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Defects investigation in additively manufactured steel products for injection moulding

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Abstract

Additive manufacturing refers to the group of new manufacturing methods where parts are built layer by layer starting from a digital file. Using these technologies, it is possible to produce parts with an incomparable design freedom with, potentially, any material. The quality of the built products depend mainly on the machine capabilities, the quality and type of metal powder used, and the choice of process parameters. The paper presents aims to study the origin of defects that appear on the polished surface of the metal additive manufactured parts using selective laser melting of maraging steel grade 300 and how they can be reduced. The main purpose is to understand how these defects can influence the quality of the injection moulded products, when additive manufacturing is used to produce the moulds.

Additive Manufacturing, 3D printing, Metal Additive Manufacturing, Defects, Selective Laser Melting, Homogeneity, Microporosity, Maraging steel, Injection Moulding

Introduction

Metal Additive Manufacturing (MAM) is a group of manufacturing technologies capable of producing near-net-shape parts starting from powder or wire feedstock. The most common MAM technology is powder bed fusion, like Selective Laser Melting (SLM). With this process, parts are produced layer by layer, based on the sliced-version of the design prepared on a CAD software, by a laser that scans the specific areas on a single layer of powder [1]–[3]. This uniquely digital nature of additive manufacturing allows unprecedented process management possibilities and control [4]–[6]. The industries in which such a technology can be used has already been broadly discussed in literature [7], [8], as well as the great benefits that can be derived from implementing it in production [9]–[11].

One of the applications of interest, especially for consumer goods manufacturers, is the possibility of producing toolings such as mould inserts for injection moulding. Here, SLM-produced inserts allow multiple advantages like reduction of injection moulding cycle time and reduction of lead-time to produce new inserts. The former is enabled through conformal cooling channels that can improve the thermal management of the mould, and the latter through the design freedom since SLM is capable of producing a near-net-shape part with reduced post-processing requirements [12]–[14]. However, depending on the final application of the injection moulded parts, the resultant surface quality of the mould cavities becomes important - specifically since the defects on the tool surface can be replicated on the polymer final products [15]. Typically, injection moulded parts for consumer goods industries have stringent surface requirements for the polymer which, in turn, ascribes higher requirements for the metal tool’s surface quality.

In the following paper, the authors have analyzed the nature of micro-porosities appearing on the polished surface of SLM parts made out of maraging steel grade 300, and their effect on the injection moulding products.

Materials and methods

The material investigated in this study is steel 1.2709, i.e. maraging steel grade 300 powder, with a chemical composition as shown in table 1. The average size of the powder particles is in the range of 53-63 µm and the corresponding SEM pictures of the powder are presented in fig.1.
Table 1 Chemical composition of the maraging steel powder grade 300.

<table>
<thead>
<tr>
<th>Element</th>
<th>Composition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe</td>
<td>9.02</td>
</tr>
<tr>
<td>Co</td>
<td>18.42</td>
</tr>
<tr>
<td>Ni</td>
<td>4.97</td>
</tr>
<tr>
<td>Mo</td>
<td>0.63</td>
</tr>
<tr>
<td>Ti</td>
<td>0.07</td>
</tr>
<tr>
<td>Al</td>
<td>0.04</td>
</tr>
<tr>
<td>Cu</td>
<td>0.20</td>
</tr>
<tr>
<td>Cr</td>
<td>0.05</td>
</tr>
<tr>
<td>Mg</td>
<td>0.08</td>
</tr>
<tr>
<td>Si</td>
<td>0.01</td>
</tr>
<tr>
<td>C</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>P</td>
<td>0.01</td>
</tr>
</tbody>
</table>

The parts have been produced with a EOS M270 SLM machine, that uses nitrogen atmosphere inside the building chamber. The machine is equipped with a Yb-fibre laser that can reach a maximum of 200 W of power and up to 7.0 m/s of scan speed. The parts are produced using 40 µm of layer thickness. After completion of each job, the unused powder in the building chamber of the machine is collected and sieved before it can be re-used for another job. However, each sieving cycle undergone by the powder increase the quantity of contaminations due to the exposure to external unprotected environment. Typically, after production in an SLM machine, the parts are cut from the building platform, cleaned from the residual loose powder, and heat treated, to reduce the residual stresses and improve their mechanical properties. The heat treatment procedure used in this study starts with a 2 hours exposure in a furnace at 350°C, followed by 8 hours at 530°C, after which the part is allowed to cool down slowly in the furnace.

In this research, 3 different types of samples with dimension 30mmx30mmx20mm have been investigated:

- Using new powder, the part was then heat treated
- Using new powder, the part was not heat treated
- Using sieved powder, the part was then heat treated.

Examples of these samples can be seen in figure 2.

The parts were subsequently grinded and mirror-polished on the top surface (on the x-y surface according to the building platform in the job) to the same tolerances and specifications as the internal surface of injection mould cavity. At this stage, it was already possible to distinguish little spots through manual visual inspection, where the light was reflecting differently from the rest of the surface potentially due to the presence of porosities.

These surfaces were then observed with a Zeiss EVO LS25 SEM microscope, equipped with the EDS, and analysed with the Aztec software, a Nikon measuring optical microscope MM-800 and an Olympus LEXT OLS4100 laser scanning digital microscope to reconstruct the 3D image of the defects. To understand the consequence of these defects on the injection moulding products, the injection moulding process was simulated using a COLLIN hot press machine by replicating the metal surface on polymer ABS granulates (samples shown in figure 3).
The parts produced in this way were subsequently observed and analysed with the Nikon microscope to understand the replication of the defects from the metal surface.

Results and discussion

Two elements within the chemical composition of maraging steel grade 300, namely titanium and aluminium, are particularly dangerous when exposed to the open air in the ambient due to their propensity to be oxidized into titanium and aluminium oxides. Residual porosity in SLM parts ([16]–[21]) and internal defects, like inclusion, in maraging steel ([22]–[24]) are topics already extensively investigated in literature.

In Table 2 is presented a collection of optical micrographs taken with the Nikon microscope on the metallic and polymeric specimens presented in the previous section.

Table 2 Surface pictures of the metal SLM parts and the replicated polymer surface

<table>
<thead>
<tr>
<th></th>
<th>Metal</th>
<th>Polymer</th>
</tr>
</thead>
<tbody>
<tr>
<td>New powder, not</td>
<td></td>
<td></td>
</tr>
<tr>
<td>heat treated</td>
<td></td>
<td></td>
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<tr>
<td>New powder, heat</td>
<td></td>
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<tr>
<td>treated</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sieved powder,</td>
<td></td>
<td></td>
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<tr>
<td>heat treated</td>
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</table>
The spots visible from the above pictures of the metal surface were then analysed with the SEM and EDS, to have a better understanding of their nature. Some of the images are summarized in Figure 4.

![Figure 4 SEM pictures of the metal SLM surface](image)

**Figure 4 SEM pictures of the metal SLM surface** (a) new powder, heat treated; (b) new powder, not heat treated; (c) sieved powder, heat treated

From the EDS analysis, the darker spots and micropores visible in these pictures were found to be primarily titanium oxides, which is in accordance to what found in literature [22]. One example is presented in Figure 5.

![Figure 5 SEM and EDS analysis of a surface inclusion in the sample with new powder, heat treated.](image)

**Figure 5 SEM and EDS analysis of a surface inclusion in the sample with new powder, heat treated.**

For all three types of samples, the dimension and shape of the defects did not show any specific pattern. Considering the shape and the chemical composition of the micro-pores investigated, the origin of these pores can be attributed to oxide inclusions (mostly titanium) that are fractured and then dislodged during the post-processing steps for the surface preparation (i.e. grinding and polishing). The inference is corroborated through the LEXT images, presented in Figure 6, where it is possible to notice the pores and the surrounding scratches that the hard oxides left on the surface while rolling out.

![Figure 6 LEXT image of micropores in the SLM sample with sieved powder, heat treated.](image)

**Figure 6 LEXT image of micropores in the SLM sample with sieved powder, heat treated.**

The optical micrographs, as shown in Table 2, were then analysed with the image processing software Image J to determine the percentage of the defects present on the surface of metal moulds as well as
polymer part. Figure 7 compares the three different metal surfaces and the replicated polymers with respect to the porosity:

![Figure 7 Results of the measurements of percentage of defects in the metal SLM and polymer parts](image)

Figure 7 shows clearly that the defects on the metal SLM surface do not totally replicate on the polymer surface. User blind tests were done on the polymeric specimens produced to check if the defects highlighted with the microscope were also recognisable at naked eye. The tests confirmed that the replicated defects were too small to be detected.

**Conclusions**

This work is an early analysis of the micro-porosity appearing on the polished surface of SLM parts, and their effect on the functional surfaces of injection moulded consumer goods. The results indicate that the defects appearing on the surface are coming from oxide inclusions due to powder contaminations and are not actual porosities from the SLM process itself (like those arising from lack of fusion or keyhole formation), thanks to the right choice of process parameters. At the same time, the influence of these inclusions and pores on the injection moulding process can generate defects on the polymer surface. Depending on the final application of the polymeric moulded product, the replicated defects can be considered either acceptable or not. In the case of consumer goods products produced with dark coloured ABS, the defect above investigated are not visible with the naked eye, however, it is expected that the situation can change when using other type of polymer with a different viscosity or with other contrasting colours and especially in case of moulding transparent parts. The acceptance criteria of the moulded parts will depend primarily on the final application of the products. Some aspects observed in the current study are also identified to require further investigation, such as the influence of the heat treatment on the number of defects. In literature, Shibata at al. have observed a change in morphology and chemical composition of the oxides inclusions in stainless steels when heat treated, however this aspect should be investigated more in details for maraging steel [25]. What is clear from this research is the significant influence of powder reuse and the requirement for better control. When not performed in a controlled manner, as in this case, the amount of contamination increases considerably generating problems in the final quality of the products produced with injection moulding.

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**References**


