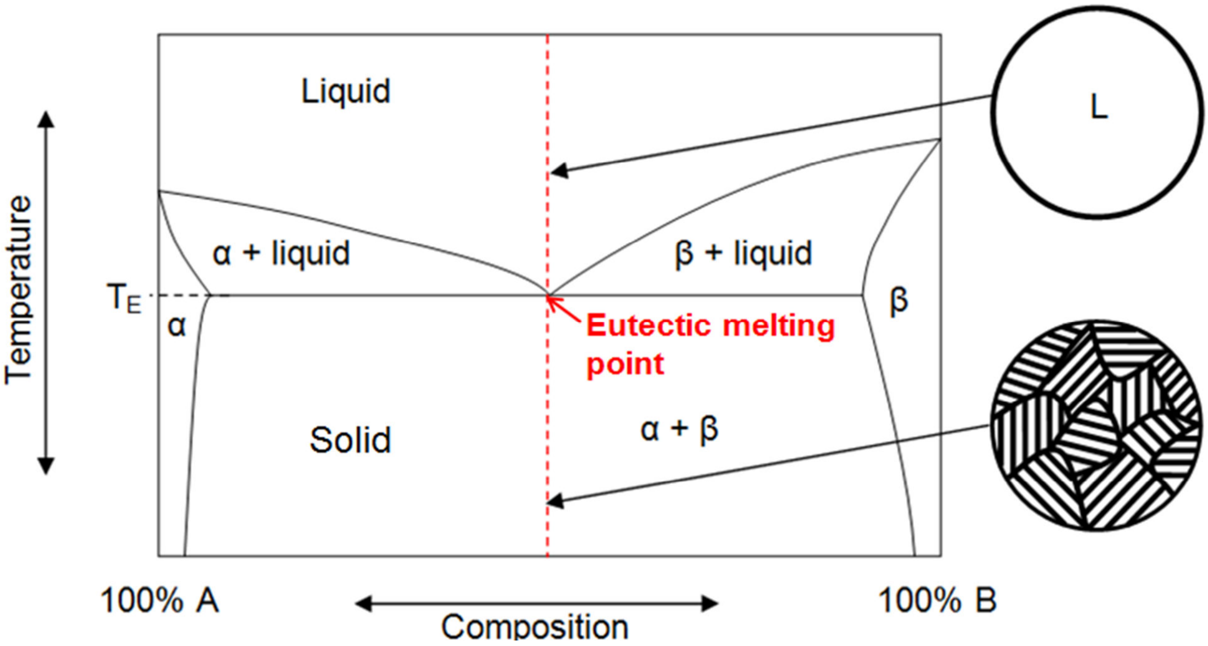

Figure 2 Eutectic phase diagram containing material A & B.

1.5 Anchorless SLM

Removing or alleviating stress build up and the requirement for anchors within SLM can be achieved by preventing parts from completely solidifying during processing. ASLM has been developed to prevent processed metal from completely solidifying during an SLM build (Furlong M., Hopkinson N. et al. 2011). This is achieved by forming a eutectic alloy or eutectic system (hyper /hypo eutectic) from two or more un-alloyed materials while maintaining powder bed pre-heating above the newly formed eutectic melting/solidification point. The following example demonstrates this method; a batch of bismuth and zinc powder are mixed in their un-alloyed eutectic proportions (Bi97%Wt. and Zn3%Wt.). These materials are then deposited during the SLM process while maintaining a bed temperature near 254°C (eutectic point of alloy). This bed temperature would not melt the unprocessed powder as the original melt temperatures of bismuth and zinc are still applicable and above the set bed temperature. When the laser scans regions of the powder bed the individual bismuth and zinc powders will melt and form a eutectic alloy that will now only solidify at temperatures below the eutectic solidification point. Because the bed temperature is set near the eutectic point the melted/alloyed regions will not rapidly solidify and form stress concentrations (as with the SLS process). Other eutectic composition such as Al66Mg offer large processing windows (temperature difference between eutectic melt point and lowest melting point of individual un-alloyed materials 212°C). A large processing window is advantageous as the bed temperature control would not need to be regulated as precisely compared to a small processing window.

2 Experimental Methodology and Testing

ASLM experiments were conducted on an MTT SLM 100, this system utilises a 50W fibre laser focused to a 20-100µm spot size melting powder deposited onto a steel substrate. The steel substrate is attached to a platform capable of pre-heating to a maximum temperature of 250°C. SLM processing is maintained under a controlled argon atmosphere with oxygen content less than 100ppm. Powdered bismuth and zinc were measured out in their eutectic proportions and mixed for 3 hours in a rotating tumbler. Both materials possessed an irregular shaped morphology and were seized to below 200µm mesh

3.1 Results and Discussion

A sample from the mixed batch of BiZn was tested using Differential Scanning Calorimetry (DSC) to ensure that the correct material proportion had been mixed and the correct melting and solidification points were achieved. Figure 3 shows the DSC plot for the mixed BiZn sample. The plot shows the temperature of the sample being ramped up to 450°C, during this time the bismuth melts (as indicated by the first trough at 275°C) followed by zinc melting (second trough at 416°C). The DSC then ramps down the heating allowing the sample to cool to room temperature. One peak is shown indicating material solidification at 235°C, this is below the melting point of both bismuth and zinc proving that the materials had alloyed in their correct eutectic proportions (solidification temperature is lower than 254°C eutectic point due to material undercooling and DSC response lag). If the material had not alloyed correctly you would expect two cooling peaks indicating two re-solidification points for both zinc and bismuth.

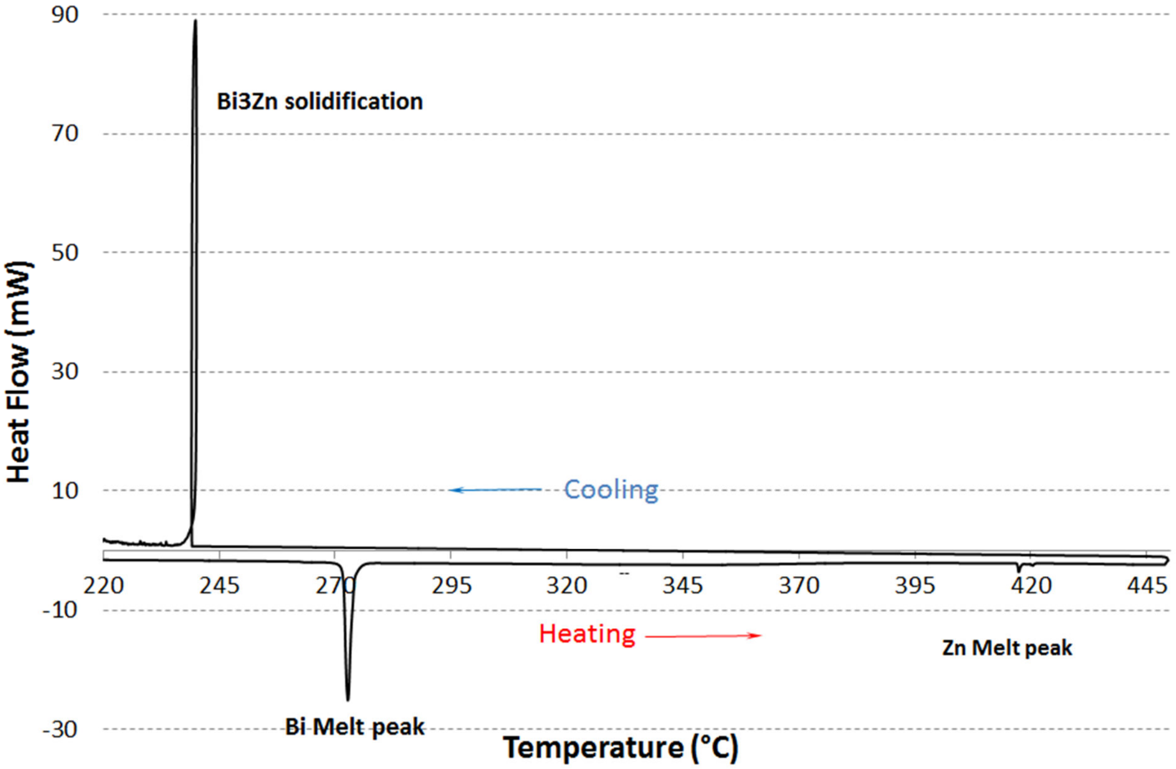

Figure 3 DSC Bismuth and Zinc (unalloyed powder mixed in proportions of Bi97%Wt. & Zn3%Wt.)

3.2 SLM Anchorless component

This mixed powder composition was deposited onto a powder bed maintained at 250°C (near eutectic melt point for alloyed Bi3Zn). A geometry with overhanging and unsupported features was built using the ASLM method, the first layer was built onto a 5mm thick powder (to ensure the component did not attach to substrate) followed by 100µm thick powder layers, this part and a thin wall component are shown in Figure 4. This type of un-anchored geometry would warp when processed using conventional SLM. The Bi3Zn geometry does not warp and maintains its overhanging features when processed over a loose powder bed. Small cylindrical and thin wall features were included on the part to demonstrate resolution and capabilities of material and process (0.3mm minimum wall thickness). Once the part had been completed and allowed to cool the part was removed from the process chamber and loose powder easily brushed off (no evidence of powder caking). A cross section of the overhanging geometry was analysed using an electron microscopy and is shown in Figure 5. The microstructure displays regions containing a laminar structure, this is characteristic of a eutectic structure. A compositional analysis of these areas was undertaken using Energy Dispersive X-ray spectroscopy (EDX) and displayed the presence of both bismuth and zinc. Areas that did not visually display this eutectic structure contained no zinc elements. Due to the low proportion of zinc within the material composition and rapid solidification of melt pools across the component (without a eutectic material composition within the melt pool) a eutectic structure could not form throughout the whole of the component. Instead, only regions in which a zinc and bismuth powder particle entered the melt pool a eutectic microstructure would form.

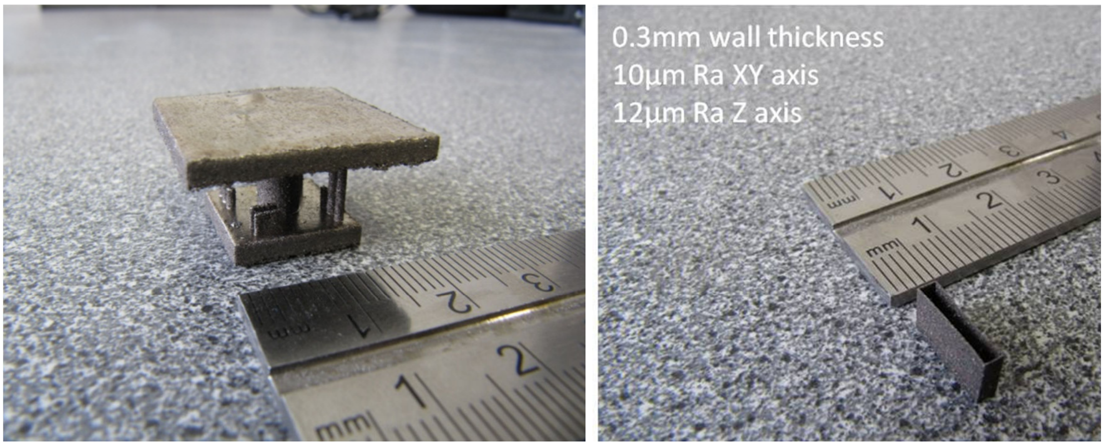

Figure 4 Anchorless Bi3Zn eutectic component

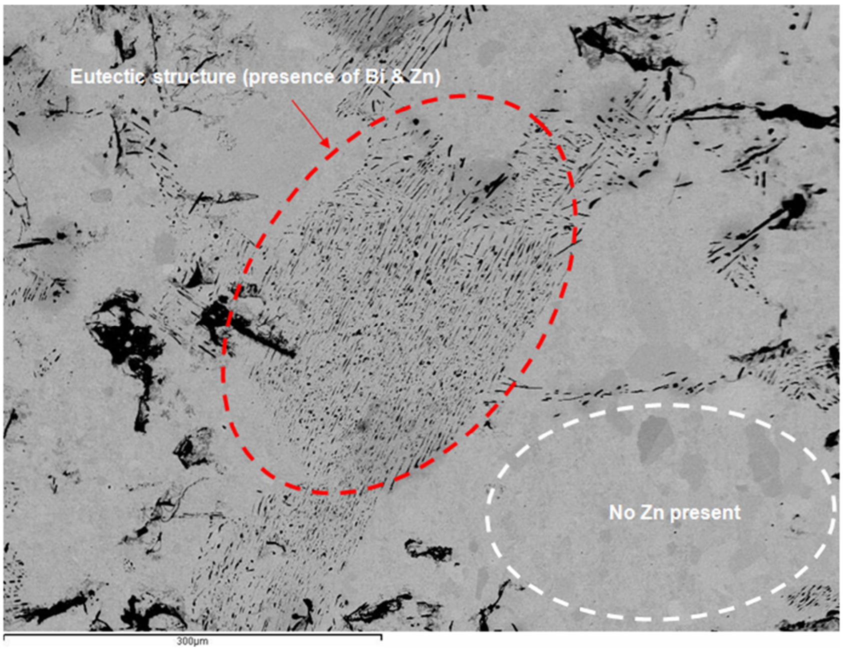

Figure 5 Backscattered electron image of cross-sectioned Bi3Zn sample

A number of problems can arise during ASLM of eutectic materials, elements within the composition (especially those with low melting points) can vaporise during laser processing causing the eutectic proportions to offset and potential cause the part to fail during a build. Alternatively laser powers may not be great enough to melt all materials within the composition and form a complete alloy. Another problem is related to the rapid movement of the laser beam across the powder bed, this may not provide sufficient time for material stirring and alloying within the melt pool. Both of these issues can be further investigated using DSC to confirm complete alloying of material and whether this was achieved using correct material proportions. A sample was taken from the laser processed Bi3Zn component shown in Figure 4 and examined using DSC. The DSC plot shown in Figure 6 shows that melting is initiated at approximately 250°C and solidifies at approximately 233°C (again solidifies lower than eutectic point due to material undercooling and DSC response lag). Melting initiated at a temperature lower than that of bismuth's melt temperature (270°C), this confirms that a eutectic element had formed during the SLM process.

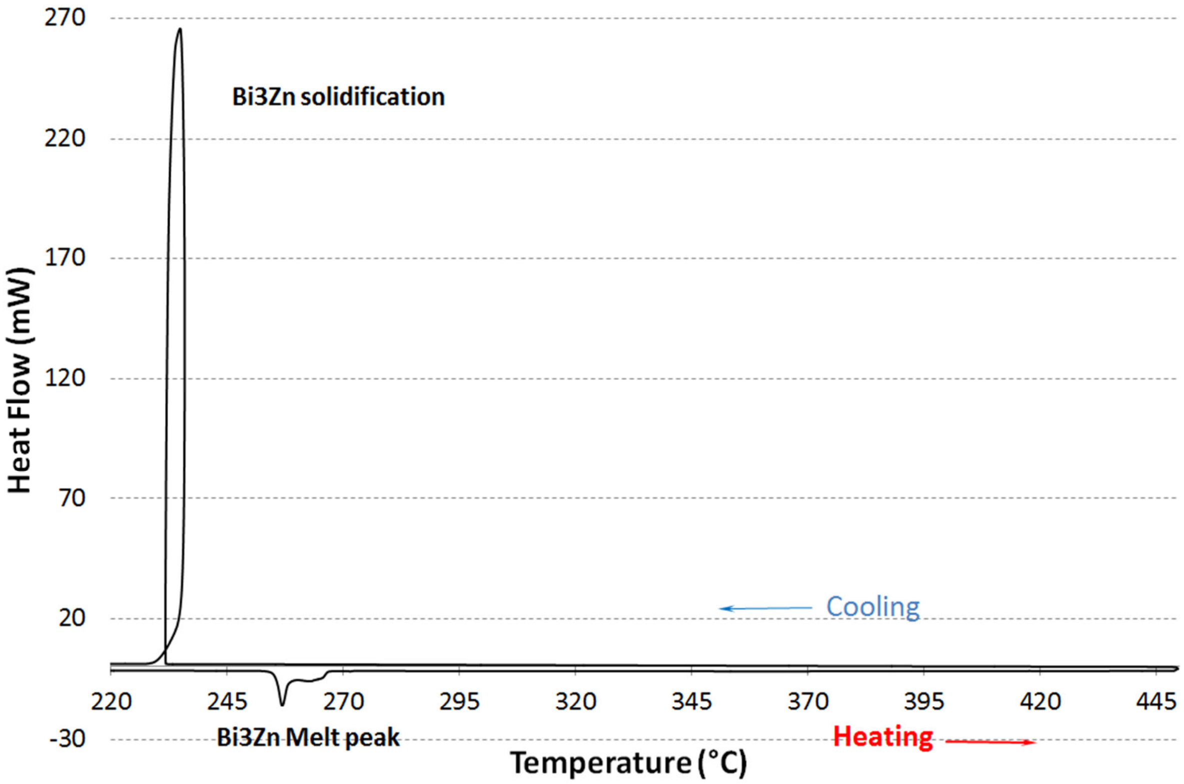

Figure 6 SLM Bi3Zn sample DSC plot

To further test the Bi3Zn material and push the boundaries of ASLM a more complex set of geometries were formed. Figure 7 shows spherical parts created with structures within them. These parts were built successfully with all loose un-processed powder within the sphere being easily removed with a light air jet. The internal star structures within the spheres were not attached to the sphere and able to move freely within the confines of the spherical structure.

These parts were also built from a non eutectic 316L stainless steel powder and failed after a few layers due to there being no anchors to support structure. When successfully building these geometries with anchors in 316L, anchors were required within the sphere and were later found impossible to remove.

Figure 7 Anchorless Bi3Zn eutectic parts fabricated using ASLM

ASLM has been successful in producing parts from re-used powder, this is providing the melting point of any of the materials within the powdered composition are not reached during pre-heating.

4.Conclusions and further work

Low melt temperature materials such as bismuth, tin and zinc are able to form eutectic alloys with low eutectic melting points, however these materials provide limited engineering potential due to their poor mechanical properties. Materials such as aluminium, magnesium, copper and silicon can form eutectic alloys that possess much improved mechanical properties and are similar to commercially available aluminium 6000 and 7000 series alloys (Hirsch, Skrotzki et al. 2008). However many of these materials possess eutectic melting temperatures that are 450°C and above. SLM bed temperatures would therefore need to maintain these elevated bed temperatures in order to process these materials using the ASLM method. Loughborough/Sheffield University is currently developing a high temperature bed capable of reaching pre-heating temperatures of up to 600°C. Some of the materials available for ASLM future research are shown in Table 1.

Alloy	Eutectic Melting Temp °C	Process Window °C*
AZ91 (Mg-Al)	470	190
AM60 (Mg-Al)	540	120
5086 (High Strength Al-Mg)	588	72
5456 (High Strength Al-Mg)	570	90
A356 (Al foundry alloys)	555	105

* *Process Window is the temperature difference between lowest melting temperature of un-alloyed composition and the alloyed eutectic melting temperature*

Table 1 Eutectic Alloys

ASLM may be restricted to only eutectic materials however the variety of materials available is far greater than supercooling polymers available to SLS. Further to this the composition of materials required do not need to achieve the pure eutectic point and can contain a hyper or hypo eutectic proportion so that melt temperatures and mechanical properties can be fully controlled. Materials can contain two, three or more materials with one or more of the materials being pre-alloyed (providing that there are at least one un-alloyed component) (Woodruff 1973). In addition it may not be required for a part to remain fully molten in order prevent warpage, a semi-liquid composition may be sufficient to reduce stresses. This again offers flexibility in terms of bed temperature and material composition. Establishing a method for mixing powders and ensuring a balanced spread of elements throughout a powder batch/bed will be critical in ASLM's future success.

ASLM has the potential to allow designers to freely design for their application and not be restricted by the manufacturing method. This new found freedom will introduce new industries and applications to ASLM and the additive manufacturing industry.

5 References

Askeland, D. R. and P. P. Fulay (2009). Essentials of Materials Science and Engineering: SI Edition, Cengage Learning.

Furlong M., Hopkinson N., et al. (2011). A method, apparatus, computer readable storage medium and computer program for forming an object. UK.

Hirsch, J., B. Skrotzki, et al. (2008). Aluminium Alloys: Their Physical and Mechanical Properties, John Wiley & Sons.

Kruth, J. P., L. Froyen, et al. (2003). "New ferro powder for selective laser sintering of dense parts." CIRP Annals - Manufacturing Technology **1**(52): 139-142.

Kruth, J. P., P. Mercelis, et al. (2005). "Binding mechanisms in selective laser sintering and selective laser melting." Rapid Prototyping Journal **11**(1): 26-36.

Li, R., Y. Shi, et al. (2009). "Effects of processing parameters on the temperature field of selective laser melting metal powder." Powder Metallurgy and Metal Ceramics **48**(3): 186-195.

Mercelis, P. and J.-P. Kruth (2006). "Residual stresses in selective laser sintering and selective laser melting." Rapid Prototyping Journal **12**(5): 254-265.

Morgan, R., C. J. Sutcliffe, et al. (2004). "Density analysis of direct metal laser re-melted 316L stainless steel cubic primitives." Journal of Materials Science **39**(4): 1195-1205.

Okamoto, H. (1997). "Bi-zn (bismuth-zinc)." Journal of Phase Equilibria **18**(2): 218-218.

Santos, E. C., K. Osakada, et al. (2004). "Microstructure and mechanical properties of pure titanium models fabricated by selective laser melting." Proceedings of the I MECH E Part C Journal of Mechanical Engineering Science **218**(7): 711-719.

Scholten H. and W. Christoph (2001). Use of a nylon-12 for selective laser sintering. **1**.

Shi Y., Li Z., et al. (2004). "Effect of the properties of the polymer materials on the quality of selective laser sintering parts." Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications **218**(3): 247-252.

Shiomi, M., K. Osakada, et al. (2004). "Residual Stress within Metallic Model Made by Selective Laser Melting Process." CIRP Annals - Manufacturing Technology **53**(1): 195-198.

Thijs, L., F. Verhaeghe, et al. (2010). "A study of the microstructural evolution during selective laser melting of Ti-6Al-4V." Acta Materialia **58**(9): 3303-3312.

Tontowi A. and Childs T. (2001). "Density prediction of crystalline polymer sintered parts at various powder bed temperatures." Rapid Prototyping Journal **7**(3): 180-184.

Vandenbroucke B. and Kruth J.P. (2007). "Selective laser melting of biocompatible metals for rapid manufacturing of medical parts." Rapid Prototyping Journal **13**(4): 196-203.

Woodruff, D. P. (1973). The solid-liquid interface, Cambridge University Press.

Zaeh M. and Branner G. (2010). "Investigations on residual stresses and deformations in selective laser melting." Production Engineering **4**(1): 35-45.