1. Introduction

There are only very limited applications where metal foam can be directly employed without further processing.

On the other hand, established metal foam production methods have one feature in common, they produce foam and not metal parts containing metal foam. In most cases, additional joining steps are necessary to transform the metal foam into a working functional element. As a result, the whole process chain is in general long and expensive. Integral foam moulding is a cost-effective approach to produce metal castings with solid skin and integrated cellular core. The transition between skin and core is gradual, i.e. there is no distinct interface between both regions. The concentration of the material within the skin optimizes the moment of inertia and thus flexural stiffness and strength.

The development of metal based integral foam moves along analogous paths as that of polymers where integral foam has been commercially introduced in the late 1960s. Polymer integral foam parts are now accepted as a material system with own properties which simplifies designs, reduces production costs and weight, and increases stiffness and overall strength. Starting from low-pressure injection of polymers with small amounts of gas content, highly sophisticated processes have been developed where injection is at very high pressure into mould cavities with moving cores. Integral foam moulding processes at WTM moves along analogous paths as that of polymers by transferring and adapting successful moulding technologies for polymer integral foam to metals. Two moulding techniques for metal integral foam are presented, a low and a high pressure process. In the low pressure process, the molten metal charged with blowing agent is injected into a permanent steel mould without completely filling it. In this case, the mould gets eventually filled by foam expansion.

In the high pressure process foaming is initiated by expansion of the mould cavity after it has been filled completely with the mixture of the metal melt and the blowing agent. The moulded parts are characterized with respect to their cellular structure, density profile and pore size distribution. Mechanical properties such as stiffness and damping behaviour are discussed. [doi:10.2320/matertrans.47.2188]

2. Integral Foam Moulding Technology

Generally, polymer integral foam is defined as a moulded or extruded part having a cellular core and an integral solid skin with the transition from the skin to the core being gradual.

Polymer integral foam moulding is far more complex than conventional moulding techniques and consists of three steps: admixing of a blowing agent to the polymer, filling of the mould cavity and foaming the part in the cavity during cooling. We define metal integral foam in a fully analogous way. Our strategy to develop metal integral foam moulding techniques based on die casting or injection moulding follows analogous paths. It is well known that moulding processes for polymers and metals have many similarities. We exploit these similarities in a systematic way by transferring successful moulding methods for polymer integral foams to metals. On the other hand, we also take advantage of the differences between metals and polymers, particularly the low viscosity and the high thermal conductivity of metals.

Generally, the realization of an integral foam moulding process for metals involves technical solutions for two challenges:

- Admixing of a blowing agent to the molten metal.
- Development of adapted mould filling processes and mould techniques.

In the following, two moulding techniques—low and high pressure integral foam moulding—are presented.

2.1 Feeding of the blowing agent

The blowing agent is admixed to the melt in the runner and gating system located in between injection cylinder and part cavity. This has various advantages:

- Short contact time < 100 ms. The short time prevents premature gas release from the blowing agent. That is, foaming of the melt starts after injection into the mould cavity.
- High Reynolds number when the melt gets in contact with the blowing agent powder. Thus, turbulent mixing is expected.
Figure 1 shows how the addition of blowing agent is accomplished within the runner system.

### 2.2 Low pressure integral foam moulding (LP-IFM)

The low pressure integral foam moulding process for metals is depicted in Fig. 2.

In the low pressure process the molten metal is injected into a steel mould under standard die casting conditions with the difference that in contrast to the standard casting process the mould cavity is not filled completely and no or only a very low dwell pressure is applied. The latter is the reason why this process is referred to as low pressure integral foam moulding. The incoming melt wets the mould surface where it solidifies to a compact skin. Gas release from the blowing agent eventually leads to the development of a foamed core. The success of the integral foam moulding process is thus strongly determined by the mould filling behaviour of the molten metal. High local filling velocities (10–100 ms⁻¹) combined with the chilling effect of the mould wall lead to rather good surface qualities of the castings which are—if wetting is complete—nearly comparable to those of standard compact die castings.

A clear advantage of the LP-IFM process is its simplicity. Shortcomings are the mechanical roughness and visible defects at the surface if the relative density falls below a critical value, which is a function of the geometry of the casting. Another drawback is the poor quality of extremities of moulded parts. The main reason for these shortcomings is the relatively low decomposition pressure of the chemical blowing agent.

### 2.3 High pressure integral foam moulding (HP-IFM)

The high pressure integral foam moulding process is designed to overcome the inherent limitations of the low pressure process. High pressure moulding is much the same as conventional die casting or injection moulding, except that the volume of the cavity is initially smaller than that of the final part, see Fig. 3.

In the HP-IFM process the melt is injected into the mould cavity with standard die casting conditions. The mold is completely filled and a high dwell pressure of some 100 bar is applied. After a time delay of 10–100 ms the mold is locally expanded in order to initiate foam evolution.

Figure 3 High pressure integral foam molding of metals. The liquid metal is injected into a steel mould under standard die casting conditions. The mold is completely filled and a high dwell pressure of some 100 bar is applied. After a time delay of 10–100 ms the mold is locally expanded in order to initiate foam evolution.

Besides an improved surface quality and a high quality of extremities of the part, lower densities can be expected. Drawbacks are a complex mould design due to moving cores or a vertical flash design and limitations to part geometry. An inherent drawback of this method is the appearance of visible marks along those surface areas where mould motion takes place.

### 3. Experiment

Various magnesium integral foam samples (AZ91, AM60) were produced by LP-IFM with an injection molding machine JSW JLM-220MG at Neue Materialien Fürth GmbH.
Aluminum foam samples (LP-IFM: 175 × 175 × 6 mm$^3$ and HP-IFM: 175 × 175 × (6–10) mm$^3$) were produced by LP-IFM as well as HP-IFM with a cold-chamber die casting machine FRECH DAK450-54 at WTM Institute. For the aluminum foam parts the standard die casting alloy AlSi9Cu3 was used. For all experiments MgH$_2$ powder was applied as the blowing agent.

The density profile and the pore size distribution of the integral foams were investigated with a micro computed tomography system $\mu$-CT40 from Scanco Medical (resolution 10μm).

The Young’s modulus and the internal friction $Q^{-1}$ were determined by impulse excitation technique at room temperature and ambient atmosphere. The measurement setup is shown in Fig. 4. For both measurements an impulse excitation measurement system (Integrated Material Control Engineering N.V.–RFDA System 23) was used. Young’s modulus is determined by the software of the measurement system from the fundamental flexural resonant frequency (out-of-plane flexure) according to ASTM E 1876. Two different sample geometries (70 × 6 × 6 mm$^3$ and 100 × 10 × 10 mm$^3$) were used. The internal friction $Q^{-1}$ is determined by the software of the measurement system from the damped oscillation (sample geometry 100 × 10 × 10 mm$^3$).

4. Results

4.1 Low pressure integral foam castings

Generally, the castings show a dense surface skin of about 1 mm and a cellular core, see Fig. 5.

Surprisingly, we find no qualitative differences between magnesium und aluminium alloys.$^{11}$ The maximum core porosity depends on the thickness of the part and is about 60% for a thickness of 10 mm in the LP-IFM process. Higher porosities lead to sink marks. The thickness of the foam core increases with increasing sample thickness, whereas the extension of the solid skin is more or less constant in all cases.$^{11}$ A lower mean density always results in a lower density of the foam core. The density profiles of the integral foams (Fig. 6) are analogous to the well known density profiles of thermoplastic integral foams.$^2$

Figure 7 shows an aluminum integral foam plate produced by LP-IFM. The periphery of the plate has a thickness of 2 mm whereas the remainder of the plate is 6 mm thick (see Fig. 9). There is a very homogeneous foam structure within the 6 mm region. The 2 mm periphery also shows porosity which can be—as in this extreme example—rather high. This porosity reflects the inherent problem associated with the low pressure process. Extremities of the mould are difficult to fill since a dwell pressure is not applied.

Thus, extremities have to be filled by the dynamic pressure of the melt during mould filling. This can hardly be guaranteed for complex parts. Consequently, LP-IFM is restricted to castings with comparatively low complexity and short flow paths.

Figure 8 shows a magnesium demonstrator door-handle produced by LP-IFM. This demonstrator part was designed taking into account the above indicated restrictions for the LP-IFM process. As can be seen in Fig. 8, the same behaviour as obtained for
plate geometries—approximately 1 mm dense surface skin and a completely filled cellular core—also holds for more voluminous parts. Good surface quality accompanied by a weight reduction of up to 30% compared to a solid door-handle has been obtained.

4.2 High pressure integral foam castings

So far, the HP-IFM process was tested for aluminium, forming a plate with a footprint of \(175 \times 175\ mm^2\), see Fig. 9.

The plate consists of a fixed periphery with a dimension of \(12 \times 5\ mm^2\) and an expandable internal region with a dimension of 150 mm. For these experiments, the initial thickness of the expandable region is 6 mm. The final thickness after expansion is 10 mm.

The casting parameters are: melt temperature: 740°C, mould temperature: 240°C, part weight: 420 g, blowing agent \(\text{MgH}_2\): 6 g, time delay after the dwell pressure is reached: \(0\ s + \text{reaction time of the system (~10 ms)}\).

A lateral view of the cast part is depicted in Fig. 10. The already solidified surface layer follows the movement of the mould wall. As a consequence, a gap of 4 mm height develops, which appears in the photograph as a bright strip. The gap is refilled with foaming melt during the expansion of the mould. The new surface which develops due to foam expansion is not sound and is comparable with the surface of metal foams produced by powder compacts.

Cross sections from three different castings are depicted in Fig. 11. Figure 12 shows a detailed view of the cell structure of the casting of Fig. 11.

We find a distinctive compact skin of more than 1 mm followed by a transition zone. The core shows a high porosity. The appearance of the porosity ranges from disrupted to foam-like with pronounced cell walls. The differences in the pore morphology result from the melt condition during foaming. If the solid phase fraction is too high, the viscosity is high and the cells are not able to assume
a round shape after coalescence. A similar influence of the heat content is observed for the visible marks, Fig. 13. During mould expansion, the solidified skin ruptures and has to be refilled by the foaming melt. If the temperature is already too low, the opening gets filled incompletely (Fig. 13, top and middle).

Even if it is filled completely (Fig. 13, bottom), the new surface is rather thin and comparable to the surface of metal foams produced by the expansion of powder compacts. The surface of the remainder of the casting is comparable to standard die casting qualities. In addition, the high pressure guarantees that extremities of the casting get filled (compare Fig. 13 with Fig. 7).

There are some essential advantages of the high pressure compared to the low pressure approach:

- Parts with complex elements can be realized. Also extremities get filled.
- Higher porosities can be reached (>60%).
- Large-area parts can be realized.

4.3 Cell morphology

A noticeable result is that the cell morphology is in fact foam-like, although foam stabilizers are not added to the melt, see Fig. 12. We find very fine pores with pronounced cell walls and Plateau borders.

Numerical calculations\(^{(12)}\) show, that the prerequisite for the development of straight, very thin cell walls is the presence of a stabilization mechanism. In the case of integral foam moulding endogenous stabilization\(^{(7)}\) was identified as the primary mechanism. Foam evolution takes place during solidification. Stabilization results from the solid phase, which is distributed throughout the melt. The solid phase is wetted by the melt and gets captured within the cell walls. It slows down cell wall thinning by a barrier effect.\(^{(13)}\)

The mean cell diameter \(D\) and the phase ratio \(\phi = V_g/V_m\), defined as the quotient of the total gas volume \(V_g\) and the total metal volume \(V_m\), of IFM castings are intimately correlated, see Fig. 14.

At low phase ratios, up to 0.4, the mean cell diameter is well predicted by the free growth of a fixed number of pore nuclei

\[
D = \sqrt[3]{\frac{6}{n_0 \pi}} \phi \propto \phi^{\frac{1}{3}}\]

where \(n_0\) denotes the nuclei density.

At high phase ratios the mean cell diameter follows the functional dependence of growth coalescence, i.e. expansion is only possible at the expense of cell coalescence\(^{(13,14)}\)

\[
D = \frac{\delta}{\sqrt{\frac{\phi + 1}{\phi} - 1}} \propto 3\delta \phi \propto \phi\]

where \(\delta\) denotes the mean material thickness. Phase ratios of 3 and 5 result in mean cell diameters of about 1.0 and 1.6 mm, respectively.

4.4 Mechanical properties

4.4.1 Flexural stiffness

Using the impulse excitation technique, the flexural bending stiffness of the beams is determined since the specimen beams are excited in out-of-plane flexure (cf. Fig. 4).

The normalized flexural stiffness \(E/E_0\), where \(E\) and \(E_0\) are the Young’s modulus (flexural stiffness) of the foam and the corresponding dense material, of bending beams of different thickness is depicted in Fig. 15.

A nearly linear decrease of the normalized flexural stiffness with decreasing relative density is observed. The
data of the 10 mm samples seems to be a little bit lower than that of the 6 mm samples. The measured stiffness always lies below the rule of mixture, although density reduction is by removing material from the core whose contribution to the overall stiffness is small compared to the skin. This implies that by substituting material for gas the loss of rigidity is dominating the reduction of density.

For fitting data of metal foams and metal integral foams most often the empirical function
\[ E = E_0 \rho_{rel}^n \]
(3)
is used, where \( \rho_{rel} \) is the relative density and \( n \) is a fitting constant. Equations based upon analytical deductions contain quantities such as the fraction of solid in the cell edges or fraction of solid in the cell faces, \(^{15}\) which are not known for most materials of interest. Furthermore the gradual density distribution (cf. Fig. 6) is not accounted for in such equations. However, polymer integral foam shows a completely analogous behaviour. \(^{2} \) Even so, if beams with constant mass are compared, the increase of bending stiffness is obvious.

### 4.4.2 Damping behaviour

The damping behaviour of 10 mm integral foam samples is depicted in Fig. 16.

The internal friction increases with decreasing relative density. The dependence on the relative density is best fitted by a linear dependence on the relative density \( \rho_{rel} \)
\[ Q^{-1} = Q_0^{-1} + a \cdot (1 - \rho_{rel}) \]
(4)
where \( a \) is a constant and \( Q_0^{-1} \) denotes the internal friction of the compact material.

Aluminium integral foam shows an analogous behaviour. Various mechanisms of internal losses accounting for the increased damping of metal foams compared with corresponding dense materials have been proposed. \(^{16}\) Thermoeelastic currents, increased dislocation motion due to a higher stress-strain localisation compared with corresponding dense materials, pump effects of entrapped gas and many more are discussed. However, many aspects of damping mechanisms in metal foams are still not clear.

### 5. Conclusions

Integral foam parts are castings with a solid skin and a foamed core. The production of metal integral foam moves along the same paths as that of polymers. Two different moulding strategies have been investigated.

In the low pressure integral foam moulding (LP-IFM) process, liquid metal containing a blowing agent is injected into a steel mould without completely filling it. There is no or only a very low dwell pressure applied. A compact surface skin develops due to the chilling effect of the cold mould surface. The decomposition of the blowing agent in the inner part of the casting leads to foam expansion. The surface qualities are quite good as long as the relative density is not too low. The latter depends on the geometry of the casting. Due to the absence of a dwell pressure, the LP-IFM process is suitable for castings with a low degree of complexity and short flow paths.

In the high pressure integral foam moulding (HP-IFM) process, the mould is completely filled with the melt and a dwell pressure in the range of some 100 bar is applied. After a time delay of 10–100 ms the cavity of the mould is expanded to allow foam evolution within the core of the casting. The expansion leads to the development of visible marks at the surface. Advantages of the HP-IFM process are a high surface quality, extremities of the casting are filled (analogous to standard die castings) and lower relative densities.

We ascribe both, LP-IFM as well as HP-IFM a high economical potential.

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### REFERENCES