Surface and mechanical properties of laser melted Maraging Steel

Marc Jobin, Raphael Foschia, François de Mestral, Eric Vittecoq
hepia, University of Applied Science HES-SO, 4 rue de la Prairie, 1202 Genève, Switzerland

Denis Boisseleau, Alexis Saitta, Pierre Escourou
Turbomeca , SG/FE - BP Piano 2, 64511 BORDES Cedex, France

Guillaume Vansteenkiste
Pôle Européen de Plasturgie (PEP), 2 rue P. et M. Curie - 01100 Bellignat, France

Cyril Gouverd, Laurent Cataldo
BESTinCLASS SA, Chemin de la Caisserie, 1272 Genolier, Switzerland

Carmen Sanz, Oscar Gonzalo
Fundacion TEKNIKER, Avda.Otaola 20, Eibar 20600, Spain

Abstract

In order to drastically reduce the cycle and cost production of engine parts in the transport industry, we have developed laser powder melting processes to produce several key engine parts in maraging steel, Co-Cr and Inconel 718. Results presented here concerns maraging steel only. Laser melted samples were polished with three different treatments: Abrasive Flow Machining (from Extrudehone), Vibratory finishing (from Rösler) and MMP (Micro Machining Process from BESTinCLASS). The dimensional tolerance after polishing was 5µm.
The resulting surface topographies were measured with Stylus Profilometry and Atomic Force Microscopy. The MMP process allows reducing the rms roughness (Rq) to 12 nm only for a 20µm x 20µm field of view. In order to investigate the surface treatments in terms of what characteristic length (i.e spatial frequency) have been filtered, we present the results with the help of power spectral density. Concerning the mechanical properties, the anisotropy of fatigue and tensile strength is not significant as a consequence of the direct melting process compared to sintering.

Introduction

This work is part of our RC2 European project (“Reduction of cycle and cost” www.rc2project.eu), which aimed to reduce both the time-to-market and the production cost of nine engine parts (turbine wheel, straightener, etc...) by 50%. Each of those 9 parts was produced by rapid prototyping techniques in 3 materials: Maraging Steel (MS), Cobalt-Chromium (Co-Cr) and Inconel 718. Although all of them have specific and interesting applications in various industries (mechanical, medical, aeronautic…), will present in this paper the results for MS only for the sake of conciseness.
We have used a commercial Selective Laser Melting (SLM, or commercial denomination DMLS for Direct Metal Laser Sintering) machine (EOS M270) which allows the actual

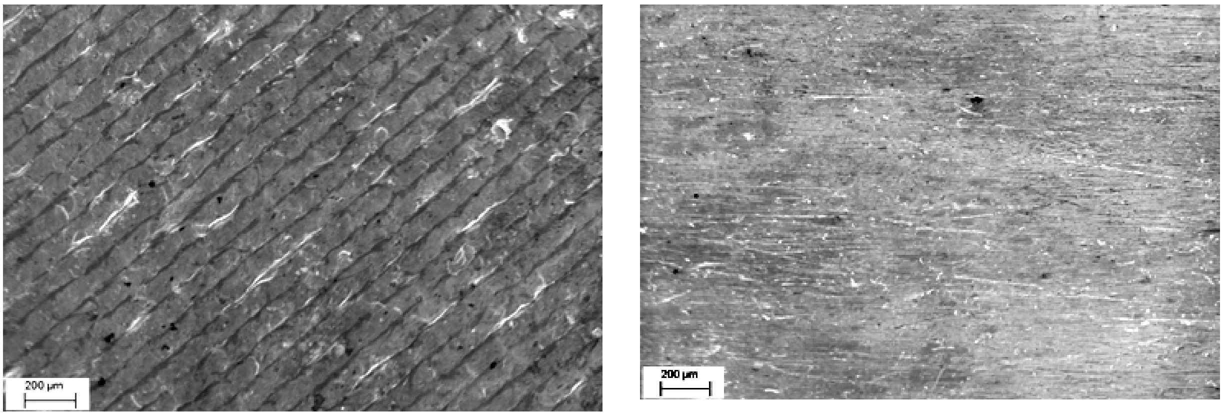
melting of the powder to a depth of 30-40 microns. We will then refer to the produced materials as "laser melted" rather than "sintered".

The surface finishes of the pieces are potentially important for both the mechanical properties and the visual aspect. Indeed, as standard sintered materials have a porosity which very likely will destroy tensile strength or fatigue resistance, we first expected a strong correlation between the polishing treatments and the mechanical properties. However, we found that laser melted materials had very few surface defects or porosity. The analysis of the microstructure after fracture revealed that the cracks mainly originated from *non-metallic* inclusions close to the surface. We therefore investigate the surface topography in term of roughness rather than in term of defects or porosity.

Sample preparation

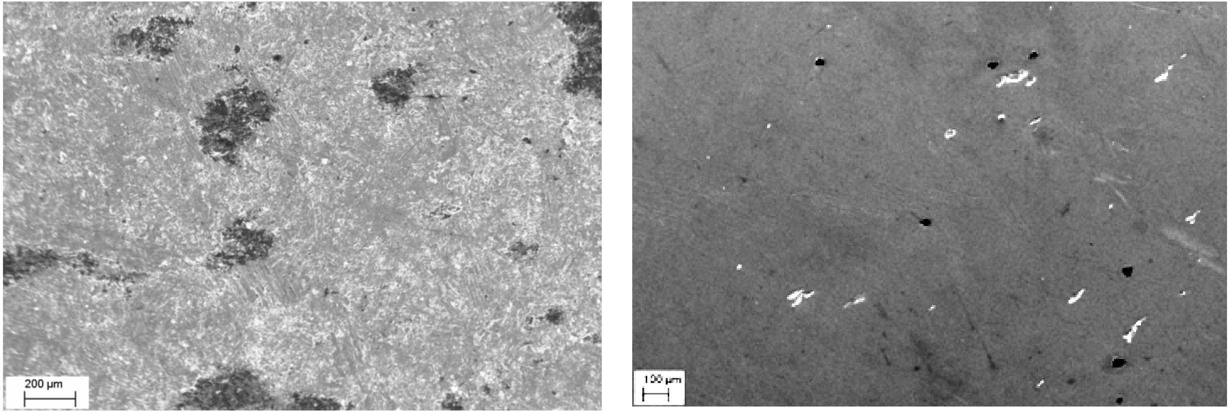
All samples have been produced as 5cm x 5cm x 2cm parallelepiped with a commercial selective laser machine from EOS (model M270). The MS powder had a typical diameter of 20 µm and was bought from EOS directly. Microstructure investigations revealed the melting process very nicely, as crystallites were clearly extended over the thickness of the powder film.

Fig 1a) is a SEM micrograph (50x, 2.3mm x 1.6 mm) showing the surface of the laser melted MS without any additional treatment ("raw"). We clearly see the laser path, each track typically 100 um wide. To a large extent, this is the structure that has to be polished.



a) Raw laser melted

b) Abrasive Flow Machining



c) Vibratory finishing

d) MMP

Fig. 1 SEM pictures of Maraging Steel

Three different polishing treatments have been used on raw MS: Abrasive Flow Machining, Vibratory finishing and MMP (Micro Machining Process) from the company BESTinCLASS

(BinC). The parameters of the polishing processes have been chosen by the industrial provider of the process directly. The target was the smallest roughness under the following constraint: 5µm dimensional tolerance on a standard sample with various geometrical structures (including a cylinder of 2mm diameter and 3mm high, and a corresponding hole).
Fig 1b), 1c) and 1d) are SEM micrographs (same magnification than Fig1a) of the polished samples. In all cases, we see a complete removal of structure due to the laser path. For Abrasive Flow Machining, the direction of the abrasive flow is quite visible, as expected, while for Vibratory finishing and MMP, the polishing is isotropic (no preferential polishing direction). In the case of Vibratory finishing, we have a structure which can be seen as 150-400um spot in the backscattered SEM image.

Surface Profilometry

Both surface profilometry (SP) and Atomic Force Microscopy (AFM) have been use for surface topography analysis. For SP, we choose a standard ISO scan length of 5.7 mm acquired on 8'000 points. Data were taken with a 1µm tip radius probe on a Mahr Perthomer PGK instrument. Although any 5.7mm scan is reasonably representative (i.e. without any particular attention paid to the location), we measured 5 different profiles for FFT analysis
As an illustration, the top (colored) profiles of Fig. 2 have been measured on the raw MS and the bottom (black profiles) has been measured on the MMP.

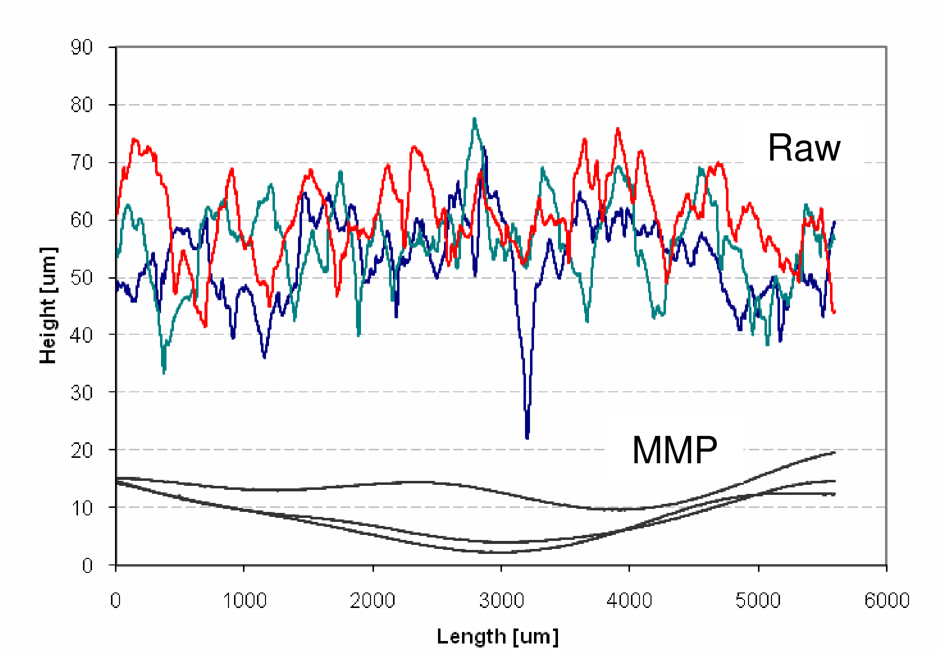


Fig. 2 Actual SP profiles on MS raw and MS MMP.

Topographic profiles such as those of Fig. 2 are usually characterized with amplitude (including standard Ra and Rq roughness), spacing or hybrid parameters [1]. In this study, we choose to analyze the SP profiles in terms of Fourier power spectrum:

$$F(k)=\left(\frac{L}{N}\right)^2\sum_{x=0}^{N-1} z(x)\left\{\cos(\frac{2\pi}{N}(k_x x)+i\sin(\frac{2\pi}{N}(k_x x)\right\}$$

where *z(x)* is the height profile acquired by the profilometer. Each wave vector *k* corresponds to a spatial wavelength λ given by:

$\lambda = 2\pi / k$

The motivations for representing the topographic profiles as *F(k)* were:

- the various polishing treatment do not operate uniformly over the spatial wavelength of the topography. A key aspect of this work was to analyze and to understand what wavelengths are filtered by the polishing process and what wavelengths are not;
- we found a direct correlation between the optical reflectivity (and thus the visual aspect) and the partially integrated Fourier spectrum.

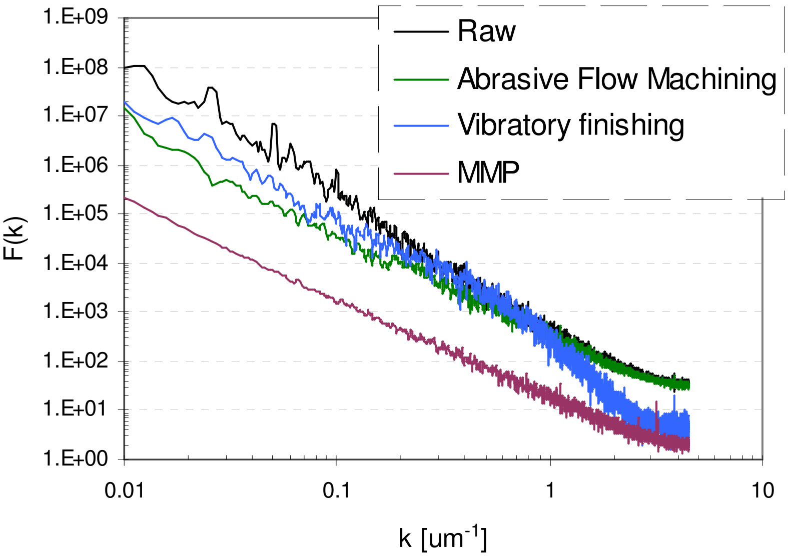
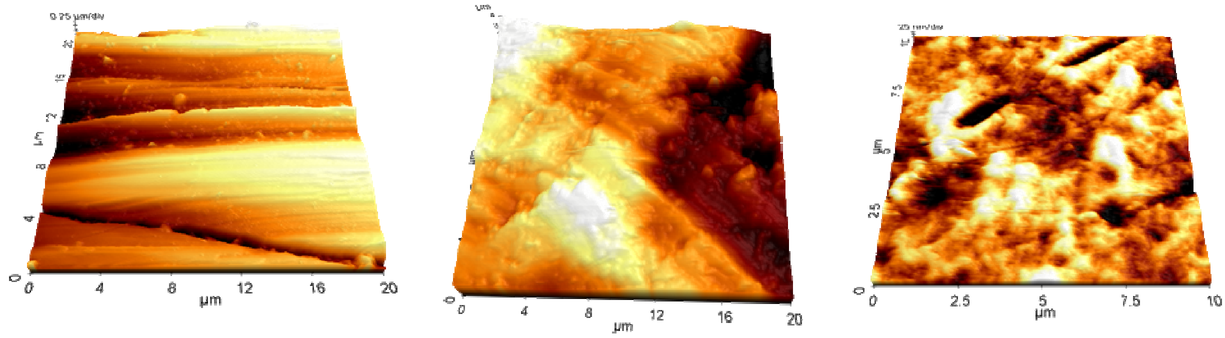


Fig. 3 F(k) of the SP profiles for the raw and polished MS samples

Fig. 3 is a log-log plot of *F(k)* for the raw and polished Maraging Steel samples. The MMP treatment provides with the most efficient polishing over the entire spectrum, reducing each Fourier component by at least two orders of magnitude. By contrast, the Abrasive Flow Machining and Vibratory finishing treatment have no effect in the $k \in [0.3; 1]$ (µm^{-1}) range. The Vibratory finishing process is however quite efficient for k>2 (µm^{-1}).

Atomic Force Microscopy

For AFM, we decided to perform 20µm x 20µm scan on a location which exhibited no particular structure a long as optical microscopy is concerned. All images were done in contact mode with high aspect ratio conical silicon probes
(PointProbe from NanoWorld). We have used a commercial AFM from Park Systems (model XE-100).
High definition (1024 x 1024 pixels) images were acquired in order to perform Power Spectral Density (PSD) analysis, the 2D counterpart of the 1D FFT of the surface profile reported above.



Abrasive Flow Machining (Rq = 1.23 µm)

Vibratory finishing (Rq = 4.74 µm)

MMP (Rq = 12 nm)

Fig. 4 AFM images and Rq roughness on the polished maraging steel

Typical AFM images on the polished Maraging Steel samples (raw sample was too rough for AFM) are shown in Fig. 4. The directionality of the Abrasive Flow Machining process is clearly observable, even at the scale (20um x 20um).

As for SP profiles, analysis in the wavelength space has been performed with AFM images. While SP provides results only on the direction of the profile, AFM, as providing with a 2D images, gives information in all directions. We decided to choose to represent the result in terms of Power Spectral Density (PSD), which is the integration of the Fourier power spectrum over the k-space:

$$PSD(f) = \frac{1}{L^2} \sum_{f=\sqrt{f_x^2+f_<^2}} \left| F(f_x, f_y) \right|^2$$

NB : For PSD in AFM, the spatial frequency f=1/λ is usually used instead of the wavevector k=2π/λ.

As the Rq (i.e rms roughness) is given by the integration of the PSD

$$R_q = \int_f PSD(f)df$$

each PSD(f) point corresponds to the contribution to the roughness of the structure having a characteristic spatial frequency of λ=1/k, referred to as "superstructure".

PSD analysis on AFM images is very powerful [2, 3] provided one take care of the following possible artifact: during AFM imaging, a topographic line can be "shifted" because of instability due to a surface impurity (dust). If such a line scan is not properly interpolate by image processing, a strong oscillation will appear in the PSD.

Fig. 5 shows the PSD analysis for the Maraging Steel polished samples. At such high spatial frequencies, we see that MMP is more efficient at any frequencies than Abrasive Flow Machining, itself more efficient than Vibratory finishing (again at any frequencies). The *k* values in the [7; 20] interval correspond to the optical wavelength and is well correlated with optical reflectivity results.

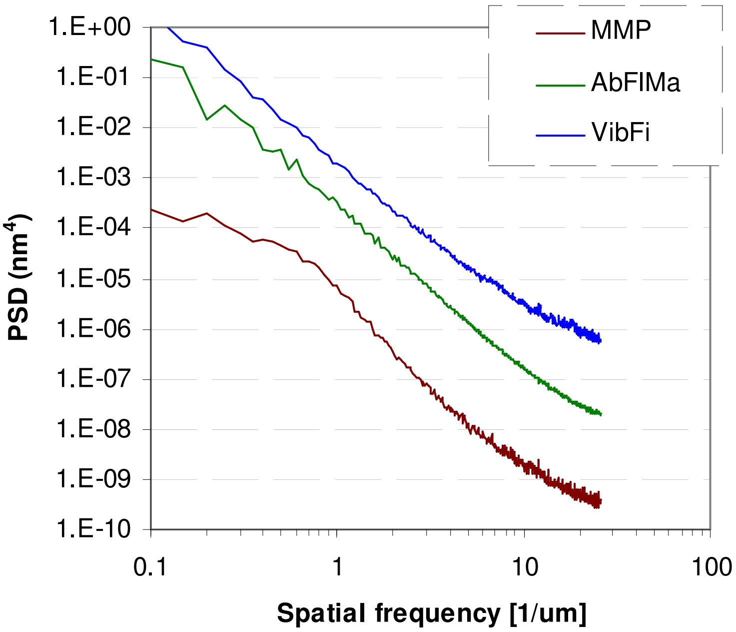


Fig. 5 PSD calculated from 20µm x 20µm AFM images on polished MS samples.

Mechanical properties

Although the laser melting process is very anisotropic by nature (layer by layer fabrication), we did not notice large differences of the mechanical properties depending on the direction: both fatigue and tensile strength were rather isotropic. However, we get significant difference depending on the height (the first melted layer is at height zero) on which the mechanical properties have been measured. This is due to thermal diffusion process (which is faster at lower height), which results in a differentiated thermal treatment depending on the height (the temperature of the part rises with increasing height). Extensive results on the heterogeneity mechanical properties of laser melted samples will be published elsewhere [4].

References

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