Liquidmetal® and Metal Injection Moulding: Two complementary metal forming technologies

Metal Injection Moulding (MIM) is just one of a number of innovative technologies now available for the production of complex metal components. Whilst MIM itself is considered to be a disruptive technology to processes such as machining and investment casting, Liquidmetal is also expected to compete with these conventional technologies as well as with MIM. Paul Hauck recently joined Liquidmetal Technologies following a career of more than 27 years in MIM. In this article he introduces Liquidmetal technology and highlights both the differences and similarities in the two processes.

When I was first introduced to the Liquidmetal process I invested a great deal of time learning what the process was capable of accomplishing and how the process compared to Metal Injection Moulding (MIM). This included developing an understanding of any overlaps in the applications each technology was best suited to serve.

During more than 27 years in the MIM industry I looked at thousands of potential MIM applications, manufactured hundreds and witnessed hundreds more through my various industry activities and participation in trade organisations like the Metal Powder Industries Federation (MPIF) and the Metal Injection Molding Association (MIMA). I estimate that nearly 90% of those parts produced by MIM were ideally suited for the process and not economically practical with any other manufacturing route. MIM has essentially enabled metal-part designs that were not possible before its arrival as a commercially viable technology. The other 10% of the parts were not well suited for MIM, but still somehow found their way to be produced by the process.

This either happened through increasing customer requirements and specification changes over time (scope-creep) or as a result of overconfident MIM parts producers who struggled to be successful with their original planned processes and costs.

While I have only been with Liquidmetal Technologies for a short time, I have discovered that MIM and the Liquidmetal processes are actually complementary technologies. Both processes employ injection moulding technologies and each serves a niche with little to no overlap.

Fig. 1 Liquidmetal Technologies, Inc. Corporate Headquarters and Manufacturing Center of Excellence in Rancho Santa Margarita, California, USA

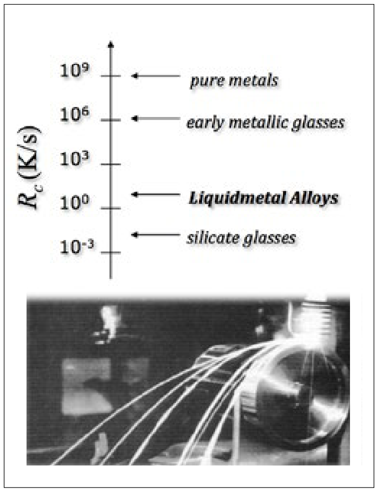

Fig. 2 Cooling rates required to achieve an amorphous atomic structure in various materials. Inset: early amorphous alloys could only be manufactured in very thin ribbons using a sputtering method to achieve the massive cooling rates required

Fig. 3 Four-point bend test demonstrating the high elastic limit of Liquidmetal alloys. Test specimen is 45 mm long x 15 mm wide x 1.85 mm thick. This load represents 3% elastic strain, which is higher than the published strain limit of the material

		Composition by Weight %	
		LM-001B	LM-105
Zirconium	Zr	67.02%	65.67%
Titanium	Ti	8.80%	3.28%
Copper	Cu	10.61%	15.60%
Nickel	Ni	9.80%	11.75%
Niobium	Nb	-	-
Beryllium	Be	3.76%	-
Aluminium	Al	-	3.70%

Table 1 The chemistries of two key Liquidmetal alloys, LM-001B and LM-105

The purpose of this article is to provide a brief Liquidmetal history and share insights about the two processes. I will also discuss how the Liquidmetal process works and compare its capabilities to MIM.

The Liquidmetal story

The fundamental innovations leading up to Liquidmetal technology date back over fifty years. At that time, however, amorphous alloys could only be manufactured in very thin ribbons using a sputtering method to achieve the massive cooling rates required to defeat the normal crystallisation that occurs when metal changes from a liquid to a solid. In the early 1990s, with support from NASA, CalTech formulated Vitreloy, the first Bulk Metallic Glass (BMG) alloy with a thickness much greater than 1 mm. Adding to this significant discovery, this was the first amorphous alloy that required modest cooling rates of only tens of degrees per second, providing orders of magnitude improvement over earlier alloys (see Fig. 2).

> *'Liquidmetal alloys are generally stronger than conventional alloys because they do not have grain boundaries or crystal defects such as vacancies, interstitials, dislocations, or stacking faults'*

Liquidmetal's company history begins in 1987 as Amorphous Technologies, Inc. (ATI), established in Southern California as a privately held company. By the 1990s the company acquired the exclusive patent rights to Vitreloy from CalTech. ATI later changed its name to Liquidmetal Technologies, Inc. while developing the manufacturing process for producing amorphous alloy products.

Liquidmetal Technologies' amorphous metals have remarkable physical properties compared to conventional alloys. In the molten state, conventional alloys also possess an amorphous structure or liquid-like molecular structure. However, during the cooling process while transitioning to their solid phase, conventional alloys naturally tend to crystalise into regular geometric atomic structures. These structures often result in weak regions along the boundaries of these crystalline geometric structures, which are commonly referred to as grain boundaries. In contrast, Liquidmetal alloys retain an amorphous, liquid-like atomic structure in their solid state. Liquidmetal alloys solidify as a frozen liquid without a phase transformation. The chemistries of two key Liquidmetal alloys are shown in Table 1.

Liquidmetal alloys are generally stronger than conventional alloys because they do not have grain boundaries or crystal defects such as vacancies, interstitials, dislocations, or stacking faults. In addition to high strength, Liquidmetal parts exhibit very high elastic strain limits compared to conventional alloys (Fig. 3). I occasionally hear concerns of amorphous alloys being "brittle" or easy to break, but usually the criticism comes in the absence of recognising the highly elastic characteristic of the material. Combining these levels of strength and elasticity produces a very robust material. When amorphous alloys do fail the failure mode is quite abrupt. Part design freedom is, however, tremendous due to the overall unique properties of the alloys.

The company

Liquidmetal Technologies, Inc. became a publicly traded company with its Initial Public Offering in 2002, focusing the business on producing parts for the consumer electronics market. The company invested IPO proceeds into building a manufacturing centre in South Korea, developed custom modified vacuum die-casting machines and sourced all its raw materials and alloys. Short consumer electronics product life cycles and tremendous production volume ramp-up demands tested the scalability of the process at the time and challenged the company's ability to maintain a profitable business.

Liquidmetal Technologies, Inc. had a re-start in 2010 when it sold an exclusive licence to Apple Inc for consumer electronics applications. At around the same time, The Swatch Group Ltd. converted its non-exclusive licence to an exclusive licence for watch applications.

While there was a clear understanding of material requirements for the process, moulding machine technology had not yet been perfected to desired standards for mass production. Both of these issues have been addressed since 2010 and now the company offers technology licensing opportunities to metal-part fabrication businesses and customers.

Today, Liquidmetal Technologies retains rights to 63 patents and has 53 additional patents pending. Liquidmetal's corporate headquarters and Manufacturing Center of Excellence are located in Ranch Santa Margarita, California, USA.

Fig. 4 Omega's Seamaster Planet Ocean Liquidmetal® watch with a ceramic and Liquidmetal bezel

Fig. 5 Materion's facility in Elmore, Ohio, USA

Technology partners

Liquidmetal Technologies has developed two key strategic relationships. The first priority was to find an experienced global materials processor that could manage the requirements of vacuum melting the Liquidmetal alloys in large production volumes. The company established a strong working relationship with Materion Brush, Inc. which is now a provider of certified Liquidmetal alloys.

Materion is an integrated producer of high performance engineered materials used in a wide variety of applications and markets globally. Founded in 1931, the company now serves customers in more than 50 countries with operating, service centre and major office locations throughout North America, Europe and Asia. Materion's global reach was critical to Liquidmetal's interest to serve global needs with its process technology.

Liquidmetal Technologies also joined forces with Austria's Engel GmbH to develop a certified injection moulding machine for the mass production of Liquidmetal alloys into three-dimensionally complex parts. Engel was an ideal fit to Liquidmetal's

Fig. 6 Engel e-motion injection moulding machine for processing Liquidmetal alloys

Fig. 7 Precise process and flow control allow small parts with high cavitation moulds to fill with high yields. This part was prototyped with 32 cavities and filled so well that the number of cavities could have been easily increased

ecosystem due to its position in the market as a technology leader for thermoplastics, elastomers and corresponding automation systems. Engel's global sales and aftersales support was a key attribute needed to support global manufacturing interests and to offer Liquidmetal customers global support for these special machines. The two companies began their collaboration in 2010 and Engel now commercially offers its machines, capable of processing Liquidmetal alloys in a fully automatic cycle, to Liquidmetal licensees.

The process today

The Liquidmetal process starts with ingots. Liquidmetal alloy ingots in the shape of rods weighing up to 100 g are heated to over 1000°C under vacuum. When the ingots are fully molten they are injected under pressure into near conventional injection moulds. Mould temperatures are controlled to cool and solidify the Liquidmetal alloy into final part geometries, which achieve physical properties immediately after this single step moulding process. Early generation machines were hybrid die casting machines. Whilst Engel could have used major components of a 110 (120 US) ton e-Motion machine from its fully electric machine series, the injection system required unique design changes for processing amorphous metals. This resulted in eliminating the conventional screw and barrel assembly, which was replaced by a special injection unit tailored to the application. The injection of amorphous metals is completely different from plastics processing, requiring precise control over melt temperatures and viscosities while under vacuum.

The e-Motion machine developments for processing amorphous alloys resulted in a very compact material melting and injection system with a melt chamber that holds the raw Liquidmetal ingot. This ingot is heated to a molten state by a special induction heating system and once the alloy is molten the material is injected into the mould, using profile parameters that are similar to conventional plastic injection moulding. The entire system is kept under an extreme vacuum level in order to prevent the formation of crystals and oxides allowing for the best possible amorphous alloy parts.

Engel successfully developed a fully integrated turn-key solution extending process control beyond the injection moulding machine (Fig. 6). The control of auxiliary equipment has also been integrated into Engel's proprietary control system. This integrated solution eliminates communication problems with external devices and enables efficient repeatable operation of the total production cell, which includes vacuum generation, induction heating, and temperature measurement just to name a few.

In order to make the machine as convenient for the operator to use as possible, the injection moulding machine was re-designed to monitor specific process controls that facilitate fully automatic production. Additionally, Engel added an automation system that picks ingots from a magazine and loads them into the melt chamber using a servo-driven

Fig. 8 Engel injection moulding machine alloy ingot loading magazine

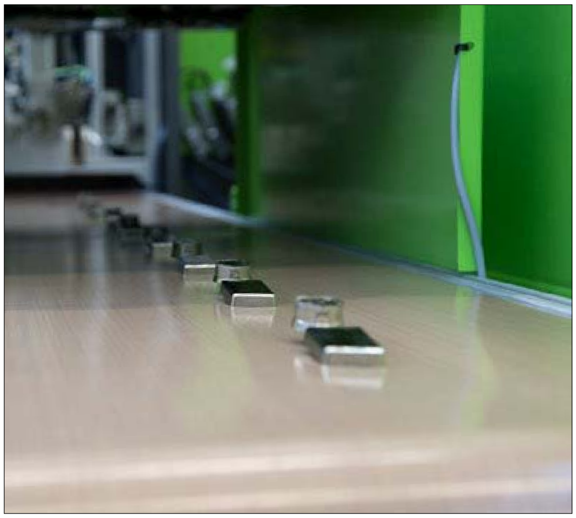

Fig. 9 Engel injection moulding machine parts conveyor belt with integrated cooling fans

robot. After ingot insertion, the robot then removes the finished parts from the previous moulding cycle within the same sequence, and places them onto a conveyor belt with cooling fans (Figs. 8 and 9).

Temperature control of the entire process is a key parameter that affects the quality of the finished parts. The process starts with controlling the temperature of the injection chamber to the mould. A new development from Engel, the FLOMO system (flow monitoring), manages accurate temperature control for the injection system and the mould conditioning. FLOMO is the state-of-art alternative to the legacy cooling water manifold with sight glasses.

In order to manage the complex combination of critical process parameters such as temperature, vacuum level and injection speed, Engel equipped the machine with their latest CC300 controls. This sophisticated real time control system manages the end-to-end moulding process, including the challenge of managing the end of the injection cycle, which comes to an abrupt stop once the mould cavities are filled. This occurs because the material is not compressible as is the case with plastic materials. The machine carefully controls each parameter for precise repeatability.

Once parts have been injection moulded, they are finished except for removing gates and runners. To remove gates and runners, there are a number of suitable approaches depending on the requirements of the finished part. If slight gate vestige is acceptable, waterjet cutting can be used. In cases where little or no gate witness is desired, CNC machining can be employed. Both approaches can be seen at Liquidmetal's Manufacturing Center of Excellence.

The uniqueness of Liquidmetal alloys and the manufacturing process provide results that are impressive for a fully automated complex metal part manufacturing process. Application opportunities exist in a very broad range of markets, including automotive, aerospace, defence, dental, industrial, medical, and sporting equipment to name a few.

> *'Although the future opportunity for volume-based cost improvements are solid, Liquidmetal material costs will likely remain at small multiples of MIM feedstocks in the foreseeable future'*

The economics of MIM and Liquidmetal

The cost models for MIM and Liquidmetal processing are quite different, which leads to interesting discussions as you compare one process against the other. High feedstock costs have been a complaint among MIM parts manufacturers for as long as I can remember. Frankly though, in the most recent years, improvements in global metal powder quality and feedstock costs have been impressive. Currently Liquidmetal raw material costs in a form ready for moulding are multiples of that for MIM. Much of what drives this cost are the input materials themselves, such as titanium and zirconium. Although the future opportunity for volume-based cost improvements is realistic, Liquidmetal material costs

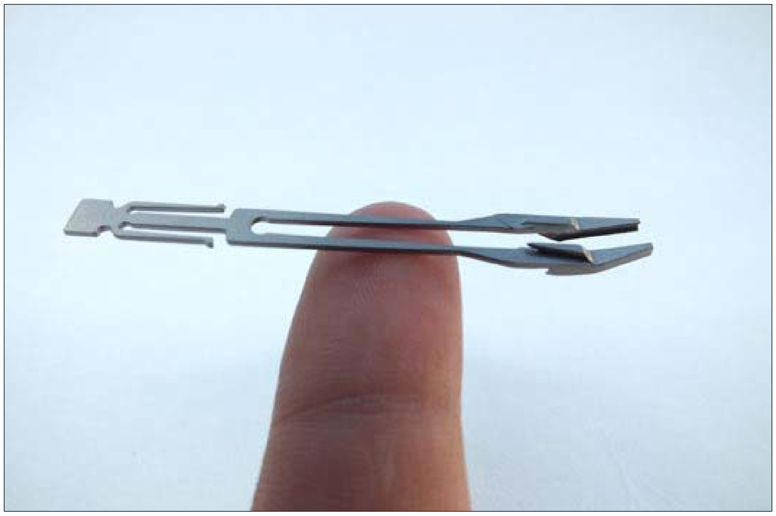

Fig. 10 Medical suturing component produced by Liquidmetal Technologies

will likely remain at small multiples of MIM feedstocks in the foreseeable future.

The second significant contrast between Liquidmetal and MIM is the injection moulding cycle time. Cycle times for Liquidmetal melt and injection cycles range from two to three minutes (mould close to open) as compared to MIM injection cycles of five to 45 seconds. So high material costs and long moulding cycle times for Liquidmetal alloys compared to MIM are two very distinguishable differences.

Now let's compare MIM and Liquidmetal processing requirements beyond material costs and moulding cycle times. A key offset to the long moulding cycles with the Liquidmetal process is the ability to run high cavitation tooling. Moulds with as many as 64 cavities have been run successfully with Liquidmetal alloys, which is a major cost driver for the process. As with MIM, small parts lend themselves well to the Liquidmetal technology. Small parts require less material (less cost) and allow for higher cavitation moulds (more parts per shot). Both aspects are particularly important for driving costs down on Liquidmetal applications.

Another consideration is mould life. With the Liquidmetal process, mould life is currently measured in terms of tens of thousands of shots versus hundreds of thousands of shots for some MIM applications. Liquidmetal is continuing to evaluate alternative materials to extend mould life, but today mould life remains an important consideration. Any time you can increase the number of mould cavities for the Liquidmetal process, the quantity of parts that can be

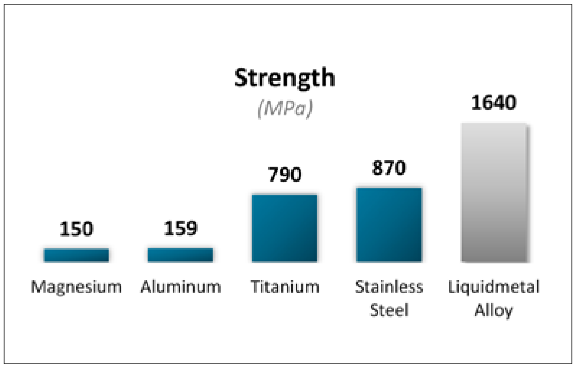

Fig. 11 Ultimate strength of various materials

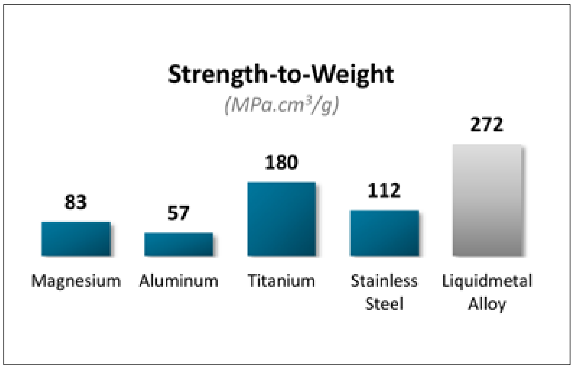

Fig. 12 Strength-to-weight ratio of various materials

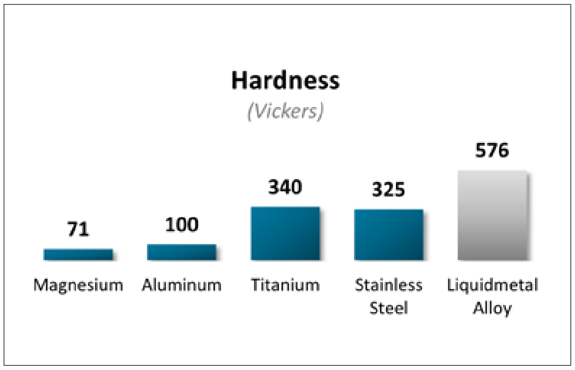

Fig. 13 Hardness of various materials

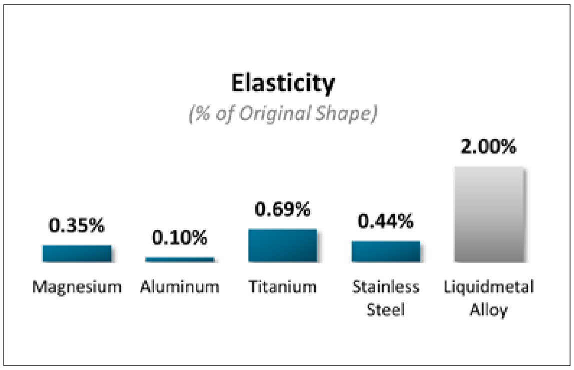

Fig. 14 Elasticity of various materials

produced over the life of the mould increases.

Another key difference between Liquidmetal and MIM is that when Liquidmetal parts are ejected from the mould they are complete and exhibit their final material properties, often leaving only the runner system and gate removal as the final step to having a finished part. Of course with MIM the moulding process is just the beginning. The MIM process has multiple conversion steps to reach a finished part. Green MIM parts require careful handling at moulding, followed by debinding and sintering. After sintering, coining or sizing steps are very common. Additionally, processes such as machining, heat treating, plating, Hot Isostatic Pressing for improved material properties, and surface finishing operations are often required to complete a part before it can be shipped to the customer. It is these multiple process steps for MIM that can allow Liquidmetal's process to compete on certain applications regardless of Liquidmetal's higher material costs and longer moulding cycle times.

Aside from the process requirements, Liquidmetal material costs today will prohibit it from achieving part costs below $0.50 USD, regardless of the number of mould cavities used.

Fig. 15 As-moulded surface finish of Liquidmetal alloy parts

Test	Purpose	Result
Sensitisation	Skin sensitisation and elicitation of contact dermatitis	Non-sensitising
Irritation	Irritant effect of toxic leachables	Non-irritating
Systemic Toxicity	Effect on system from absorption and distribution of toxicant	Non-systemic-toxic
Hemocompatibility	Rupturing of red blood cells and release of cytoplasm into blood plasma	Non-hemolytic
Cytotoxicity	Toxicity due to leachables on cells	Non-cytotoxic
OVERALL BIOCOMPATIBLE		

Table 2 ISO 10993 biocompatibility tests. Parts 4, 5, 10, and 11 were conducted on as-cast LM105 Liquidmetal injection moulded specimens

MIM and Liquidmetal: Application characteristics

A comparison of part-geometry limitations for Liquidmetal and MIM sets a critical foundation when defining key differences in the processes and the resulting parts that either technology can successfully produce.

With MIM, a fundamental design requirement is to start with a flat surface or provide a part design that allows the part to be placed on a flat surface for debinding and sintering by having several of the part-features fall on a single plane. This is critical due to the substantial shrinkage (near 20%) MIM parts experience during debinding and sintering processes and the resulting impact that gravity and friction have on part-dimensions while this large amount of shrinkage occurs.

Liquidmetal parts only experience 0.2% shrinkage or 100 times less shrinkage than MIM. Additionally, parts exhibit finished material properties when ejected from the mould, so no downstream thermal processes are necessary to achieve final material properties. This is a key design advantage with the Liquidmetal process as all of the limitations of MIM tied to shrinkage, debinding and sintering are eliminated. Cantilevered arms are easily accomplished with the Liquidmetal process. Additionally, no post sintering heat treatment is required to achieve material properties for Liquidmetal parts as is required for MIM.

The next area of contrast between MIM and Liquidmetal processing works to MIM's advantage. Because Liquidmetal parts exhibit slight shrinkage and achieve their final properties in the mould, part designs require draft on all internal features to ensure parts can be ejected at the end of the moulding cycle. Often, smaller amounts of external draft are also required. The properties of most MIM feedstocks allow for non-drafted features or, at a maximum, very little draft to achieve satisfactory part-ejection from moulds. This allows MIM to achieve dimensional results on small holes, internal threads and other cored features that are not possible with Liquidmetal process as the draft required often violates the

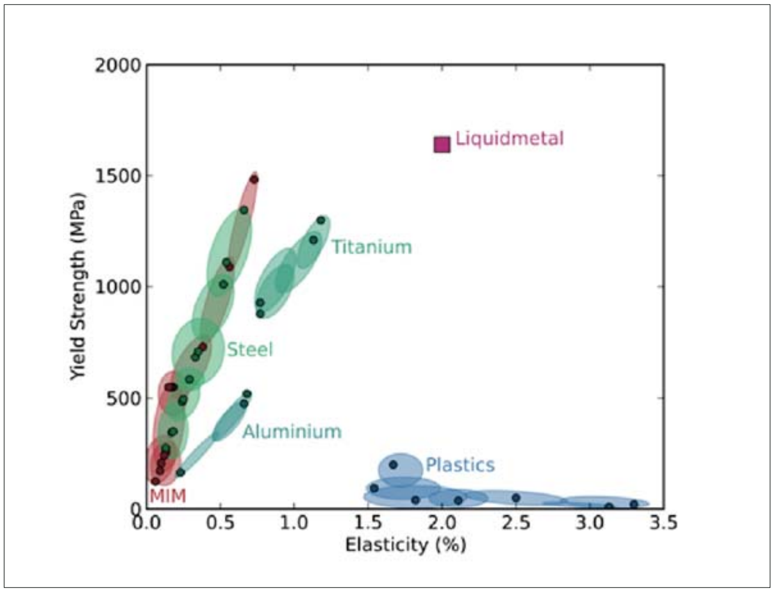

Fig. 16 Liquidmetal alloys have a unique combination of high strength of metals and the elasticity of plastics

dimensional needs of these features. However, not all is lost though, as with MIM or any metalworking process, process requirements are best recognised and incorporated in the part-design stage of new product development activities. In the case of internal threads, Liquidmetal part-designs can be developed to incorporate threaded inserts in a similar fashion to that accomplished in plastic injection moulded components.

Before looking at a few additional points of comparison between MIM and Liquidmetal, a few basic design guidelines for Liquidmetal parts are:

- Part weights up to 80 g (100 g maximum total shot size)
- Maximum dimension of 100 mm
- Outer draft angles of 0.5° to 1°
- Inner draft angles of 1° to 3°
- Wall thickness typically 1.0 – 4.0 mm

Dimensional accuracy and repeatability

Having spent a majority of my career in the MIM industry, my application design thoughts have been heavily influenced by the scope of capabilities of MIM. Now, as a new member of the Liquidmetal team, I am struck by the dimensional accuracy and repeatability of the Liquidmetal process. Process simulation software such as fluid flow analysis is used to develop part and injection mould designs to achieve optimum results with Liquidmetal alloys.

Despite the limited application history of these manufacturing process simulation and analysis tools, the Liquidmetal process can achieve dimensional accuracy and repeatability results that are only common to production CNC machining processes. The Liquidmetal process, however, accomplishes these results at much lower costs.

Recognising the limited amount of production taking place today, Liquidmetal technology is continuing to build meaningful statistical information and will release additional information in the future. Today it is reasonable to expect dimensional accuracy and repeatability of ±0.1% of a given part dimension with the process as compared with the MIM

	Liquidmetal	Die Casting	MIM	Investment Casting	Machining
Low cost / high part complexity	Yes	Yes	Yes	No	No
Fine surface finish <2.0 Ra (micro inches) without secondary operations	Yes	No	No	No	Yes
High elastic limit (2.0% Strain)	Yes	No	No	No	No
Single process step	Yes	Yes	No	No	No
No heat treating required to achieve high hardness	Yes	No	No	No	No
No heat treating required to achieve high strength	Yes	No	No	No	No
Low process scrap	Yes	Yes	Yes	No	No
Tolerance control (% of feature size)	+/- 0.1	+/- 0.4	+/- 0.3	+/- 0.5	+/- 0.1

Table 3 Comparison of the Liquidmetal process and various other metalworking technologies

industry standard of ±0.3%. Of course, recognition of mould fabrication tolerance capabilities, especially on high cavitation moulds, needs to be considered before making part specification commitments. Shrinkage is very near isotropic with Liquidmetal alloys, so design sensitivities to the 0.2% shrinkage of the material and varying dimensional sizes of features on a part are insignificant. The challenge for the Liquidmetal process will be working with injection mould fabricators who place an emphasis on the dimensional accuracy of mould cavities and those who can accomplish this with high-cavitation tooling.

Freezing non-compressible molten metal during the injection moulding process without changes to the atomic structure of the material plays a significant role in the resulting dimensional accuracy and repeatability of the process. This unique aspect of dimensional control is not common in any other metalworking technology. Furthermore, high performance material properties are achieved without any post moulding heat-treating requirements, unlike crystalline metal alloy structures. This benefit avoids further loss of dimensional control experienced with residual stress, part warpage, distortion or growth with many heat treating processes used for crystalline metal alloys.

Material properties and surface finish

Liquidmetal alloys provide a unique combination of material properties, including high strength, high hardness, unmatched elasticity, superior surface finish, excellent welding capabilities, and corrosion resistance. Liquidmetal alloys also offer two and a half times the strength of titanium. Figs. 11-14 show various physical properties of Liquidmetal versus various wrought materials.

One very notable characteristic of Liquidmetal is the ability to produce brilliant as-moulded surface finishes. Parts replicate the finish of the mould and part surface finishes of under 0.1 Ra micro-meters are easily achievable, with some results better than 0.05 Ra micro-meters surface finish. With other metalworking technologies this level of surface finish results usually require expensive, time-consuming finishing operations. Such surface finishes are attributes of the Liquidmetal moulding process and its alloys. Liquidmetal alloys are also highly corrosion resistant and recent biocompatibility testing of Liquidmetal's LM105 alloy showed very encouraging results, as can be seen in Table 2.

Technology comparison summary

There is no one technology that does it all; no single solution to fix any problem. So, as new products are developed, both proven and leading edge technologies are considered to solve problems and to meet performance, quality and cost objectives. The Liquidmetal process has its place and provides a unique set of characteristics that differentiate it from other manufacturing technologies. Table 3 shows the core strengths of Liquidmetal against other metal-working technologies, notably the unique combination of high strength and elastic properties of Liquidmetal alloys.

Many plastics are known for their elastic properties, but their strengths levels are generally low. There are many crystalline metal alloys that offer a wide range of strength characteristics, but none offer high strength combined with high elastic limits as Liquidmetal alloys do. The Liquidmetal process is therefore an ideal manufacturing solution for three-dimensionally complex parts, including those with unsupported features, and parts that require all or some of the following:

- Extremely high accuracy and repeatability
- Remarkable properties
- Brilliant surface finish
- Scratch resistance
- Corrosion resistance

Conclusions

As I reflect on my time in the MIM industry and all that has been accomplished with the technology, I see Liquidmetal starting at a familiar point and following a similar path. Liquidmetal hopes to accelerate the growth and adoption of the technology through licensing partners and providing a leadership role in continuing technology development. The future is clearly bright for MIM and I see the same for Liquidmetal. As both technologies grow, I see them co-operatively coexisting and their application capabilities complementing each other.

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Liquidmetal will be hosting an open house at its Manufacturing Center of Excellence in Rancho Santa Margarita, CA for customers and potential licensees on October 14, 2014. For information on how to attend this event or learn more about the company, email: Brandy.McClay@Liquidmetal.com