THERMAL BEHAVIOR OF PARTS MADE BY DIRECT METAL LASER SINTERING

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Abstract

The Direct Metal Laser Sintering (DMLS) manufacturing technique induces thermal stresses in parts. When such parts are used at elevated temperatures, residual stresses are relaxed and the part can suffer significant distortion. This study presents values of geometrical distortion for two laser exposure strategies and for different heat treatment temperatures and durations. Surface and bulk hardness data are provided as well as porosity measurements. At temperatures above 300 °C, the geometrical changes become important. A stabilization treatment at 600 °C can help reduce distortions.

1. INTRODUCTION

Freeform fabrication is most often based on the generative manufacturing of parts. In the case of Selective Laser Sintering (SLS), and particularly when fully metallic powders are considered, the heating and cooling of the layers induce heterogeneous dimensional changes of the part. Due to the temperature gradients, residual stresses are generated in the part [1]. These stresses can be very high and cause compact warping, cracking and/or failure. Furthermore, when the sintered part is exposed to relatively high temperatures, residual stresses are relaxed, leading to geometrical deformations and loss of tolerances. The purpose of this paper is to present an experimental observation of the behavior of DMLS parts under several heating conditions. Dimensional variations are provided, together with hardness data and porosity values.

2. EXPERIMENTAL METHOD

2.1. Specimens

The test samples were DMLS plates 20x30x4 mm^3, made of conventional EOS MCu 3201 Nickel-Bronze powder. Two standard EOS exposures were used to fabricate the specimens: the Skin and Core strategy (see below) and a usual strategy where the whole layer is sintered with the same parameters (skin parameters). The upper face (z direction) was milled (-0.5 mm) to create an initial planarity before thermal treatments.

2.1.1. The Skin & Core strategy

With the Skin & Core strategy (SK), the outer region (skin) of the part is sintered with a greater laser energy concentration and has a higher sintered density. The bulk of the part (core) is exposed to a lower energy concentration and has a lower density (Figure 1). Different stripe widths are used for the skin and for the core. Moreover, the core zones are sintered every second layer. Reportedly, buildup time can be reduced by about 10%, and residual stresses are decreased [2].

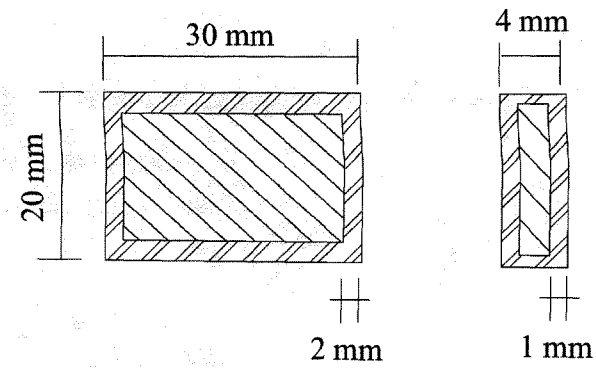


Figure 1: schematic of the SK samples, with skin depths.

2.2. Thermal treatments

2.2.1. One-step treatments

The DMLS specimens were put into a conventional, pre-heated oven, at temperatures ranging from 200 °C to 700 °C, for 2 and 4 hours. After treatment, the samples were cooled in air. Thermal treatment conditions are summarized in Table I.

Table I: treatment conditions for the one-step experiments.

Sample	Temperatures (°C)	Duration (hours)
High density (skin - S)	200, 300, 400 ,500, 600, 700	2 and 4
Low density (skin/core - SK)	200, 300, 400 ,500, 600, 700	2 and 4

2.2.2. Two-step treatments

Some specimens were treated in two steps to study a possible stabilization by a first thermal treatment (similar to post-sintering). The stabilization treatment consisted of 2 hours at 600 °C. The second treatment lasted 2 hours at 200, 300 and 400 °C (Table II).

Table II: treatment conditions for the two-step experiments.

Sample		Temperatures (°C)	Duration (hours)
High density (skin - S)	First treatment	600	2
	Second treatment	200, 300, 400	2
Low density (skin/core - SK)	First treatment	600	2
	Second treatment	200, 300, 400	2

2.3. Measurements and characterization

2.3.1. Geometry

Pre-defined points were measured on a coordinate measuring machine (CMM), according to Figure 2, in order to determine the planarity of the horizontal upper face of the platens, before and after thermal treatment. The planarity is defined as the distance between the two remotest points in the z direction, as shown in Figure 2.

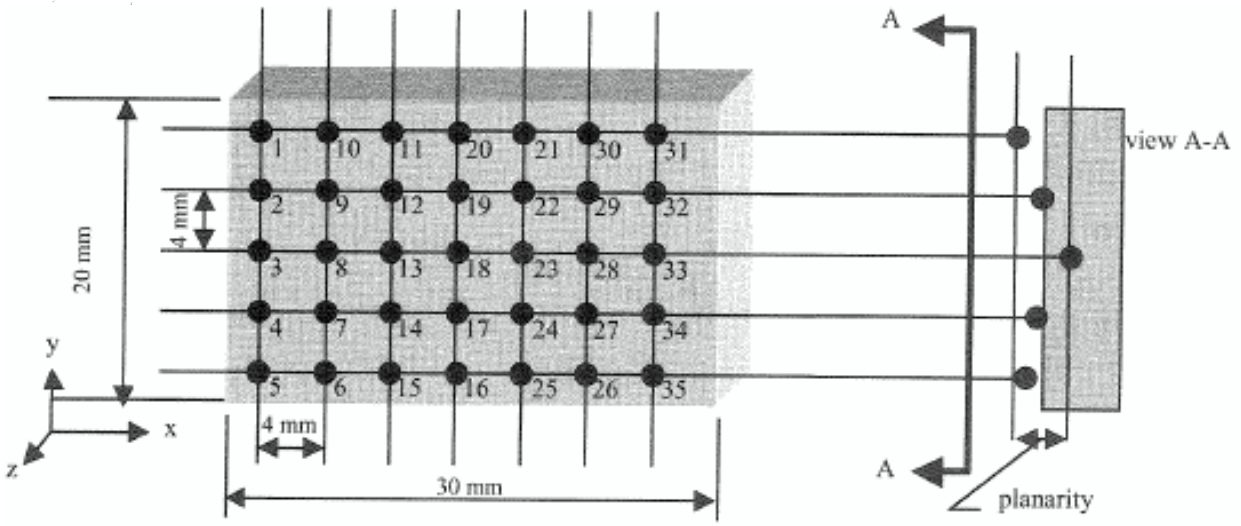


Figure 2: measurement locations at the sample surface and definition of planarity.

The curvature was measured at the plates center (point 18) according to:

$$\frac{1}{\rho_X} = \frac{z_{13} + z_{23} - 2 \cdot z_{18}}{\Delta x^2} ; \frac{1}{\rho_Y} = \frac{z_{17} + z_{19} - 2 \cdot z_{18}}{\Delta y^2}$$

Where: z_i = coordinate measured at location i
Δx, Δy = spacing between measurement points in the x, respectively y direction
ρ_x, ρ_y = radius of curvature in the x, respectively y direction.

2.3.2. Hardness

Hardness measurements were carried out according to ISO 4498/1. Five stamps were performed on the upper face of each plate with a load of 50 N (HV 5).

2.3.3. Microstructure

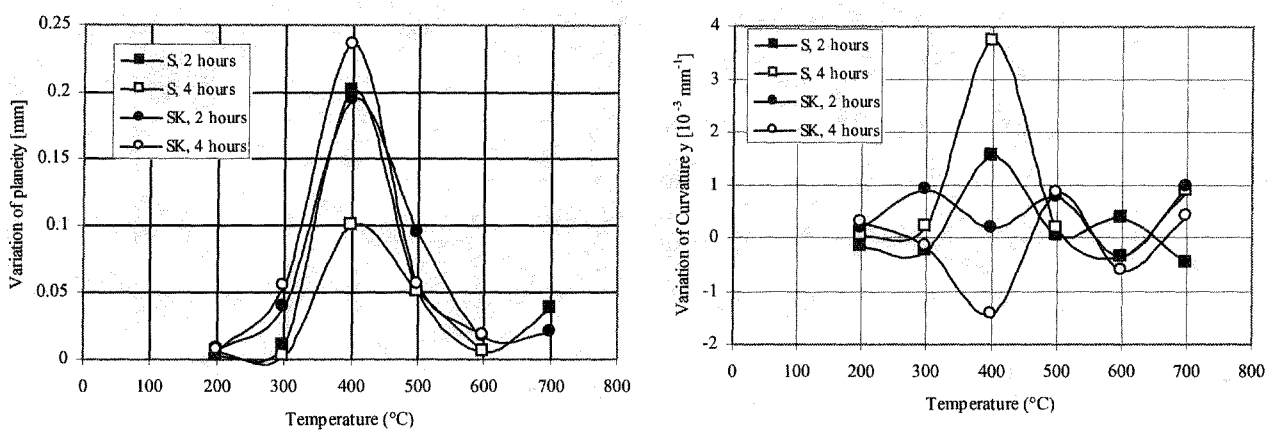
Cross-sections (perpendicular to the x axis, Figure 2) were prepared and micrographs (50 x and 500 x) taken in order to measure porosity. The micrographs were systematically taken in the middle of the section. Therefore, these porosity measurements may not be representative of the whole sample. This is important, especially in the case of low density samples, where the core zones are much less dense than the skin.

3. RESULTS

3.1. Planarity and curvature

3.1.1. One-step treatments

Figure 3 shows important variations of planarity and curvature at temperatures around 400 °C, for all strategies and treatment durations. Above and below this point, the variations are much smaller. Variation of planarity is significantly lower for the S sample treated for four hours. The other samples exhibit a similar behavior.



(a) (b)

Figure 3: variations of (a) planarity and (b) curvature in the y direction, as a function of the treatment temperature, for the different treatment durations and strategies.

3.1.2. Two-step treatments

After a first stabilizing treatment of 2 hours at 600 °C, the variation of planarity observed at temperatures ranging from 200 to 400 °C are approximately 25 to 50 times smaller than without a stabilizing heat treatment (Figure 4a).

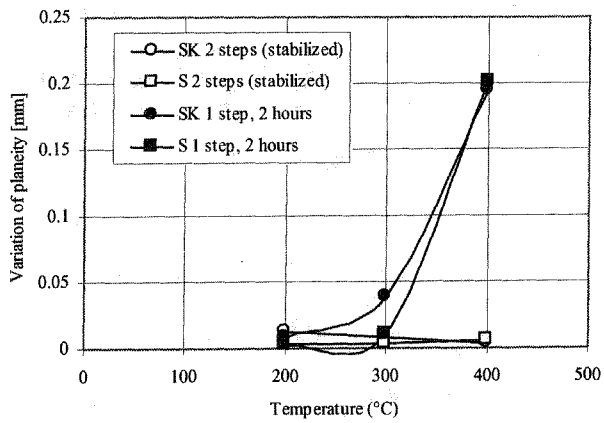
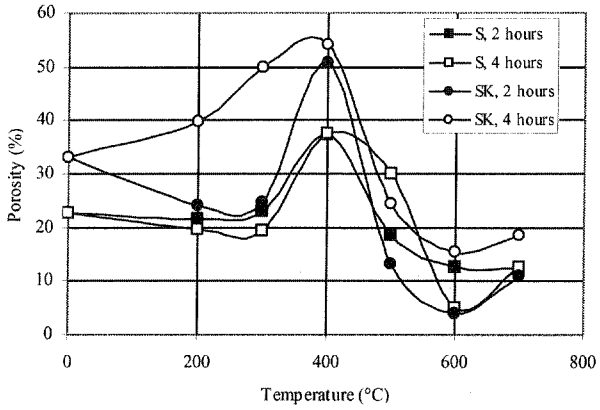


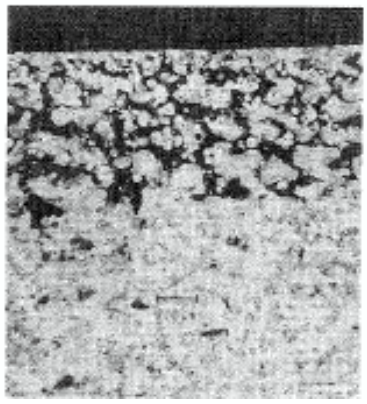
Figure 4: Variation of planarity due to the second step heat treatment after a first stabilization treatment (2 hours at 600 °C).

3.2. Porosity

3.2.1. One-step treatments

The porosity measurements (Figure 5) reveal a similar behavior to the geometrical variations presented above. They exhibit a local maximum at 400 °C, regardless of the treatment duration and sample initial density and then drop below 20 % at 600 °C and 700 °C.





(a) (b)

Figure 5: (a) bulk porosity of the one-step samples, measured at the center of the cross-section, as a function of temperature, for the different durations and exposures. (b) Microstructure indicating a porosity increase at the surface on an SK specimen after 2 hours at 600 °C.

3.2.2. Two-step treatments

After a stabilizing treatment of 2 hours at 600 °C, the porosity observed at 200 °C is about 2 to 3 times lower than without stabilization (Figure 6). However, at 300 °C and 400 °C, similar values are measured for the less dense SK specimens. For the more dense S specimens, the porosity remains about half of its value without previous stabilization.

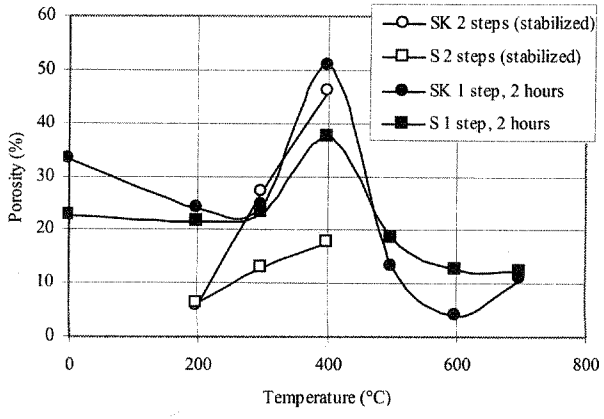
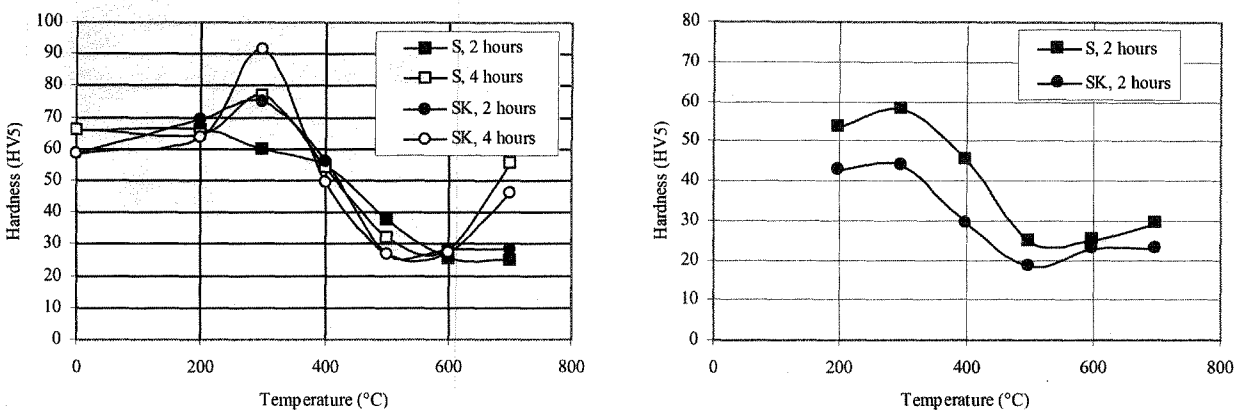


Figure 6: effect of a stabilization heat treatment (2 hours at 600 °C) on the porosity.

3.3. Hardness

Figure 7a presents the surface hardness of the various samples. The values of the S and SK samples treated for two hours decrease from about 60 HV for temperatures up to 400 °C down to 30 HV at 600 °C and 700 °C. For the longer treatment durations, a hardness increase can be observed at 300 °C, followed by a rapid decrease down to about 30 HV at 600 °C. At 700 °C, the hardness of these samples increases again up to around 50 HV, while the two hours values remain at about 30 HV.



(a) (b)

Figure 7: (a) surface hardness as a function of treatment temperature, for different treatment times. (b) Bulk hardness of the one-step samples treated 2 hours, measured in the cross-section.

Figure 7b shows the hardness values measured in the transverse cross-sections, in the middle of the samples, for the two hours treatments. Roughly the same behavior can be observed as for the surface hardness (Figure 7). The denser S structure exhibits a higher hardness at all treatment temperatures. Figure 8 compares the hardness values at the surface and in the sample for the less dense SK samples. The hardness inside the SK samples is lower than at the surface, for treatment temperatures up to 400 °C, as expected according to the laser scanning strategy (Figure 1). However, from 500 °C up to 700 °C, surface and inside values come closer together.

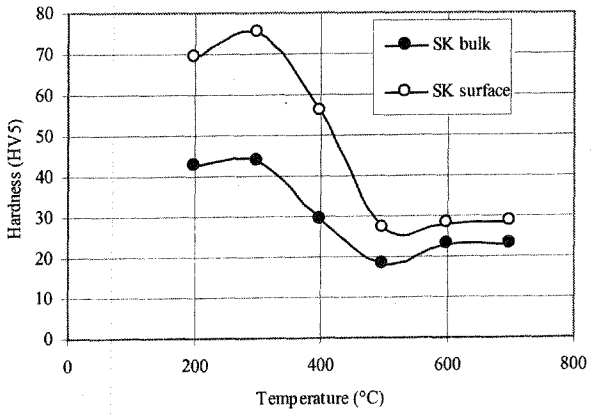
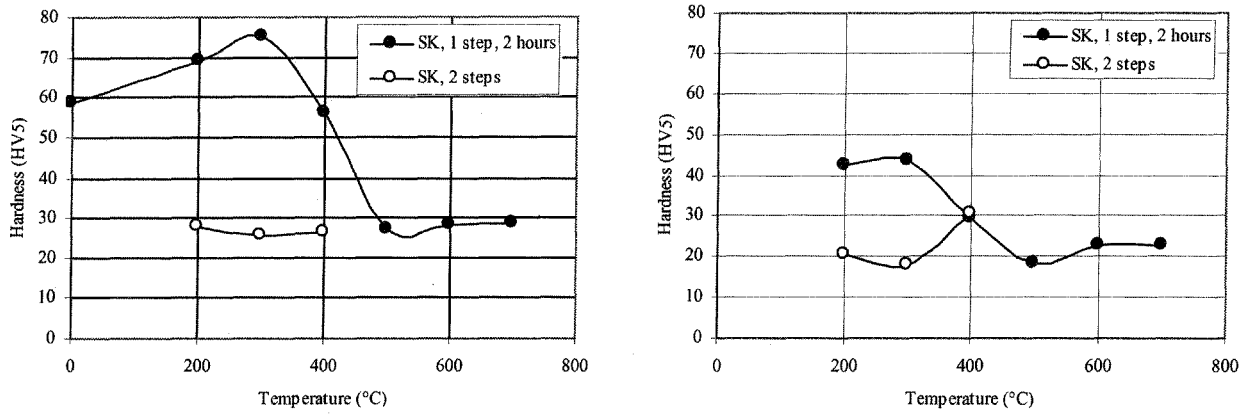


Figure 8: surface and bulk hardness (measured in the middle of the sample), for SK specimens.

In all two-step experiments (Figure 9), the hardness remains at low values similar to those observed after the first treatment at 600 °C. This indicates that the material has been partially stabilized.



(a) (b)

Figure 9: (a) surface and (b) bulk hardness for the one-step samples and after the two-step treatment (stabilization).

4. DISCUSSION

4.1. Geometrical variations

Figure 3 shows an important variation of planarity at around 400 °C, for both sample densities and treatment durations. Curvature looks roughly the same, although the SK samples exhibit smaller curvature change. This could be explained by a lower level of residual stresses in SK samples, leading to less severe distortion. 400 °C appears to be a critical temperature for dimensional variations. Above and below 400 °C, the variations of planarity and curvature are much smaller. Further investigations are required here to understand the observed behavior. This could be done by testing the effect of time and temperature more extensively or by differential thermal analysis measurements. The diffusion coefficients and activation energy may also give a clue for the observed phenomena. Looking at the geometrical changes occurring in the two-step treatment, the variation of planarity in both S and SK samples is 25 to 50 times smaller than in the one-step experiments, indicating a possible stabilization of the structure by the 600 °C treatment.

4.2. Porosity

All porosity values must be taken with care since they were measured in a single location in the transverse cross-section of the samples. The porosity of the one-step samples appears to increase up to 400 °C (Figure 5), with the maximum value reached by the SK samples. At higher temperatures, porosity decreases to a value lower than the initial porosity, for all samples. Looking at Figure 5b, the decrease in porosity observed at 600 °C may be due to a diffusion of matter toward the inside of the sample, leading to a densification of its inner part. For the two-step experiments, the porosity of both samples type (S and SK) increases, with a steeper slope for the SK samples. No satisfactory explanation has been found for this behavior at this stage of the study.

4.3. Hardness

Considering the bulk hardness of the samples (Figure 7b), all values of the S samples are above those of the SK samples, in conformity with the higher porosity of the SK structure. The comparison between the surface and bulk hardness (Figure 8) of the SK samples shows a higher surface hardness than in the bulk, as the surface of SK samples is sintered similarly to the S samples. At higher temperatures, this difference is less important, probably because of the surface porosity increase observed in Figure 5b. The decrease by a factor 2 of the bulk hardness between 300°C and 600 °C indicates a reduction in the mechanical strength that could explain the recovery of the geometry observed at high temperatures (Figure 3). The curves obtained for the two-step experiments (Figure 9) show that little hardness changes occur at the different temperatures, for both the S and SK curves. This indicates that the material has been partially stabilized by the first thermal treatment.

5. CONCLUSIONS

According to these preliminary results, 300 °C appears to constitute an upper temperature limit for practical use. This can be of significance as DMLS is a potential technology for the rapid manufacturing of complex tools like injection molds [3]. However, if structural and geometrical changes occur at temperatures normally reached in these processes, this could strongly limit the use of this material/process combination for Rapid Tooling. The present results indicate that a stabilization heat treatment around 600 °C may somewhat improve this situation. Still, additional work is required to confirm and extend the present results, as well as to better understand the physical and metallurgical phenomena governing the observed behavior.

6. REFERENCES

[1] A. Coremans, D. Groot, "Residual stresses and thermal stability of laser beam sintered metal parts", Proceeding of Lane '97, pp. 577-588.

[2] J. Weilhammer, EOS GmbH, personal communication.

[3] N. Karapatis, J.-P. van Griethuysen, R. Glardon, "Direct rapid tooling: a review of current research", Rapid Prototyping Journal, Vol. 4 No 2, 1998, pp. 77 – 89.

Keywords : SLS, DMLS, rapid tooling, residual stresses, dimensional changes, hardness, porosity.