Casting of microstructured shark skin surfaces and possible applications on aluminum casting parts

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Abstract:

Within the project “Functional Surfaces via Micro- and Nanoscaled Structures” which is part of the Cluster of Excellence “Integrative Production Technology” established and financed by the German Research Foundation (DFG), an investment casting process to produce 3-dimensional functional surfaces down to a structural size of 1µm on near-net-shape-casting parts will be developed. The common way to realise functional microstructures on metallic surfaces is to use laser ablation, electro discharge machining or micro milling. The handicap of these processes is their limited productivity. The approach of this project to raise the efficiency is to use the investment casting process to replicate microstructured surfaces by moulding from a laser-microstructured grand master pattern. The main research objective deals with the investigation of the single process steps of the investment casting process with regard to the moulding accuracy. Actual results concerning making of the wax pattern, suitability of ceramic mould and core materials for casting of an AlSi7Mg0,3 alloy as well as the knock-out behaviour of the shells will be presented. Using the example of an intake manifold of a gasoline race car engine, a technical shark skin surface will be realised to reduce the drag of the intake air. The intake manifold consists of an air-restrictor with a defined inner diameter which will be microstructured with technical shark skin riblets. For this reason the inner diameter cannot be drilled after casting and demands a very high accuracy of the casting part. A technology for the fabrication and demoulding of accurate microstructured castings will be shown. Shrinkage factors of different moulding steps of the macroscopic casting part as well as the microscopic riblet structure will be examined.

Keywords: investment casting, microstructured surfaces, shark skin,

1. Introduction

A lot of microstructured surfaces are known in nature such as shark skin, lotus leaves, sandskink skin, moth eyes and insect feet structures. By understanding these structures and employing this knowledge to technical applications, several material properties such as drag reduction, friction, adhesion, hydrophoby and reflectivity can be optimised. Possible ultraprecision technologies for the manufacturing of microstructured surfaces are laser ablation, electro discharge machining, micro milling and LIGA as well as replication technologies such as micro-injection moulding. The shortcomings of these processes are their limited productivity or geometrical constraints in the surface processing such as attainable accuracy, undercuts, ejection-angles and the maximal machining area [1]. Furthermore, no inner areas of technical parts can be microstructured. Regarding the microstructuring of metal surfaces, LIGA and plastic injection-moulding cannot be applied. Possible technologies for metal processing and microstructuring such as embossing and rolling are currently developed and not ready to be used in an industrial scale yet. In any case these processes are subjected to several geometrical constraints as mentioned above. A reproducing process that seems to be promising to meet all the confronted requirements is the investment casting process. By moulding from a grand master pattern parts of a discretionary geometry can be achieved at relatively low cost compared to common ultraprecision technologies.

There are two objectives of this project. The first is the characterisation of the investment casting process in order to cast microstructured functional surfaces with common aluminium alloys. Second, an investment casting process to realise microstructured surfaces on technical parts will be developed by using the example of an aluminium intake manifold of a gasoline engine with an inner technical shark skin surface.

2. State of the art: Microcasting

Several analyses were conducted to examine the moulding accuracy of the investment casting process. The physical properties and shrinkage factors for certain waxes and their influence on the casting accuracy were examined [2]. The casting accuracy of micro parts using aluminium/zinc alloys and stainless steel [3] as well as low melting Au-Ag-based precious metal alloys were investigated [4]. According to these results, microparts with geometrical features in a range of 700 to 50µm can be casted with permissible geometrical variation and an average surface roughness between 0.5 and 1µm. The possibility of casting micropatternd surfaces on a casting part such as a turbine blade dummy with a structure size of 50µm with an aspect ratio of 1 were shown for an aluminium alloy and a Ni-based superalloy. In addition, the castabilty of a Bismuth-Indium solder alloy onto a quarz grand master pattern with grooves of 4µm width and 200nm depth was demonstrated [5].

3. Examine the moulding accuracy of investment casting process in order to achieve microscale riblet structures [6]

Table 1 shows the geometry and the size of the microscale features which were examined. To determine the moulding accuracy of the used gypsum-bonded-investment mould (Hinrivest G, Ernst Hinrichs GmbH, Germany), only the micropatterned side of the wax pattern was embedded. Afterwards the wax was melt out to lay open the mircostructured field. In order to examine the moulding accuracy of the casting, the microstructured wax patterns were assembled to wax trees and vacuum-embedded. The moulds were baked at 700°C and cooled down to a mould temperatur of 430°C for casting. The chosen AlSi7-alloy was casted under counter pressure at 730°C into the preheated mould. The microstructured surface was measured with a white light interferometer and on the cross-sections of metallographic polishes.

Table 1: Geometry and sizes of microstructured surface

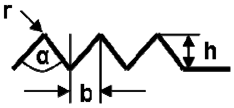
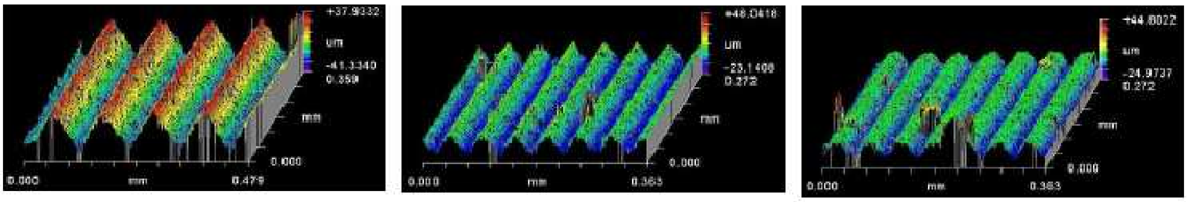
Geometry	b [µm]	h [µm]	r [µm]	α [°]
	50	50	4,5	90
	25	20	4,5	90
	25	15	4,5	90

Figure 1 shows the results of the measurement of the gypsum-bonded-ceramic as well as cross-section polishes of the casting. The structural parameters b, h, r and α of the gypsum-bonded-investment were measured in the grooves. They are similar to the original structures of the wax pattern, which were measured on top of the relief. Microscopic examinations of the whole micropatterned field showed that there are only small areas which were damaged possibly by the handling of the specimen.

The metallic microscale surface texture, which was measured on top of the structure, shows a sufficient moulding accuracy for the structural parameters b, h and α. The radius r at the peak of the structure was not reproduced sufficiently. One reason is that the contraction of the metal during solidification also influences the peak-shape. Furthermore, metal penetrations were observed on the peak and the structure valleys. Also some gas entrapments were found. Several specimens barely show any casting defects in the microstructured area whereas others contained areas with damaged and irregular microstruture geometry. There are quite a few reasons for casting defects in microstructured surfaces which will be examined in the future work.



Ceramic: b=50µm, h= 50µm
r=4,5µm, α=90°

Ceramic: b=25µm, h=20µm
r= 4,5µm, α=90°

Ceramic: b=25µm, h=15µm
r= 4,5µm, α=90 °

Casting: b=50µm, h=50µm
r=15µm, α=90 °

Casting: b=25µm, h=20µm
r=10µm, α=90 °

Casting: b=25µm, h=15µm
r=7µm, α=90 °

Figure 1: White light interferometer measurements of gypsum-bonded-ceramic (above) and cross-section polishes of the casted microscale texture (below)

4. Demonstrator part: Intake manifold with inner shark skin surface

4.1 Casting part and the definition of microstructure geometry [6]

The intake manifold with a length of 417mm and a wall thickness of 2mm is used for a formula racing car (**Figure 2**). The regulations of this racing series (Formula SAE/Student) specify that the intake air for the engine has to pass an air restrictor with an inner diameter of maximal 19mm. In order to show the potential of microscale surface textures, this part was chosen with the idea of realising a riblet shark skin structure on the restrictor surface to reduce the drag of air flow.

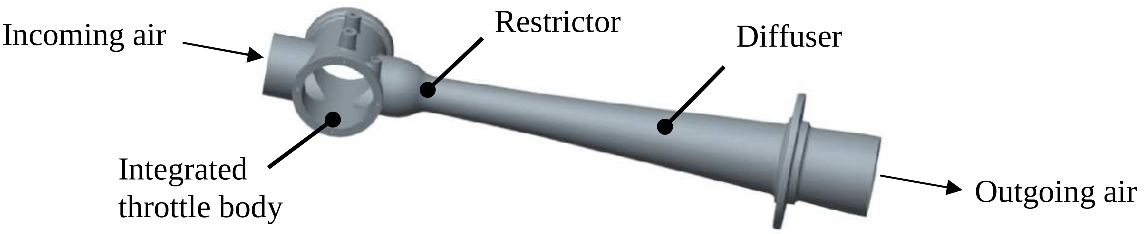
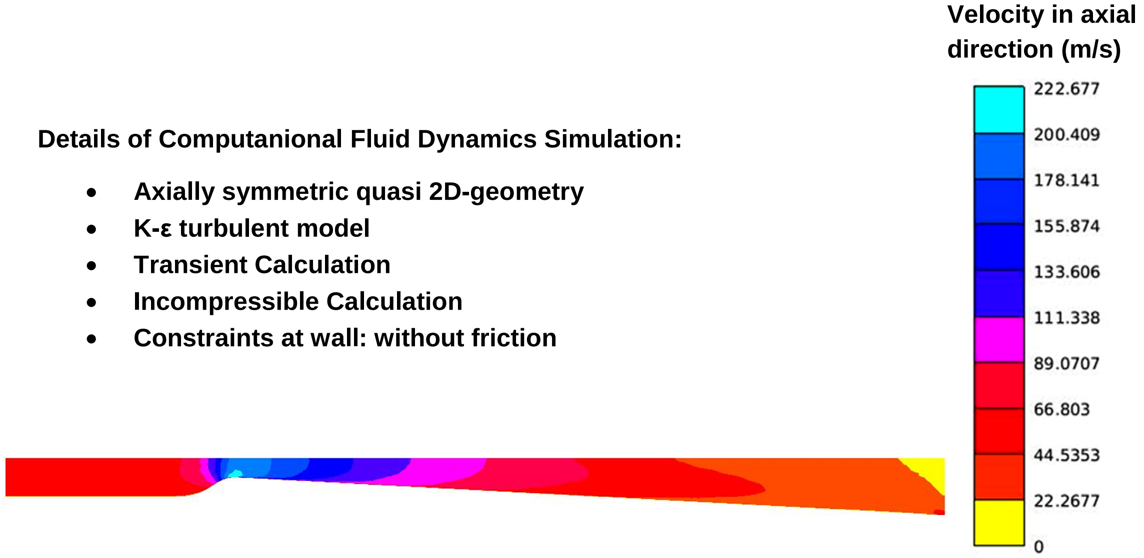


Figure 2: Intake manifold with air restrictor for a formula racing car (FORMULA STUDENT TEAM OF RWTH AACHEN UNIVERSITY)

A flow simulation was carried out to define the size of the riblets. **Figure 3** shows the velocity of the incoming air under full throttle position, which reaches approxamitly 220m/s (Mach 0,65) in the restrictor cross-section. The results were verified at two control points with a charge-cycle-calculation of the engine. With the simulation results of the turbulent kinetic energy and the wall shear stresses, sizes for the microscale texture could be estimated by applying the calculations of Bechert et al. [7]. These optimal structural parameters are: b=9µm, h=9µm, α<=60°, r<=1µm (**Figure 4**). The riblets should be arranged in the direcion of flow to achieve a drag reduction up to 4% as several experiments in literature have demonstrated [7].


Details of Computanional Fluid Dynamics Simulation:

- **Axially symmetric quasi 2D-geometry**
- **K-ε turbulent model**
- **Transient Calculation**
- **Incompressible Calculation**
- **Constraints at wall: without friction**

Figure 3: Velocity in axial direction
(half of axially symmetric cross-section of intake manifold)

Figure 4: Optimal riblet structure [7] (left) and fabricable riblet structure (right)

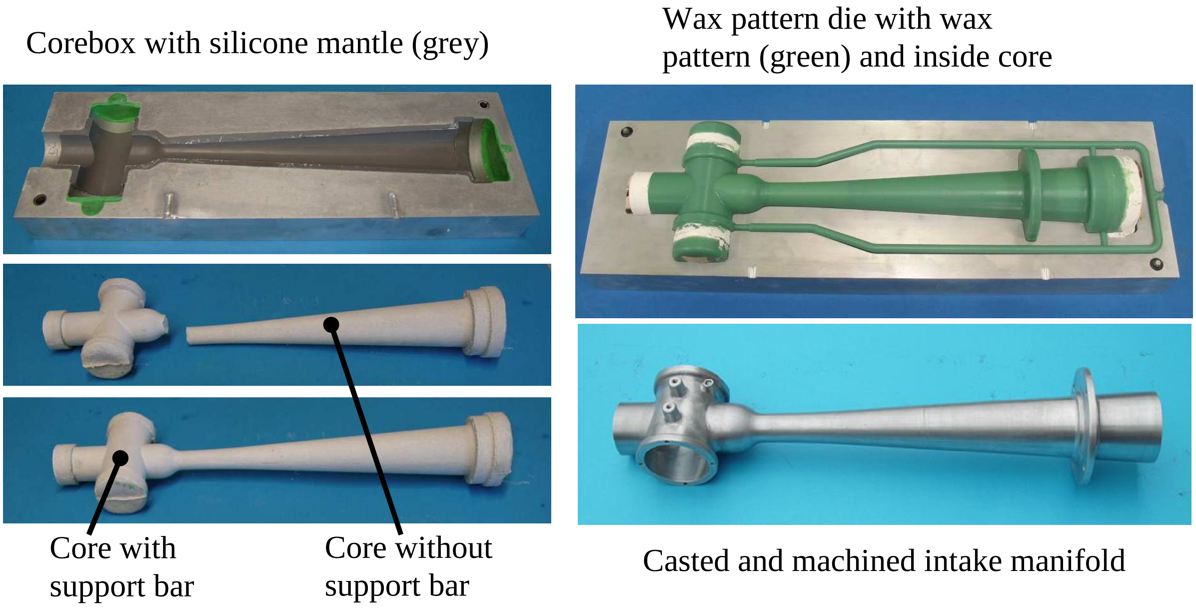
4.2 Process routes to realise a microscale texture on interior surfaces [6]

To realise a microscale texture on the rotation-symmetric inner surface of the intake manifold, only process steps that allow a demoulding of the texture without damaging it are suitable. Accordingly, three possible process chains are recommended. First, a polymer film with a microscale texture could be glued on the wax pattern, while it is difficult to handle it on the interior surface of the housing. Two alternative routes are suitable which allow a demoulding of either the wax pattern or a lost core from a microtextured grand master pattern. The grand master pattern is made of very elastic silicon and can be stripped off the assigned micropatterned surface without damaging it. The more promising route seems to be the microstructuring of a lost core in which the microstructured surface does not need to be moulded into the wax pattern, since the wax will be melted out later on. In this way, an additional process step of moulding the microstructure can be saved and thus reduces the loss of moulding accuracy. Other advantages of this process route are the better handling of the microstructured exterior surface on the core instead of the interior surface on the wax pattern in terms of demoulding as well as inspection of reproducibility and quality.

4.3. Process route: Microstructuring of the lost core

In the first step, the technology of microstructuring the ceramic core was developed. The contraction/expanding factors of the whole process, including hardening and burning of a gypsum-bonded ceramic core, making of the wax pattern and shrinkage of the casting part needed to be determined in order to realise the required inner diameter in the restrictor of 19mm. Afterwards, a steel core was drilled and will be microstructured via lasering later. From this microstructured steel core, a silicone mantle inlay (Elastosil® M 4643 A/B, Wacker Chemie AG, Germany) was moulded and placed into the core box. **Figure 5** shows the core box with the silicon mantle inlay without microstructure. After filling the evacuated core box (p=-950mBar) with a very fine-grained gypsum-bonded-invesment (Hinrivest G, Ernst Hinrichs GmbH, Germany), sufficient mechanical strength and shake out properties, the core was given several hours for the setting of the gypsum plaster. Subsequently, the core was taken out of the core box together with the silicon mantle. The mantle could be carefully stripped off the core, which is of high importance for the manufacturing of a microstructured core. When demoulding the ceramic core of the core box, there is high risk of breaking it at its weakpoint. Therefore, a bar made of stainless-steel was used to support the ceramic green body. Afterwards, the core was placed into the wax pattern die, which was injected with wax. The wax pattern was embedded into a gypsum-bonded-compact mould (Goldstar XXX, Hoben Int. Ltd., UK). The wax was melted out and the mould was burnded at 700°C for 4 hours. In order to achieve a good mould filling, the part was casted in AlSi7Mg0,3 at 740°C under counter-pressure and the mould was preheated to 420°C.

The investigations showed that the contractions and expansions during different process steps offset each other. Moreover, the stability of the core needs to be improved to avoid cracking during demoulding and burning. By using a support bar made of stainless steel, the core could be demoulded from the core box without any cracks. Also when burning the core, cracks could not be observed due to a similar thermal expansion behaviour of the steel bar and the gypsum-bonded-investment (linear expansion of both materials at 700°C approx. 0,8-0,9%). However, when cooling down the core to the preheating temperature of 420°C for casting, cracking of the core at its thinest cross-section was observed corresponding to the high contraction of the gypsum material, which results in tensile load in axial direction on the core. Using reinforcement inside the core reduces the mechanically resilient cross-section of the gypsum material. During these examinations several cores cracked which caused a thin flash on the inner surface of the casted restrictor. In case of casting a microstructured surface, this flash cannot be removed without damaging the riblet structure. Future work will concentrate on the improvement of the strength of the gypsum investment. Nevertheless, by adjusting the mixing and vacuum-filling process of the gypsum material, defect free cores without any gas pores could be manufactured. At a preheating mould temperature of 420°C, almost penetration free casting surfaces could be realised. A roughness measurement on the interior surface showed an average roughness (r_a) of 0,65µm (average of 3 line measurements with a length of 15mm).



Fiure 5: Core box with gypsum-bonded green cores (left), wax pattern and machined casting part (right)

5. Summary and outlook

It was shown that groove structures down to a width of 25µm and a height of 15µm can be realised with the common investment casting process using an AlSi7-alloy. The challenge is to achieve edges with roundings of less than 1µm. This is especially interesting for drag reducing riblet structures. To demonstrate the potential of microstructure surfaces manufactured in the investment casting process, an intake manifold was chosen as use case part. Possible process chains for the realisation of riblet structures were shown. The most promising process route seems to be the microstructuring of a lost core. The core material has to meet several requirements concerning moulding accuracy and shaking out behaviour. Accordingly, a gypsum-bonded-investment was chosen. To manufacture cores without cracks when demoulding, burning and casting, it is necessary to improve the core making process by using reinforcement materials as well as raising the mechanical properties of the core material. Up to now, the restrictor was casted without a micorstructured inner surface in order to advance the investment casting process. In the second step, the whole process chain will be passed through with the microstructured riblet structure. Afterwards, the improvement in performance of the intake manifold with an inner shark skin surface will be tested on an engine test bench.

6. Acknowledgements

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7. References

[1] Uriarte, L.; Herrero, A.; Ivanov, A.; Oosterling, H.; Staemmler, L.; Tang, P.T.; Allen, D.: Comparison between microfabrication technologies for metal tooling. J. Mech. Engineering Science, 2006, Vol. 220 Part C,

[2] Hock, et al.: Experimental study on the accuracy of wax patterns used in investment casting. J. Engineering Manufacture, Vol. 217, Part B:

[3] Charmeux, et al.: Benchmarking of three processes for producing castings incorporating micro/mesoscale features with a high aspect ratio. J. Eng. Manufacture, Vol. 221, Part B

[4] Wöllmer, H.: Untersuchung zum Präzisionsgießen metallischer Mikroteile. Dissertation, 2000, University of Freiburg, Germany

[5] Schmitz, G.J.; Grohn, M.; Bührig-Polaczek, A.: Fabrication of micropatterned surfaces by improved investment casting. Advanced Engineering Materials 2007, 9, No. 4

[6] Ivanov, T.; Bührig-Polaczek, A.; Vroomen, U.: Replication of Microscale Features via Investment Casting Using the Example of an Aluminium Intake Manifold of a Gasoline Engine with an Inner Technical Shark Skin Surface. Materials science forum, ISSN 0255-5476, 2009, vol. 618-19, pp. 581-584

[7] Bechert, D.W.; Bruse, M.; Hage, W.; Van der Hoeven, J.G.T.: Hoppe, G.; Experiments on drag-reducing surfaces and their optimization with an adjustable geometry. J.Fluid Mech. (1997), vol. 338, pp. 59-87