Tailoring microstructures and properties in metal based AM parts

Project Proposal on Additive Manufacturing (AM) – STI, EPFL – March 31st 2014

Roland Logé[1], Jean-Marie Drezet[2], Eric Boillat[3]

[1]Laboratory of Thermomechanical Metallurgy (LMTM) – PX Group Chair, IMX
[2]Computational Materials Laboratory (LSMX), IMX
[3]Laboratory for Production Management and Processes (LGPP), IGM

The AM process

Selective Laser Sintering or Melting (SLS or SLM) is an AM process where the part is built layer by layer out of a metallic, ceramic or polymer powder. At each step, a powder bed is deposited on a substrate and selectively melted (or partially melted in SLS) by a laser beam piloted by the CAM system. After cooling, the material gets consolidated and a new powder layer is deposited. The operation sequence is repeated until completion of the part. At the end the unused powder is removed and recycled.

Applicants expertise

LGPP has more than 20 years of expertise in SLS/SLM for metallic/ceramic powders. The main domains of activity are parameters optimization (for new materials, lasers and applications), process monitoring and control, and parts characterization. The research is based on theoretical aspects [1-3] and on experimental investigations [4-6]. The LGPP is running a modular sintering platform (Fig. 1a) equipped with sensors like IR cameras for temperature measurements.
LSMX has an extended expertise in advanced solidification processes and related microstructures, including the numerical modelling of cracking in the semi-solid state, and the prediction of thermal residual stresses.
LMTM is involved in the control of microstructures of metals and alloys through thermomechanical processing [7-10], with a focus on the induced properties. From September 2014, thermomechanical treatments will be performed with a Gleeble machine, using direct resistance heating (Joule effect), with possible testing in tension, compression, plane strain compression, and multi-axis compression (Fig 1b). The design of the machine allows to heat up and cool down the samples very quickly, and independently from the mechanical loading.

a) 

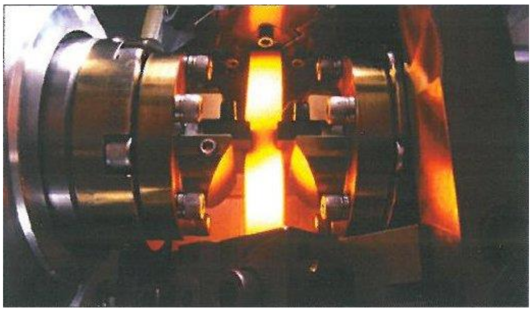
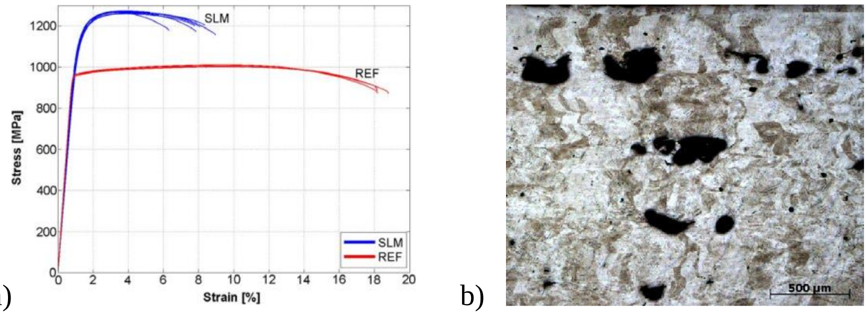
b) 

Fig. 1: (a) Selective Laser Sintering/Melting platform at LGPP, (b) Gleeble machine in multi-axis configuration at LMTM

Project objectives

A first step in the project will consist in linking the AM parts microstructures with the different processing parameters : laser power and speed, laser scanning strategy, pre-heating temperature, etc. It must be underlined that **finding a process window is usually a lengthy, tedious task**, which can take months for a given material. For some materials, such a process window simply cannot be found. The criteria for finding an acceptable process window are: (i) capacity to “glue” the powder particles together, (ii) minimal residual porosity or full density, (iii) limited negative thermal effects possibly leading to cracking or balling phenomena.

The second step of the project will then study how the inherited **microstructures** can be **optimized**, based on **thermal and/or thermomechanical treatments**. Fig. 2a shows an example of the well-known and widespread titanium alloy Ti6Al4V, where it is apparent that the SLM material is harder but much less ductile than the forged material [11]. In Fig. 2b porosities may be observed (in black), for a given laser scan strategy [12]. Additional heat treatments may improve the mechanical behavior of the SLM material, but the combination of strength and ductility will never reach the values shown in Fig. 2a for the conventional, forged material. Furthermore, the heat treatments may be long and complicated, which is unfortunate when dealing with AM where efficiency is sought.



a) b)

Fig. 2: SLM of Ti6Al4V, (a) comparison with a standard forged (REF) material [11], (b) evidence of porosity in the SLM material [12].

In the present project, the use of a Gleeble machine will be tested, to improve the mechanical features of SLM materials by applying thermal and thermomechanical treatments with direct resistance heating. It is anticipated that **local heating** within the material will concentrate **in the zones of porosities** or reduced density, since the Joule effect will be enhanced where the junction between powder particles is weak, and the resulting electric resistance ("contact" resistance) high. This would then allow local sintering/remelting in the weak zones, while the rest of the material would remain in the solid state. Additional mechanical loading preserving the external shape (e.g. multi-axis compression, see Fig. 1b) could also be used to (i) adapt grain size, and/or (ii) change the local texture inherited from columnar structures induced by the SLM conditions, leading to (usually not desired) anisotropic mechanical properties.

This approach should therefore allow defining **new processing strategies with less constraint**, due to the possibility of **healing quickly the material** afterwards. Porosity, and even localized cracking would be acceptable at the SLM/SLS stage, provided that quick, localized remelting, possibly under applied pressure, would be sufficient to heal those defects. It is underlined that **the proposed idea is new** in the context of AM, but can be found in the Spark Plasma Sintering literature [13]. It also connects very well with the **proposal of Prof. Michele Ceriotti**, which suggests to study the partial melting of powder grains through **molecular dynamics simulations**. Advanced microstructure optimization through grain size and texture control would also be accessible in this work.

Materials to be studied

Typical material which could be considered in this project are maraging steels (18Ni300) for **tooling** applications, stainless steel (316L) and silver-copper alloys for **watch industry** applications, and titanium alloys (Ti6Al4V) for **medical/dental** applications. These materials have **thermal conductivities** which **vary by two orders of magnitude**, leading to very different distributions of heat during the SLM process.
To illustrate a striking case where healing of the material would be needed, a composite material could also be tested. For example, a ceramic such as alumina, which cannot melt, combined with a metallic binder (e.g. AlSi10Mg). In that case, the targeted applications would be tooling again.

References

[1] Boillat E.and Glardon R. Numerical simulation of the selective laser sintering process. In Deville M.and Owen R., editor, 16th IMACS World Congress, 2000.

[2] S.Kolossov, E.Boillat, R.Glardon, P.Fischer, and M.Locher. 3D FE Simulation for the Temperature Evolution during the Selective Laser Sintering Process. International Journal of Machine Tools and Manufacture, 44:117– 123, 2004.

[3] S. Kolossov. Non-Linear Model and Finite Element Simulation of the Selective Laser Sintering Process. PhD thesis, EPFL, 2005. 3178.

[4] C. André. Modélisation quantitative du procédé de frittage sélectif par laser: relation paramètres / microstructure. PhD thesis, EPFL, 2007. 3716.

[5] J. Jhabvala. Study of the consolidation process under macro- and microscopic thermal effects in Selective Laser Sintering and Selective Laser Melting. PhD thesis, EPFL, 2010. 4609.

[6] J. Jhabvala, E. Boillat, and R. Glardon. On the use of EBSD analysis to investigate the microstructure of gold samples built by selective laser melting. Gold Bulletin, 44(2):113–118, 2011.

[7] P. Bernard, S. Bag, K. Huang and R.E. Logé, A two-site mean field model of discontinuous dynamic recrystallization. Materials Science and Engineering A 528: 7357-7367, 2011.

[8] N. Bozzolo, S. Jacomet and R.E. Logé, Fast *in-situ* annealing stage coupled with EBSD: A suitable tool to observe quick recrystallization mechanisms. Materials Characterization 70: 28-32, 2012.

[9] N. Bozzolo, N. Souai, R.E. Logé. Evolution of microstructure and twin density during thermomechanical processing in a γ–γ′ nickel-based superalloy", Acta Materialia 60: 5056–5066, 2012.

[10] L. Toualbi, C. Cayron, P. Olier, R. Logé, Y. de Carlan, Relationships between mechanical behavior and microstructural evolutions in Fe-9Cr-ODS during the fabrication route of SFR cladding tubes. J. Nuclear Materials 442: 410-416, 2013.

[11] B. Vrancken, L. Thijs, J-P. Kruth, J. Van Humbeeck, Heat treatment of Ti6Al4V produced by Selective Laser Melting: Microstructure and mechanical properties. J. Alloys & Compounds 541:177–185, 2012.

[12] L. Thijs, F. Verhaeghe, T. Craeghs, J. Van Humbeeck, J-P. Kruth, A study of the microstructural evolution during selective laser melting of Ti-6Al-4V. Acta Mater 58(9):3303–3312, 2010.

[13] Y. Quan, F. Zhang, H. Rebl, B. Nebe, O. Keßler, E. Burkel, Ti6Al4V foams fabricated by spark plasma sintering with post-heat treatment. Materials Science & Engineering A 565: 118–125, 2013.