Contributions to Optimization of Properties for Components Fabricated by mean of Selective Laser Sintering from Composed Materials

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Abstract: - In the context of intrinsic sustainability of fabrication techniques belonging to powder metallurgy, recent developments in rapid tooling based on Selective Laser Sintering (SLS) has proved to be an effective method for reducing time-to-market for products belonging to very different industries. Current applications already include production of die inserts, active parts for different tools and devices, orthopedic implants etc. Fabrication routes usually include indirect laser sintering of an iron based powder, burning out of polymer binder, heat treatment in controlled atmospheres and final infiltration with non-ferrous alloys. Since infiltration alloy represents a significant proportion of the final material, optimization of bronze compositions could be an important way to increase mechanical properties and durability. In order to improve conventional bronze grades that are used for infiltration, a study has been performed to determine the influence of tin on both mechanical properties and infiltration capacity of the copper-based alloy. Results of infiltration with different alloy compositions have been evaluated by mean of optical and electronic microscopy to estimate filling quality, as well as mechanical testing to determine mechanical properties of final material.

Key-Words: Intrinsic sustainability, Powder metallurgy, Rapid tooling, Selective Laser Sintering, Infiltration bronze.

1 Introduction
1.1 Sustainability of Powder Metallurgy
Technologies based on powder metallurgy (PM) have an intrinsic potential to promote sustainable development [1]. Considering one of the largely accepted definition of sustainable manufacturing as “the creation of manufactured products that use processes that are non-polluting, conserve energy and natural resources, are economically sound and safe for employees, communities and consumers”, some basic features of powder metallurgy could be mentioned:
- PM has considerable capabilities for net-shape production of various parts, with a very high material-utilization factor, which minimizes all energy inputs. With the exception of metal for powders, which is melted in the atomization step; all other technological operations are undertaken below melting temperature. In addition, there is little if any finishing to final product specifications necessary, further conserving the energy necessary to achieve final product characteristics. In some cases energy consumption could be reduced up to more than 40%, if classical fabrication routes based on forging and machining are replaced by PM technologies.
- Facility sustainability is based on the fact that more of 25% enterprises in PM industry have achieved ISO 14001 registration of their facilities. PM plants are generally well-lit, clean, and healthy workplaces with an increasingly higher level of automation, with a minimum of direct handling. Nearly the entire industry has earned ISO 9001, QS 9000, or ISO 14001, or practices Lean Manufacturing. Therefore labor represents a minor part of costs and productivity is very high.
- Extension of PM technologies improves environmental sustainability since final machining operations are minimal, resulting in minimal use of cutting oils. There are no contaminants inside the water emitted to public systems. Recent developments have removed almost entirely graphite or listed chemical, such as stearates, eliminating the potential for gaseous toxic releases from sintering operations. Since nearly all scrap produced is metallic, it is routinely recycled, thus minimizing the industry’s contribution to landfills.
1.2 Rapid Tooling

PM technologies still have high potential for innovation and increasing influence on sustainable development effect. One of the most important achievements of latest decades is the development of technologies that permit rapid fabrication of tools, from metallic powders, based on CAD model, at high mechanical properties. Shifting from polymeric to metallic materials has allowed a very significant evolution from rapid prototyping to what is known as rapid tooling. Rapid tooling is increasingly used for fabrication of injection or casting tools, high-wear or high temperature components, biological implants etc.

Among the most promising technique used in rapid tooling, selective laser sintering (SLS) has a distinctive position. Recent developments allow significant reducing of time-to-market for new products in many industries. For example, complex inserts of dies for plastic injection could be fabricated in few days. Durability of resulting components permits injection of some thousands of parts. In the case of SLS, it is the laser radiation that represents the source of concentrate energy, in order to join the particles of metallic powder.

If particle joining is realized by mean of a melted phase as effect of irradiation with a high energy laser radiation, the technique is called direct selective laser sintering. Resulting material is almost consolidated as result of a liquid phase sintering. Supplementary densification treatments are sometimes necessary to provide final strength.

Indirect SLS is produced if each metallic particle is covered by polymeric envelope, which plays the role of binder. Energy density of laser radiation is lower and heating level is moderate, only to soften the thermoplastic envelope. Indirect SLS techniques produce green parts that have to be sintered, in order to create particle joining. Final porosity could rise to more than 40% in volume, which make densification mandatory, usually as infiltration with a more fusible alloy. Therefore final properties could be roughly evaluated after the rule of mixture between base metallic alloy and infiltrated material, both components having considerable influence upon final performance of the tool. Most common combination of materials for rapid tooling y mean of indirect SLS is steel, stainless or high speed, as base material, and copper alloy, usually conventional bronze, as infiltration material.

Indirect SLS has proved so far to be simpler to operate, and has evolved to industrial application, in comparison to direct techniques, which are still mostly at experimental stage.

The objective of present study is to optimize the composition of infiltration bronze used for densification of sintered parts, considering the significant contribution to final properties. Two important aspects have to be considered for high final properties of fabricated tools:
- Densification material must have good infiltration in relation to base material, so the residual porosity has to be as reduced as possible;
- Infiltrated material must have high mechanical properties, since it represents an important proportion of tool material, and therefore influences considerable the service behavior of the tool.

2 Materials and Technology

Indirect SLS technology has been applied to RapidSteel powder, having nominal chemical composition similar to 316L stainless steel, presented by Table 1.

<table>
<thead>
<tr>
<th>Element</th>
<th>Fe</th>
<th>C</th>
<th>Cr</th>
<th>Ni</th>
<th>Mo</th>
</tr>
</thead>
<tbody>
<tr>
<td>%</td>
<td>Bal.</td>
<td>&lt;0.03</td>
<td>16-18.5</td>
<td>10-14</td>
<td>2-3</td>
</tr>
</tbody>
</table>

Table 1. Nominal composition of RapidSteel powder

Experimental components have been fabricated by mean of indirect SLS using a DTM Sinterstation™ 2500. Fabrication route consists of following operations:
- Creation of the CAD model using conventional software;
- Selective sintering of a green compact. Steel particles are joined by mean of the polymeric envelope, which covers the entire surface of each particle. Special care has to be taken during manipulation, since green compacts are very fragile;
- Consolidation treatment of green compacts, which consists in furnace sintering using nitrogen atmosphere. One preliminary phase at 600°C is dedicated to the burning of polymeric binder. Final heating at 1120°C is performed at a very low rate, in order to avoid thermal stresses and fissures. Thermal cycle for material consolidation is presented in figure 1.

![Fig. 1. Sintering treatment of green compacts.](image)
- Resulting material has a very high porosity after furnace sintering and bronze infiltration is needed in order to improve mechanical properties. Parameters of the infiltration treatment, which is performed also in nitrogen atmosphere, are shown in figure 2. Figure 3 illustrates microstructure of material after sintering operation, showing high porosity and formation of permanent joints between particles. Metallographic etching evidenced a fine-grained structure of the stainless steel. Most of former particles are already joined as effect of diffusion, which shows that sintering is completed, and there is no evidence of any binder. Dark areas in figure 3 signify the remaining pores, and they represent a very consistent proportion of sintered materials, which is not acceptable for applications in tools, so subsequent infiltration is mandatory.

Microstructure after infiltration is presented in figure 4. Dark areas represented by pores are almost disappeared; only small amount of residual pores is still present as small black areas, at the limit of former steel particles. Bright areas signify the volume which has been filled by the infiltration material.

It may be stressed out again that since infiltrated bronze represents large proportion in the final microstructure, its properties will influence considerably tool performances, therefore an optimization of bronze mechanical properties and infiltration ability would be of great benefit.

Sintering and infiltration are relatively long and energy intensive, so combined treatments are also possible. Figure 5 indicates the parameters of a treatment that could replace both sintering and infiltration.

3 Experiments and Results
Most conventional grades of bronze have been used so far for infiltration of sintered stainless steel, and little information is available regarding the influence of tin content of the bronze upon infiltration ability and final properties. Therefore, it has been designed an experiment, which uses as variable the tin content of infiltrating bronze. No other alloying elements have been considered for this stage of the experiment.

Small quantities of bronze with different tin content have been elaborated in argon atmosphere using an
induction furnace. The tin content of samples is presented in table 2.

### Table 2. Tin content of bronze samples.

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>% Sn</td>
<td>3</td>
<td>7</td>
<td>13</td>
<td>16</td>
<td>20</td>
</tr>
</tbody>
</table>

Microstructural appearance of bronze samples after elaboration is presented by figure 6.

a) Sample 1, OM (optical magnification) 50x.
b) Sample 2, OM 50x.
c) Sample 3, OM 50x.
d) Sample 4, OM 50x.
e) Sample 5, OM 50x.

Fig. 6. Microstructure of bronze samples.

After infiltration, microstructural investigations have been performed to determine the infiltration ability of bronze sample as function of tin content.

Another experimental program has been dedicated to mechanical testing, in order to evaluate possible performances of tools during service.

### 3.1 Metallographic Analysis

After sintering and infiltration with bronze grades containing different tin proportions, final material samples have been extracted and metallographically processed.

Microscopic investigations have been performed on unetched surfaces under polarized light. Areas corresponding to infiltrated bronze appear bright, and base stainless steel is darker. Similar distributions of stainless steel and bronze appear on all samples. Small black portions indicate residual pores, where melted bronze could not penetrate. In this respect, samples infiltrated with bronze containing less tin (figure 7 a, b and c) seem to contain more residual pores than samples where bronze contain more tin (figure 7 d and e).
Therefore following conclusions may be formulated:
- Even small tin content, as less as 3% allows bronze infiltration, so that residual porosity is reduced, and preliminary evaluations indicate densification over 90%.
- Higher tin content will improve infiltration and final porosity decrease considerable when tin proportion is at least 16%.

3.2 Mechanical Testing
In order to determine mechanical properties of final material infiltrated with bronze grades containing between 3 and 20% Sn, specimens for tensile test have been produced by mean of indirect SLS, and subsequently sintered and infiltrated. Size and dimensions of specimens are presented in figure 8.
Tensile test have been performed with a rate of 0.02 millimeter/second. Resulting values of ultimate tensile stress (UTS) are presented in figure 9.

An analysis of experimental values of UTS presented by the chart in figure 9, reveals that lower tin content favorize higher mechanical resistance, with a maximum value corresponding to sample 3 (13% Sn). If tin content increases mechanical resistance of final material has an obvious decline.

If elongation A is considered (figure 10), ductility has also a similar maximum value for 13% Sn. Higher tin content seems to produce material fragilization, if tin content is more than 15%. It may be supposed that if infiltration is performed with bronze grade having high tin content, tools may have an inappropriate behavior to dynamic stress.

Results of hardness investigations presented by figure 11 reveal an optimum of high hardness values in the range between 10 and 15% of tin. This may suggest that medium content of tin could provide also a good wear behavior of tools.

4 Conclusion
Experimental program revealed that rapid tooling by mean of indirect SLS applied to steel-bronze composed materials could provide high mechanical properties for tools.

Tin content of infiltrated bronze influences significantly properties of final material:
- High tin proportion promotes good infiltration, which produces only minor proportions of residual pores, if more than 16% Sn.
- Mechanical properties, such as mechanical resistance, ductility and hardness have optimum values when tin content is moderate, in the range between 10 and 15% Sn.
References:


