ESRF	**Experiment title:** Residual stress and distortion prediction for EBF and LMD additive manufacturing methods	**Experiment number**: MA/1933
Beamline: ID15A	**Date of experiment**: from: 1st of March/2014 to:4th of March/2014	**Date of report**: 2016-09-07 *Received at ESRF:*
Shifts: 6	**Local contact(s)**: Thomas Buslaps	

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Report:

Within aerospace component manufacturing, fabrication has been recognized as an efficient way to reduce the weight and lead time of complex components typically manufactured using traditional techniques, such as one-piece castings or forgings. A fabricated structure is built by joining smaller subcomponents with a possibility to combine several material forms and alloys. The weight reduction potential comes from an efficient use of different mechanical properties and achievable geometrical tolerances for castings, forgings and sheet material. An important technology in this concept is additive manufacturing (AM), which enables features such as bosses and flanges to be added on subcomponents of fabricated structures and thereby minimizes the material usage (e.g. smaller forging envelope) and shortens the lead time. The use of AM also enables changes late in the design process. It further has a great potential in the aftermarket for repair and modifications.

Additive manufacturing is a broad definition that includes several different processes and methods in which metallic material is melted in a layer-by-layer manner to form 3 dimensional geometries, either as a near net-shape part or as part of a larger structure. One important advantage with the AM method, compared to conventional manufacturing methods is the potential to significantly lower the buy-to-fly ratio, i.e. components can be manufactured with near final shape without significant machining. And because machining costs are a significant part of the total product manufacturing cost, AM therefore enables significant cost savings for both manufacturing and product pricing.

The current work focuses on exploring the Laser Metal Deposition (LMD) process and Electron Beam Free Form Fabrication (EBF^3) process of Ti-6Al-4V (Ti-64). Here a laser energy beam (see Figure 1) or electron energy beam is used to melt the metal wire of Ti-64, layer by layer, until the appropriate geometry is built. The cooling rate of the deposited material determines the microstructure and thus also the average mechanical properties of the as built part. The substrate was instrumented with thermocouples and a LVDT-gauge (Linear Variable Differential Transformer) to measure the transient temperature and deformation of the substrate during the AM-processes. The measurements are thereafter used for validation of the computational model. The residual stresses are measured by means of x-ray diffraction at the ID15A beam line in the synchrotron radiation facility at ESRF in Grenoble, France. These experimentally measured residual stresses are then compared with those predicted by the simulation model.

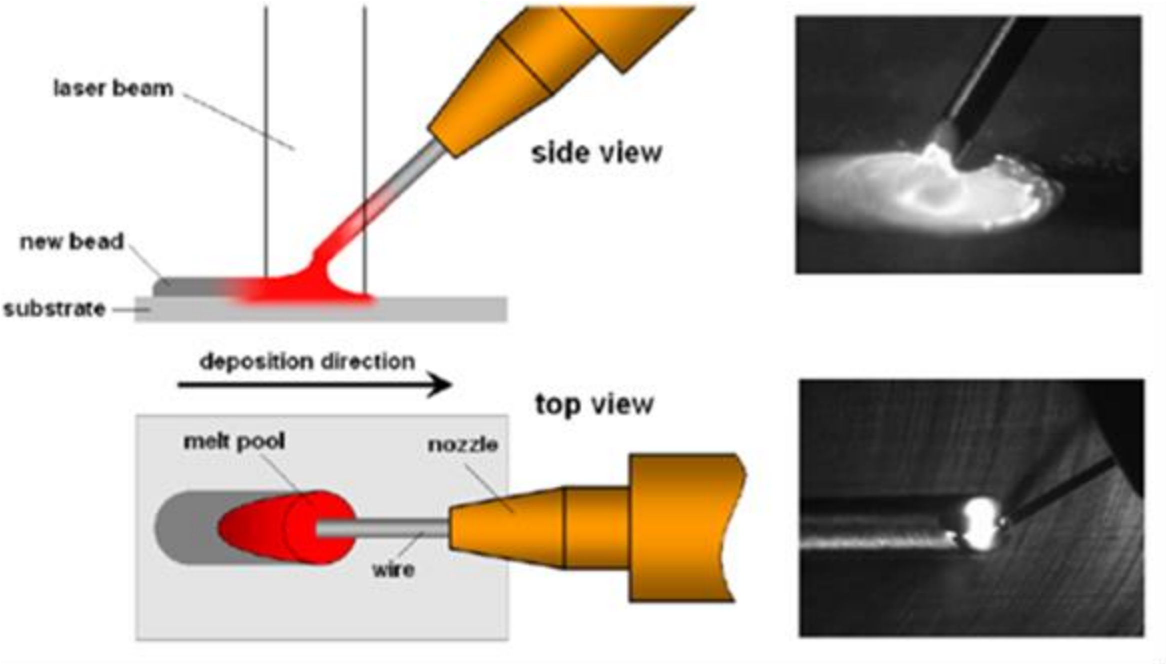

Figure 1. Left: Illustration of the laser-wire interaction. The molten metal solidifies into a bead by relative motion of the welding tool and the substrate. Right: Side- and top view images of the real process.

In Figure 2 the finished specimen, including the fixture can be seen. The building sequence is also indicated. The dimension of the substrate is 130x100x14 mm and the added material forms an open box with the dimension of 100x70 mm and with a thickness of 4 mm. 20 layers of material is added, each with a thickness of 0.7 mm giving a total wall height of 14 mm. The residual stress measurements were carried out by energy-dispersive X-ray diffraction on the high-energy beam line ID15A at the European Synchrotron Research Facility (ESRF) in Grenoble, France. The characterization used a high-flux white beam with an energy range of 50–250 keV. Measurements were done in transmission mode, with two energy-discriminating detectors positioned at 5° (2θ) horizontally and vertically from the beam direction. The setup allows collection of complete energy-intensity spectrums, which are converted to intensity vs. 2θ by the equivalent wavelength. A slit size of 100 x 100 μm^2 was used for both the incident and diffracted beam slits, giving a diamond shaped gauge volume with a length of approximately 2 mm. The residual stresses were measured in the middle of one of the long walls of each box from to directions, by illumination from the side of the wall (giving strains in the *x* and *z* directions) and from the bottom side of the plate (giving strains in the *x* and *y* directions), see Figure 3.

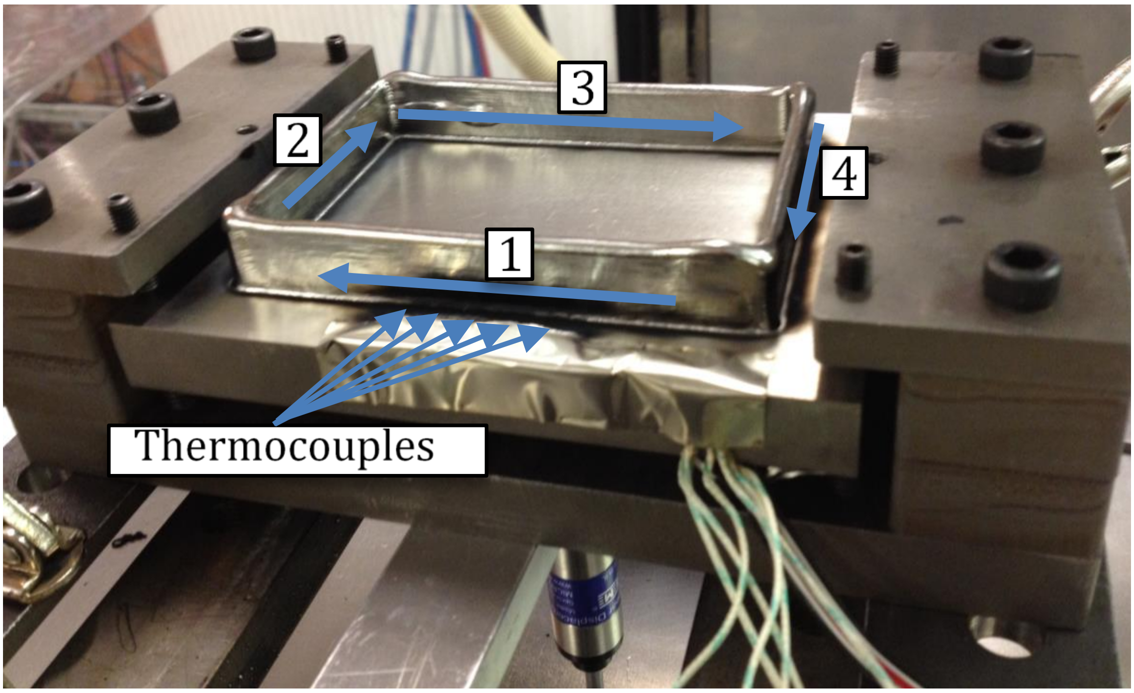

Figure 2. Finished LMD specimen including the fixture and building sequence.

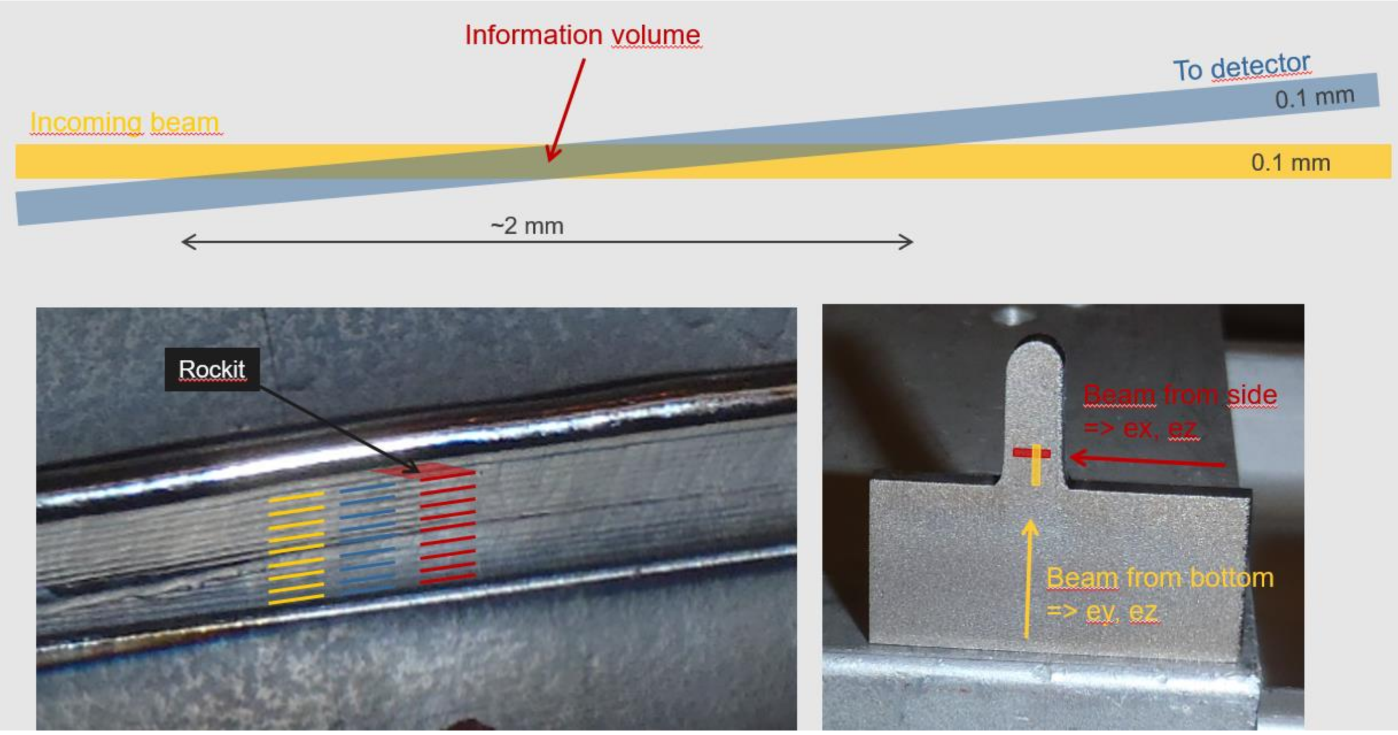

Figure 3. The residual stresses were measured in the middle of one of the long walls of each box

During illumination from the side the gauge volume was placed in the second wall, and the incident beam was allowed to penetrate the first wall. The collection time for each measurement point was 60 s, and the specimen was moved between measurements in order to perform line scans of the strains as a function of the position from the top of the wall. While collecting the spectrum during side illumination the specimen was moved back and forth ±1 mm in the *x* direction compared to the nominal position of the measurement to increase the gauge volume and statistics. Three parallel line scans were performed, spaced 2 mm apart to check repeatability. During illumination from the bottom, only one line scan was performed. Spectrum fitting was performed using the General Structure Analysis System software [1] (GSAS) in order to determine the lattice parameters, *a* and *c*, of the hcp α-phase. Because of the low amount of β-phase in the structure, this was neglected in the present study. More details are described in references [2-3].

The resulting residual stresses are shown in Figure 3(b), which also includes the results from the numerical simulations. As expected from the strains in Figure 3(a), the overall trends are in agreement between experiments and predictions, whereas the levels differ.

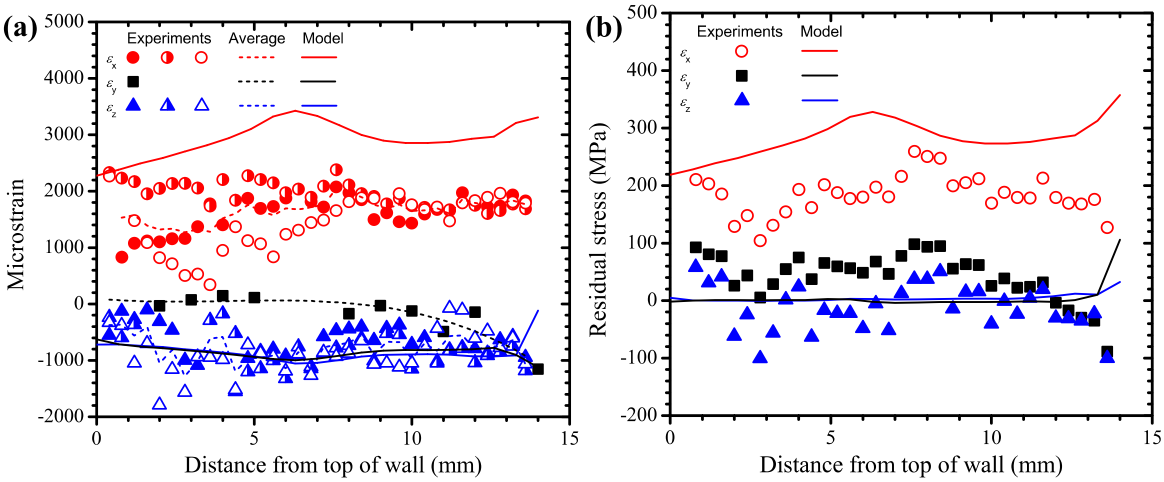

Figure 3. (a) Measured and predicted strains. (b) Measured and predicted residual stresses.

In Figure 4 the measured and computed deformations is shown. The first figure shows the out of plane deformations during the entire process. One peak corresponds to the addition of one layer. It can be seen that the overall trend is that the results is diverging. The computed deformation is also over predicted in each layer.

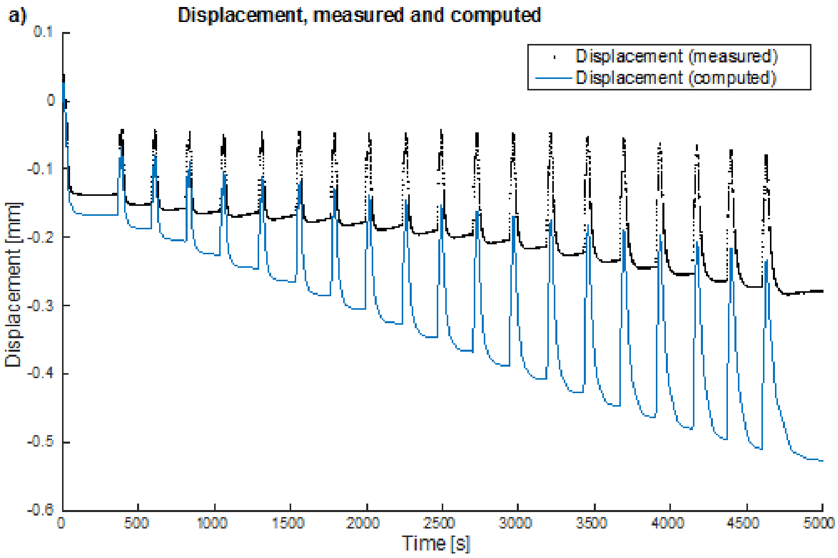

Figure 4. Measured and predicted deformation history for the entire process, measured at the center of the bottom surface.

Future work

The measurements performed at ESRF rendered in important residual stress state data in differently additivelly manufactured Ti-6Al-4V material. The next step in this research work is to perform post built heat treatments on the additivelly manufactured Ti-6Al-4V samples, and then measure change in residual stresses, in order to eventually be able to predit the new additively manufactured materials' mechanical properties through appropriate material modelling. The here involved group of scientists are working with development of a physically based material model for additive manufacturing of Ti-6Al-4V material. This model will, when fully validated, be able to predict the final mechanical properties of additive manufactured Ti-6Al-4V depending on its thermo mechanical treatment history. One of these "mechanical properties" is residual stresses, which not only affects static properties of final products, but also dynamic properties such as fatigue strenght. Complete understanding and control of these properties are fundamental needs before additive manufacturing will be mature for serial production of advanced structural componenets. Part of this modeling efforts have recently been published in reference [4].

The present research group anticipate to apply for new beam time at ESRF in order to complete the full set of measurements needed to valide the simulation model for additive manufacturing of Ti-6Al-4V presented in the article above. If the application is granted, this will enable the development of a comprehensive physically based material model for additive manufacturing of Ti-6Al-4V.

References

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