Manuscript refereed by Dr Bernhard Tabernig (Plansee SE, Austria)

Optimization of SLM Technology: Main Parameters in the Production of Gold and Platinum Jewelry

A. Carlotto, A. Loggi*, P. Sbornicchia*, D. Zito*, D. Maggian*, A. Molinari**, I. Cristofolini***

**Progold S.p.A., Trissino (VI), Italy*
***University of Trento, Trento (TN), Italy*

Abstract

The results previously obtained with gold alloys for selective laser melting (SLM) underlined the key role not only of process parameters but also of powder chemical composition for producing quality precious metal jewellery. This paper illustrates the effect of some selected chemical elements to improve laser radiation absorption and to favour the melting of metallic particles. In addition, the impact of the structure and morphology of the supports was examined in order to optimize their density and maintain an adequate thermal dissipation of laser energy.

Introduction

In 2013 we studied the selective laser melting (SLM) of precious metal jewellery and ways for improving the quality level of such parts. Our effort was aimed at obtaining jewelry pieces through SLM with a quality level similar to investment cast pieces [1,2,3,4]. In this further study we used the optimum work parameters selected in preceding experiments and evaluated the effect of alloying with some elements (Ge, Si) favoring the absorption of laser radiation. Furthermore the impact of the structure of the support system was examined regarding the shape and density of test pieces for different slope angles.

Experimental Practice

The experimental pieces were produced with a Realizer SLM™ 50 machine equipped with a 100W fiber laser having a 10μm spot and with a circular 70mm diameter build platform, placed in a chamber under an argon protective atmosphere.

Two powders were used for this study: a 750‰ red-gold alloy and a 950‰ platinum alloy. The chemical composition of the gold alloy was modified by the addition of elements selected to increase the absorption of laser radiation, thus reducing radiation reflection and diffusion by the powder particles that hinder melting of the powder.

Absorption of laser radiation by a metal (equation 1) is proportional to the square root of electrical resistivity [5]. Therefore, we looked for suitable elements to add that would increase electrical resistivity appreciably without compromising color and the mechanical characteristics required for jewelry alloys.

$$A = k\sqrt{\xi_r} \qquad \text{(equation 1)}$$

where:
A = absorptivity
k = a constant $(\Omega\cdot m)^{-1/2}$
ξ = electrical resistivity (Ω·m)

The software Magics 17.02 (Materialise) was used for the development of the supports for the experimental pieces and the experimental pieces were parallelepipeds (bricks) with the following nominal dimensions: length (L) 10.0mm, width (W) 4.50mm and thickness (H) 3.00mm. Actually, the finished thickness of the pieces was to be 2.80mm, but it was intentionally oversized to 3.0mm to accommodate subsequent grinding and polishing for the quality level evaluation. An oversize of 0.20mm was necessary to eliminate the spongy layer that is usually present at the base of items built by SLM and to avoid defects caused by support detachment. The usual production practice is to repair small defects deeper than 0.20mm or reject the piece if the defect is too awful.

After the bricks were removed from the build platform, they were embedded for metallographic sections (Figure 1). This configuration allowed precise thickness measurements during grinding and polishing using optical microscopy. The longitudinal section (A) was used to measure the thickness of the pieces so grinding and polishing could be stopped at the exact projected value and was also used to evaluate the depth of defects formed in the growth direction of the pieces. The thickness of the as-grown brick at the interface where the supports stopped and the surface of the bricks started was 3.00mm. Removing 0.20mm by grinding and polishing the transverse surface (B) removed a significant amount of normal defects and allowed quality evaluation on a surface equivalent to that of a finished piece of jewelry. However, for the first evaluation, the specimens were taken in steps to a precise thickness of 3.00mm using automated grinding and measuring the progress between each step. Once the specimens reached 3.00mm, the surface was scrutinized and compared to evaluate the general amount of defects. A second and more detailed evaluation of each specimen was carried out after removing another 0.20mm to make it 2.80mm thick.

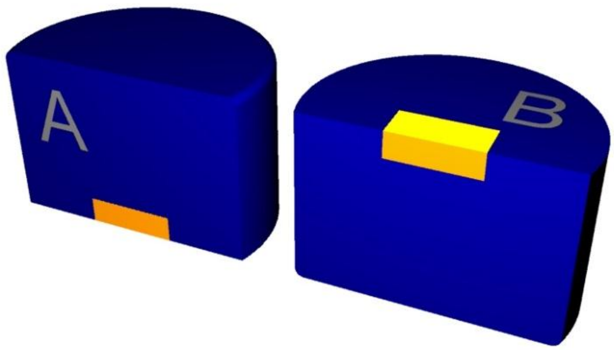

Figure 1 Longitudinal (A) and transverse (B) surfaces for defect evaluation

Many variables were considered for evaluating the alloys, namely:

- Chemical composition of alloy particles
- Supports structure and distribution
- Slope angle of the walls of the pieces contacting the supports

Chemical composition of the classic Au-Ag-Cu alloy for SLM was modified with the addition of semiconductor elements with high intrinsic electrical resistivity such as germanium and silicon. The concentration of these addition elements must be relatively low to avoid excessive deterioration of the properties required for a jewelry alloy. However, the high electrical resistivity of these additions appears to allow an important laser radiation absorption increase.
We compared the effect of doping a classical alloy with the behavior of an alloy with a high content of a more electrically resistive metal. We planned a set of experiments with the software Materialise (Magics 17.02) for the creation and application of the support system for the pieces. This study considered two main types of support structures to evaluate their behavior. Two different networks of support elements formed the first support type, called a block, where both spacing (1.00 and 1.50mm) and contact point area with the base of the piece were modified (Figure 2).

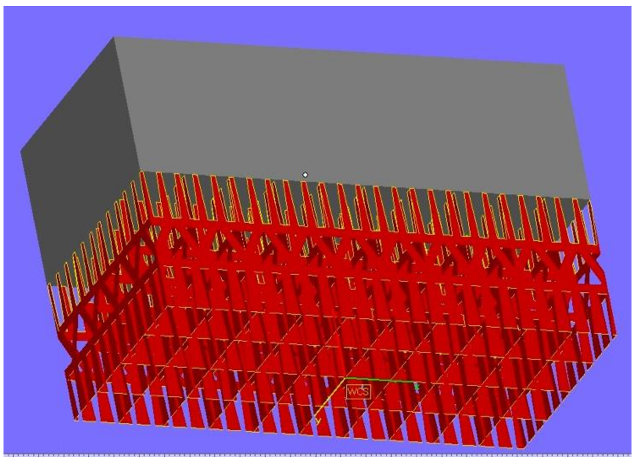

Figure 2 Block support with 0.10mm contact area with the piece

The second type, called volume supports, is a pillar array having square or rectangular cross sections and is attached to the build platform at the bottom and directly to the piece at the top. The spacing between the supports was set at 1.00 and 1.50mm. The nominal contact area of each pillar with the piece was the same for both the 1.00 and 1.50mm spacing, about 0.69mm^2. All described support configurations were applied with three different slope angles of the pieces with respect to the horizontal build platform, i.e., 0°, 20° and 40°. A design of experiment (DOE) approach was taken to subdivide the builds according to support type, support spacing, piece slope angle and alloy (Table 1).

Table 1 Parameters of supports for the germanium-doped gold alloy and for the platinum alloy

Support type	Support spacing (mm)	Slope angle (°)	Top length (mm)	Test identification
Block	1.00	0	0.25	A1
			0.10	A2
		20	0.25	A3
			0.10	A4
		40	0.25	A5
			0.10	A6
	1.50	0	0.25	B1
			0.10	B2
		20	0.25	B3
			0.10	B4
		40	0.25	B5
			0.10	B6
Volume	1.00	0	0.83	C1
		20	0.83	C2
		40	0.83	C3
	1.50	0	1.38	C4
		20	1.38	C5
		40	1.38	C6

RESULTS AND DISCUSSION

The research work was focused on the supports with the aim of finding what influence the support structure type has on the quality level of the pieces and metal loss caused by finishing. In this set of experiments, the slope angle was kept constant at 40°; only the structure of the supports was changed (Figure 3). Some macroscopic defects, such as support fracture or crumbling of partially melted particles, can be attributed to the structure of the support system. The fact that these defects are not random was demonstrated by repeating the same build experiment many times.

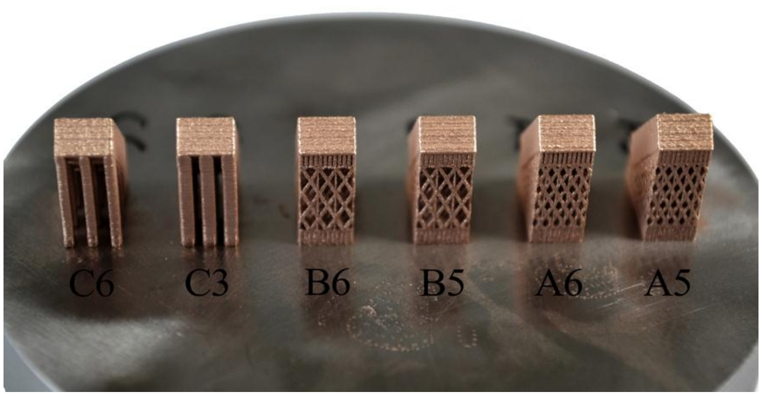

Figure 3 The build platform of gold alloy pieces with 40° slope angle

After removing the supports (Figure 4), we determined the dimensional variation of the raw specimens compared with the software design values and the weight percentage (%w) of the supports compared with the total mass (Table 2).

Figure 4 Six platinum specimens, showing the residue after removal of the supports

On average, the built length (ΔL) of both volume- and block-type supports is 0.35mm greater than the design value. In all cases, the built width shows the same increase (ΔW) of 0.20mm because of the absence of supports and the unidirectional slope of the specimens. The height (i.e., the thickness) of the specimens requires a different consideration. Initially, because of the manual detachment of the pieces, the increase is significant and very variable, in a range (ΔH) that could go from 0.20 to 0.90mm.
Then the specimens were evaluated for internal porosity using automatic equipment. The values are reported in Table 2.

Table 2 Test parameters, dimensional values and porosity data for the germanium-doped gold alloy

Support type	Support spacing (mm)	Slope angle (°)	Top length (mm)	Test identification	%w*	ΔL (mm)	ΔW (mm)	ΔH (mm)	% porosity
Block	1.00	0	0.25	A1	29	+0.30	+0.20	+0.70	0.14
			0.10	A2	16	+0.30	+0.20	+0.65	0.21
		20	0.25	A3	28	+0.30	+0.20	+0.50	0.10
			0.10	A4	30	+0.30	+0.20	+0.20	0.05
		40	0.25	A5	57	+0.40	+0.20	+0.45	0.06
			0.10	A6	44	+0.40	+0.20	+0.45	0.09
	1.50	0	0.25	B1	17	+0.30	+0.20	+0.90	0.63
			0.10	B2	13	+0.30	+0.20	+0.80	0.58
		20	0.25	B3	21	+0.30	+0.20	+0.50	0.10
			0.10	B4	26	+0.30	+0.20	+0.30	0.10
		40	0.25	B5	31	+0.60	+0.20	+0.50	0.03
			0.10	B6	22	+0.50	+0.20	+0.40	0.23
Volume	1.00	0	0.83	C1	34	+0.30	+0.20	+0.75	0.10
		20	0.83	C2	49	+0.30	+0.20	+0.70	0.12
		40	0.83	C3	89	+0.40	+0.20	+0.75	0.13
	1.50	0	1.38	C4	24	+0.30	+0.20	+0.90	0.05
		20	1.38	C5	36	+0.30	+0.20	+0.75	0.06
		40	1.38	C6	59	+0.30	+0.20	+0.50	0.04

* Weight percentage of the supports compared to the total mass

Dimensional variations and internal porosity of the 950‰ platinum alloy follow the same trends of the gold alloy but the values were lower (Table 3). The Pt supports represent a lower weight percentage in comparison to the gold alloy. This can be attributed to the higher melting point, which allowed thinner vectors to be built and consequently lighter supports. Better definition of the Pt vectors results in better dimensional compliance and, therefore, lower variability than in the gold alloy.

Table 3 Parameters and typical data for the 950‰ platinum alloy

Support type	Support spacing (mm)	Slope angle (°)	Top length (mm)	Test identification	%w*	ΔL (mm)	ΔW (mm)	ΔH (mm)	% porosity
Block	1.00	0	0.25	A1	13.5	+0.15	+0.09	+1.00	0.01
			0.10	A2	15.0	+0.15	+0.12	+0.41	0.05
		20	0.25	A3	21.5	+0.18	+0.08	+0.40	0.02
			0.10	A4	24.0	+0.38	+0.11	+0.22	0.02
		40	0.25	A5	26.0	+0.58	+0.12	+0.52	0.02
			0.10	A6	27.3	+0.30	+0.12	+0.32	0.06
	1.50	0	0.25	B1	11.2	+0.18	+0.12	+0.71	0.05
			0.10	B2	10.2	+0.18	+0.11	+0.65	0.03
		20	0.25	B3	17.1	+0.18	+0.14	+0.34	0.01
			0.10	B4	16.1	+0.20	+0.12	+0.28	0.03
		40	0.25	B5	18.8	+0.48	+0.15	+0.50	0.03
			0.10	B6	18.5	+0.40	+0.12	+0.33	0.01
Volume	1.00	0	0.83	C1	22.5	+0.18	+0.12	+0.50	0.02
		20	0.83	C2	32.3	+0.15	+0.12	+0.55	0.02
		40	0.83	C3	41.7	+0.52	+0.12	+0.58	0.05
	1.50	0	1.38	C4	17.3	+0.15	+0.11	+0.76	0.03
		20	1.38	C5	27.0	+0.20	+0.13	+0.57	0.01
		40	1.38	C6	32.6	+0.38	+0.12	+0.40	0.01

* Weight percentage of the supports compared to the total mass

The present work has demonstrated that it is possible to improve SLM of a classic 18K alloy through the addition of small quantities of semiconductor elements such as silicon and germanium. On surfaces parallel to the build platform, the germanium-doped gold alloy obtained a total roughness R_t = 55µm. That is about 30% lower than the figure obtained with the same alloy without the germanium addition (Figures 5 and 6). However, in a specimen built with alloy 1, the roughness was further reduced to about R_t = 40µm by increasing the laser power to 80W (Figure 7). This improvement resulted in smoother surfaces and consequently reduced time and weight loss in finishing.

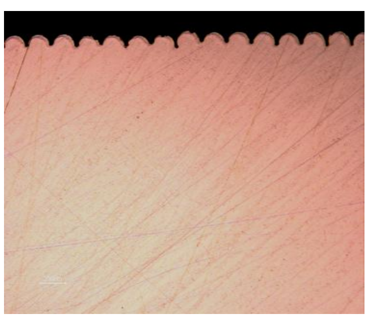

Figure 5 Germanium-free gold alloy

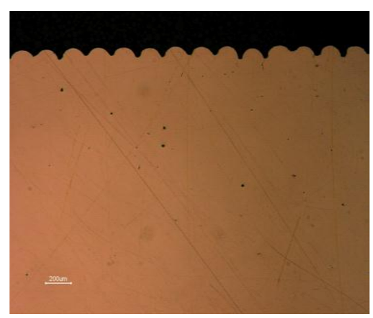

Figure 6 Gold alloy with germanium addition

Figure 7 Gold alloy with germanium addition, 80W laser power

In general, higher electrical resistivity means lower thermal conductivity of the alloy powder, leading to a better conservation of laser energy in the target zone and correspondingly more effective localized melting. Addition of low concentrations of semiconductor elements (Ge, Si, B) fundamentally improves gold alloys used for SLM, resulting in reduced surface roughness and inner porosity values.
The physical-chemical mechanism of the effect alloy composition has on absorption of laser light still waits for a thorough explanation, but it probably concerns both reflection of laser radiation and conduction of thermal energy. If we hypothesize that, initially, optical interaction could be the most important effect, the presence of extremely thin layers of oxidized compounds (GeO, SiO) or of nano-roughness could reduce reflection of laser radiation and thereby increase absorption by the alloy particles. Subsequently, the thermal energy may stay more or less confined in the target zone of the laser beam, depending on the thermal conductivity of the alloy, causing a more or less effective local melting of the powder.
In this work, an addition of germanium was used to investigate the changes caused by this element on surface roughness and interior porosity. A similar comparison was carried out with a 950‰ platinum alloy to evaluate the effect of a lower thermal conductivity (i.e., higher electrical resistivity) element, when it is by far the major component of the alloy.

CONCLUSIONS

In this work, we demonstrated the possibility of improving the quality of selected laser melted jewellery parts by increasing the absorption of laser radiation with a reduction of reflected and dispersed energy to obtain a more efficient melting of alloy particles. This objective was achieved through two ways:

1. The use of a precious alloy with a thermal conductivity significantly lower than usual gold alloys, e.g., a high fineness (950‰) platinum alloy
2. With the addition of a small concentration of semiconductor elements (Si, Ge) to 750‰ red-gold alloy that, thanks to their higher electrical resistivity, can reduce the thermal conductivity of the gold alloy and improve the SLM behavior

The presence of semiconductor elements, with a concentration of a few thousands of parts per million, produced a 30% reduction in surface roughness of the specimens and a reduction of the amount of particles ejected by the laser beam, which is a cause of the formation of bulges. Moreover, a good quality microstructure was obtained with a low 0.03% porosity near the support system, which is the most problematic area. This opened the way to a new approach for SLM that is not only based on the selection of laser parameters but also on the ability of the alloy to more efficiently transform the laser radiation into fusion heat in the alloy particles.
To study the role of the support system, we varied its shape, spacing and connection slope. In general, we found that thinner supports are more easily detached and are advisable for high-slope walls, while more massive supports are advisable for more horizontal walls. These parameters reduce defects at the support connection point due to thermal contraction stresses. Finally, the research shows that surface quality can be optimized and processing loss reduced when the correct selection between thin and massive supports is made.

REFERENCES

1. D. Zito et al., “Optimization of the Main Selective Laser Melting Technology Parameters in the Production of Gold Jewelry,” *The Santa Fe Symposium on Jewelry Manufacturing Technology 2013*, ed. E. Bell and J. Haldeman (Albuquerque: Met-Chem Research, 2013): 383-402.
2. J. Kruth et al., “Binding mechanisms in selective laser sintering and selective laser melting,” *Proceedings of the Solid Freeform Fabrication Symposium* (2004): 44-59.
3. D. Zito et al., “Latest developments in Selective Laser Melting Production of Gold Jewelry,” *The Santa Fe Symposium on Jewelry Manufacturing Technology 2012*, ed. E. Bell (Albuquerque: Met-Chem Research 2012): 537-562.
4. J.P. Kruth and S. Kumar, “Statistical Analysis of Experimental Parameters in Selective Laser Sintering,” *Advanced Engineering Materials* 7, no. 8 (August 2005): 750-755.
5. Y. Yadroitsev et al., “Factor analysis of selective laser melting process parameters and geometrical characteristics of synthesized single tracks,” *Rapid Prototyping Journal* 18, no. 3 (2012): 201-208