INVESTMENT CASTING OF SURFACES WITH MICROHOLES AND THEIR POSSIBLE APPLICATIONS

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Abstract

The usual way of realizing microstructured features on metallic surfaces is to generate the designated pattern on each single part by means of laser ablation, electro discharge machining or micro milling. A disadvantage of these process chains is the limited productivity due to the additional processing of each part. The approach taken by this project is to replicate microstructured surfaces via investment casting. The main research objective deals with the investigation of single process steps of the investment casting process with regard to the molding accuracy. To demonstrate the potential of microcast surfaces, current results for the casting of a microstructured hydrophobic surface will be shown.

Introduction

Many microstructured surfaces are known in nature such as shark skin, lotus leaf and insect feet structures. By understanding these effects and using this knowledge for technical applications, several material properties such as drag, friction, adhesion, hydrophobia can be adapted. Possible ultra precision technologies for creating microstructured surfaces on metal parts are laser ablation, electro discharge machining and micro milling. The shortcoming of these processes is their limited productivity since each part has to be separately microstructured [1]. Furthermore, micro structuring inner areas of technical parts is limited.

A promising reproduction process that meets all requirements is the investment casting process. By molding from a microstructured grand master pattern, parts of arbitrary geometry can be manufactured at relatively low cost compared to common ultra precision technologies.

As described above, laser structuring provides one possibility for creating the functional surfaces on the grand master pattern. Laser ablation has already been proven for the production of micro replication tools. In principle there are two technologies which can be employed for generating microscaled structures on tool surfaces: Direct microscale structuring by laser evaporation – which is applied in the process described here – and indirect micro structuring by laser ablation of surface layers and then subsequent etching.

The grand master pattern is then used for replicating the microstructured surface on metal parts via the lost wax investment casting process. Several analyses have been conducted to examine the molding accuracy of this process. The accuracy of casting microparts were investigated using aluminum/zinc alloys [2, 3] and stainless steel [4] as well as low melting Au-Ag-based precious metal alloys [5]. According to these results, microparts with geometrical features in a range of 700 µm to 50 µm can be cast with acceptable geometrical variations and an average surface roughness of between 0.5 µm and 1 µm. The possibility of casting microstructured surfaces on a cast part such as a dummy turbine blade with a structural size of 50 µm and an aspect ratio of 1 were demonstrated for an aluminum alloy and a Ni-based superalloy [6]. Other analyses focused on the molding accuracy achievable for casting of low melting Bismuth-Tin and Bismuth-Lead alloys. These were directly cast into polymer as well as quartz molds to avoid the process steps of wax fabrication and ceramic mold making. Owing to the very high surface quality of the used molds, grooves of 4 µm width and 200 nm depth [6] as well as ridges with a periodicity of 400 nm [7] could be cast.

The objective of the work presented here is the characterization of the investment casting process in order to cast a microstructured hydrophobic surface with a common AlSi-cast alloy. Therefore the relevant influencing parameters will be identified.

Experimental Details

In order to examine the molding accuracy of each investment casting process step (Figure 1), an inverse lotus leaf like surface was used. The grand master pattern was fabricated by laser structuring a microhole geometry into a steel plate, Figure 2.

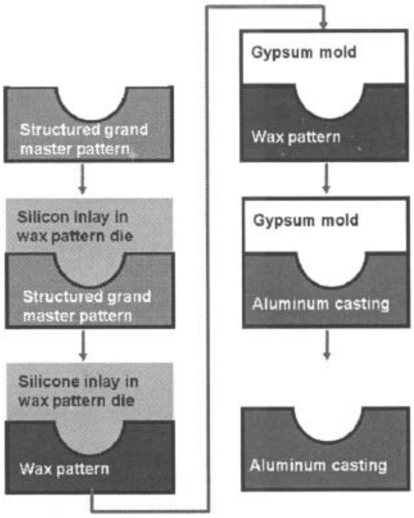

Figure 1. Micro casting process chain for producing a hole structure in aluminum parts

A silicone inlay with nep structure was molded from the grand master pattern, which served as an inlay in the wax pattern die. Following this, the microstructured surface could be replicated by manufacturing wax patterns. These were embedded into gypsum-bonded block molds and used to cast metal.

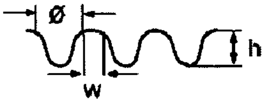

Figure 2. Laser structured geometry for the grand master pattern, Ø = 22μm, h = 10μm, w = 10μm

Structuring of Grand Master Pattern

The laser structuring experiments were carried out a fine drilled steel plate (X8CrNi18-9, AISI 303) with a diode pumped Nd:YVO4 MOPA laser (Master Oscillator Power Amplifier; Rapid, LumeraLaser) at a wavelength of λ = 355 nm. The laser operates with repetition rates of up to ν = 500 kHz and a pulse duration of τ = 12 ps.

For the micro structuring experiments, the laser focus was positioned on the surface of the samples by a galvanometer scanning system with a focal length of f = 53 mm (Fig.3). The ablated geometry consisted of holes with a diameter of 22 μm. The holes were created by cross-hatching at a line separation of 1.5 μm and 10 parallel lines in each direction. The hole depth is adjusted by repetition of the hatching. Micro structuring experiments were performed at a repetition rate ν = 250 kHz and a laser power of P = 600 mW. The mark speed was set to 50 mm/s, the cross hatching was repeated twice.

Fabrication of the Wax Pattern

The wax pattern die shown in Figure 3 was used to produce the microstructured wax patterns. The material for the silicone inlay was Elastosil M4643 A, B (Drawin Vertriebs GmbH, Riemerling - Germany) with a Shore hardness A of 48 [8].

Silicone material is often used for wax pattern molds in investment casting foundries. The advantages of using silicone over metal dies are, on the one hand, rapid manufacturing when the microstructured surface is contaminated with wax. On the other hand, the silicone material is elastic: Therefore the risk of tearing the microfeatures is reduced during ejection of the wax pattern. The lower thermal conductivity of silicone also leads to a slower solidification of the wax: Thus the microstructured features are molded more precisely since the material penetrates into the small features before solidification.

The wax pattern die was equipped with a deaeration system in order to scavenge the air out from the cavity during wax injection.

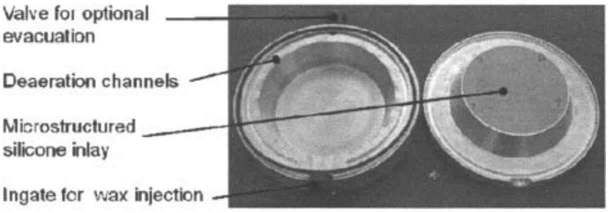

Figure 3. Wax pattern die with microstructured inlay.

The wax patterns were made of an unfilled wax (Straight Pattern Wax A7-11, Blayson Olefins Ltd, Cambridge - UK). The wax properties are shown in Table 1. To fabricate the wax pattern, an electronically controlled wax injection machine (35t C-frame hydraulic wax injection press, Modtech Machine Pvt. Ltd., Ahmedabad - India) was used. This was equipped with an adjustable heating device at the injection nozzle to precisely adjust the injection temperature of the wax. For the wax injection process, the wax temperature and the injection pressure was set to 69 °C and 16 bar, respectively. The resulting speed of the wax through the ingate could be estimated at 0.7 m/s. After injection, the pressure was maintained for 1 min in order to compensate for the shrinkage of the wax.

Table 1. Properties of Straight Pattern Wax A7-11, Blayson Olefins Ltd., Cambridge – UK.

Property	Value
Ash content	0.05 % Max
Congealing point	69-73 °C
Drop melt point	73-76 °C
Free linear contraction	0.9 - 1.1 %
Viscosity	0.8 - 1.3 Pas

Embedding the Gypsum-Bonded Mold

Typical mold materials used in foundry technology are not suitable for casting of microstructured surfaces. Foundry sand is, in general, too coarse. Ceramic shell molding materials used in investment casting as well as phosphate bonded investments are fine-grained but possess very high hardness values which impede their ejection. To remove of the ceramic layer from the cast part, sand blasting is usually used. This would damage the microstructured surface of aluminum part. For this reason, only gypsum-bonded investments fulfill the main requirements concerning moulding accuracy and shake out behavior and are used for the experiments.

The gypsum-bonded investment material Gold Star XXX (Goodwin Refractory Services Ltd., Staffordshire, UK) was used for the production of the mold. The material is characterized by a high concentration of small filler particles and has an average grain size of 18μm (manufacturer's information).

For the preparation of the block mold, the plaster was mixed with water in a ratio of 100:40 according to the manufacturer's instructions. This mixture was poured into a mold flask and then degassed in a vacuum system at about 50 mbar residual pressure. The mold was subsequently dried at room temperature for about 12 h. Following drying, the mold was dewaxed in an oven at 150 °C for about 4 hours. The subsequent burning of the mold was carried out at a heating rate of 100 °C/h up to 700 °C with a soak time of 4 h. After the burning process, the mold was cooled down in the oven to the preheating temperature of 420 °C for subsequent casting.

Counter Pressure Casting and Demolding

An AlSi7Mg0.3 cast alloy which is characterized by a good mold filling capacity [9] was used for casting. The chemical composition is given in Table 2. The melt was neither grain-refined nor modified. The casting experiments were conducted using a counter pressure system. Thus the block mold was placed into a steel sleeve. Directly before the metal was poured into the mold, the air from the sleeve was drawn into a low pressure boiler. When the cast metal sealed the inlet of the mold, a pressure of about 50 mbar was applied to the cavity; this increased the casting pressure by 0.95 bar. A resulting casting pressure of 4 bar could be estimated at the beginning of the mold filling. The melt was overheated and cast into the mold at 740°C (liquidus temperature: 613°C) in order to achieve a very good mold filling.

Table 2. Chemical composition in wt-% of aluminum cast alloy AlSi7Mg0.3 (samples were analyzed with spark spectrometer Spectromax, Spectro GmbH&Co.KG, Kleve, Germany).

Si	Mg	Fe	Cu	Ti	B	Sr
6.98	0.339	0.111	0.0053	0.118	0.0015	0.0002

Analysis and Testing

In the individual process steps, the reproduction of the microstructured surface has been studied on different samples since some measurements involve the destruction of the samples. To measures the micro feature's height, a white light interferometer (WIM) was used. An error of 1 µm was estimated for these measurements. This error results from slightly different points of measurement because the identical point could not always be found on the specimen's surface. Furthermore, the grand master pattern's surface had a roughness (Ra) of 0.53 µm, measured in the unstructured field, which superposes the microstructured surface.

SEM analyses of the gypsum-bonded mold and the casting were performed in order to get an impression of the spatial image and the reproducibility of the microstructured surface.

The structural investigations of the micro patterned surface were carried out on metallographic polished samples of the cast part using a reflecting light microscope.

Finally, contact angle measurements with ultra pure water were carried out to determine the effect of the hydrophobic surface structure. A DSA 10, Krüss GmbH, Hamburg, was used to measure the contact angle. During the measurement of one drop, 60 measurements of the contact angle were performed. Six drops for every field were analyzed to calculate a standard deviation.

Results and Discussion

The microstructured surface could be reproduced over the whole of the investment casting's process chain. However, some loss in molding accuracy of the micro features could be observed at different process steps. The highest loss in feature height occurred on injecting wax into the wax pattern die, Figure 4. The detailed results for each process step are discussed below.

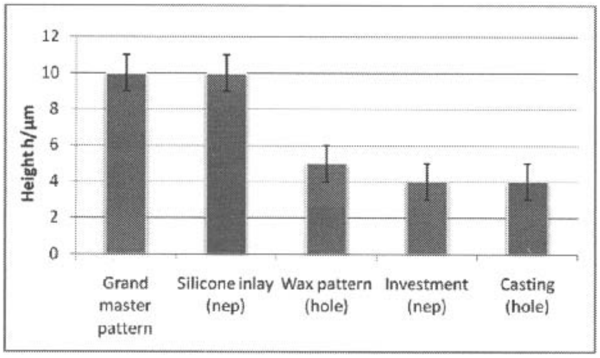

Figure 4. Moldability of microfeature height in each process step.

Grand Master Pattern

Using the parameters described above, laser structuring of a grand master pattern was performed. The reproducibility of the structure can be seen in figure 5. The difference in height can be ascribed to the rough surface of the grand master pattern's base plate. If the surface is not sufficiently smooth and flat, the laser beam is differently focused for each hole. Thus, the ablation depth varies. To increase the reproducibility and therefore the quality of the laser drilled pattern, the grand master pattern used here has to possess a higher quality regarding its roughness (e.g. polished surface) and flatness in order to guarantee a correct focal position.

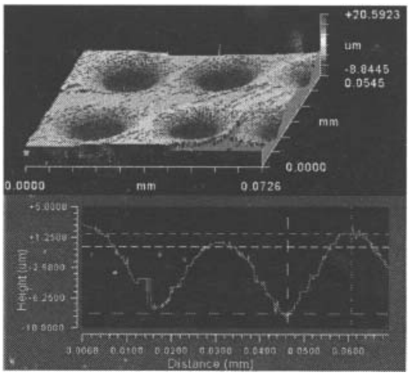

Figure 5. White light microscopy of the grand master pattern with lasered microholes. Dimensions: h = 10 µm, Ø = 22 µm.

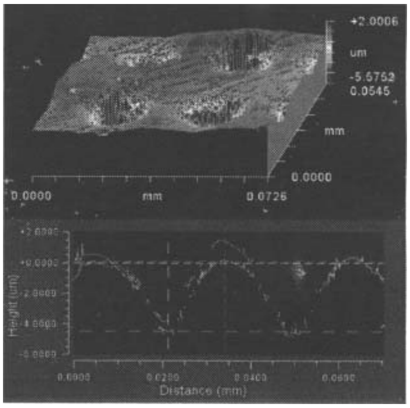

Figure 6. White light microscopy of the wax pattern. Dimension: h = 5 µm, Ø = 22 µm (scale for height varies from figure 5).

Wax Pattern

Starting the replication process from the grand master pattern, the hole structure's dimensions have been completely molded in silicone as neps over the entire area.

Using a silicone inlay which was placed in the wax pattern die, the microhole structure was molded into the wax pattern. Within this process step, the largest loss of molding accuracy occurred. Only half of the original micro feature's height could be achieved in the wax pattern, Figure 4 and Figure 6.

The results of the white light interferometer measurements showed that the grooves, which originated by fine turning the grand master pattern before laser structuring, were transferred in the wax pattern. This indicates that the microstructured surface of the silicone inlay was completely molded into the wax pattern.

Considering this excellent moldability as well as results from other examinations with similar completely molded microstructures in wax patterns, it is very unlikely that entrapped air or the material properties of the wax (surface tension, shrinkage, etc.) or the injection parameters caused the micro holes to be too shallow.

The height of the micro neps in the silicon inlay did not change even after several injection cycles. For this reason, it can be excluded that the peaks of the ribs, which form the hole structure, adhered in the wax pattern die and tore off during ejection.

The most likely reason for the shallow holes in the wax pattern is that the neps of the soft and flexible silicone inlay were compressed by the high wax injection and squeezing pressure of 16bar. If the high pressure changed the contour of the micro features could not be measured because the sides of the holes in the wax pattern did not reflect enough light back towards the white light interferometer.

Gypsum-Bonded Mold

To investigate the quality of the gypsum-bonded block mold, the hole structure was measured using WIM and SEM. The height of the micro feature (4µm) differed from the height of the wax pattern by 1µm. This difference was caused by the above mentioned measuring inaccuracy and by the roughness of the mold surface, which depends primarily on the particel size of the investment material.

As can be seen in the SEM image in Figure 7, the structure of the entire area of the microstructured field has been reproduced without any major defects. On the other hand, the surface is rugged and porous which is caused by the growth of thin gypsum needles. In order to achieve a smoother surface, it can be assumed that a finer grain size distribution of the mold material will not lead to a better molding accuracy. Rather, it is necessary to achieve smaller gypsum needles and less porosity. Therefore the water content of the gypsum mixture could be reduced, so that the gypsum oversaturated faster and a finer gypsum-needle network develops [10].

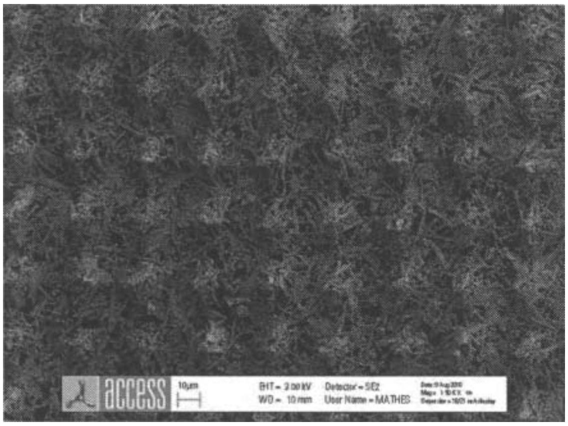

Figure 7. SEM image of gypsum-bonded investment mold

Casting

The micro structure was molded on the surface of the cast part and the feature height of the gypsum-bonded mold could be achieved on the casting. However, the hole depth and diameter were not transferred reproducibly, Figure 8. In some areas the diameter of the holes was much smaller. This may be due to the rough surface of the neps in the gypsum-bonded mold. Moreover, it could be that the strength of the gypsum-bonded investment was too low: This leads to erosion during mold filling or deformation after filling e.g. by shrinkage of the metal.

In general, it can be said that the wetting properties of the molten metal on the microstructured gypsum-surface were sufficient as the well molded areas on the cast part demonstrate. Hence, the casting and mold temperature could be lowered in order to reduce the risk of erosion caused by thermal and mechanical loads.

Another possibility is to increase the mechanical properties of the gypsum-bonded investment. Therefore, the water content could be initially lowered. Other factors which have an influence are the grain size distribution, the filler/binder ratio and the shape of the filler grains. Also, the chemical composition either of the filler (fraction of quartz and cristobalite) or of the gypsum plaster (modification of calcium sulfate and adding of set-up agents) can be adjusted.

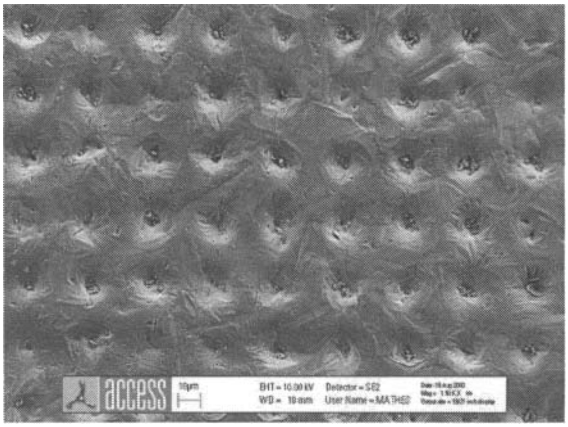

Figure 8. SEM image of cast part (the grains in the holes are the remains of investment powder)

Nevertheless, the wettability of the four structures was analyzed using contact angle measurements with ultra pure water. The contact angle of 75° on the microstructured surface demonstrates the improvement compared to the unstructured part which has a contact angle of 60°.

A further increase of the contact angle is possible by reducing the roughness of the unstructured grand master patterns as well as of the mold material and an increase in number of holes per cm^2. Additionally, it is possible that an increase of the roughness by micro structuring leads to a higher influence of the slip-stick effect which results in higher contact angles. However, based on the low standard deviations (3°) of the measured contact angels compared to the significant effect of the structures, the slip-stick effect can be excluded.

Most studies concerning hydrophobic effects used non-metallic materials with low surface energies [11, 12]. If it is possible to achieve a hydrophobic effect (contact angle > 90 °) on a common Al-alloy surface by merely improving the microstructure geometry, then this is a prospect for future examinations.

Conclusions, Prospects and Possible Applications

It has been shown that a laser structured surface consisting of microholes with a diameter of 22µm, a depth of 10µm and a separation of 10µm can be replicated in the successive investment casting process.

Micro features with the above mentioned dimensions can be completely reproduced in silicone. With such an elastic silicone inlay in the wax pattern die, the demolding of the wax pattern can be improved. On the other hand, if the silicone is too soft, the micro features of the silicone inlay can be deformed when high wax injection pressures are applied. In all probability, this was the reason for the insufficient moldability of the micro feature's heights which were 5µm in the wax pattern.

Having the microstructured wax pattern, it is possible to reproducibly mold it in the gypsum-bonded investment over the entire area. However, the gypsum-bonded mold had a porous needle-like surface which reduced the accuracy of the micro features even though the heights of 5µm given by the wax pattern could be reached.

In the last process step, the microstructured surface was cast and 4µm deep micro holes were achieved. However a few micro features could not be reproduced. This was probably caused by erosion from the liquid metal on the mold surface. Options to reduce the risk of erosion include lower casting temperatures, pressures and increased mechanical properties of the gypsum-bonded investment material. Due to the needle like surface of the gypsum-bonded mold, the roundness and diameter of the micro holes varied within a small range of sizes.

In order to determine the effect of the used hydrophobic surface, contact angle measurements were carried out. The contact angle of ultrapure water on the microstructured surface could be increased to 75° compared to 60°C on the smooth casting surface.

If it is possible to achieve a hydrophobic effect by merely producing microstructured surfaces on aluminum parts or other cast parts without changing the chemical composition of the metallic surface, then this needs to be examined in future research.

Possible applications

Possible applications include cast parts where a reduced wettability or a self-cleaning-effect is desired. Non-stick surfaces can be used on premium life style products such as cast bathroom fittings or cooking equipment. Also, cast parts which become rapidly dirty; such as wheel rims or the underbody of cars and motorbikes, represent very interesting applications for microstructured surfaces, especially in terms of corrosion protection. Another big field is industrial facilities such as chemical or power plants with complex piping and pumping systems which are very difficult to maintain and clean. Also, equipment in the food industry with high cleanliness requirements provides potential applications.

Furthermore, micro holes can be used for tribological applications, for example as reservoirs for lubricant films in cylinder-piston- pairings or bearing blocks in engines [13].

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