Microstructure and Mechanical Properties after Laser Metal Deposition of Ti6Al4V

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Abstract
Laser Metal Deposition (LMD) is a near net shape manufacturing technology to repair and/or additively build complex 3D components. Upon rapid solidification during LMD of Ti-6Al-4V alloy, a non-equilibrium structure consisting of mainly martensitic α' phase is formed. The difference in microstructure and texture of bar-shaped samples built up in different orientations is shown in this study. The static tensile properties depend on the loading direction with respect to the building direction. Heat treatment after LMD effectively improves ductility at the expense of static tensile strength. It is demonstrated that the building speed during LMD has a profound effect on the crystallographic texture and in this way impacts the static tensile properties. Apart from the static tensile properties, the dynamic mechanical properties (fatigue crack growth rate and fracture toughness) of LMD samples built in different orientations have been characterised.

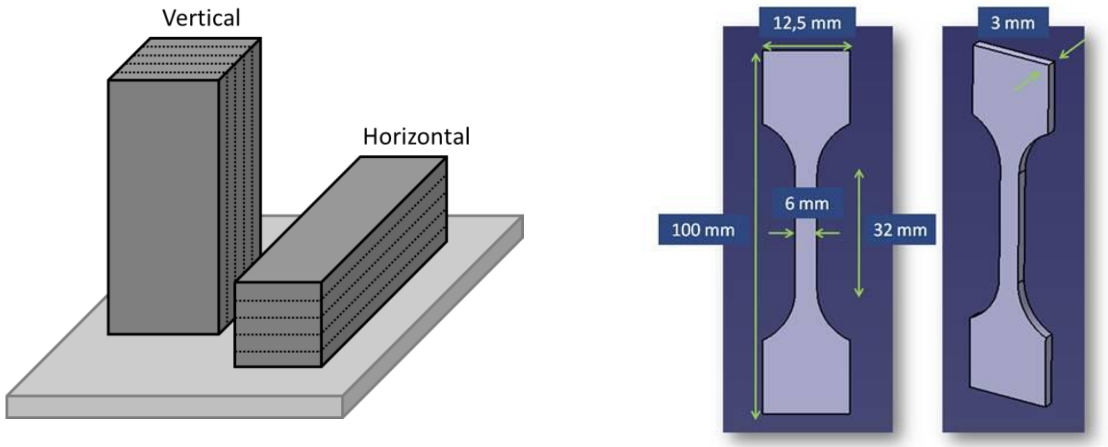
1. Introduction

Laser Metal Deposition (LMD) is a near net shape manufacturing technology to repair and/or additively build complex 3D components. The process consists in depositing different weld tracks next to and on top of each other by laser melting metal-based powder delivered with a gas stream to the metal substrate. Compared to conventional technology, LMD is characterized by high cooling rate and high thermal gradient, which leads to the formation of non-equilibrium phases and new crystal phases with extended ranges, as well as the changes in microstructure features [2-4]. The effect of the layered manufacturing, presence of porosity and texture on the magnitude and anisotropy of mechanical properties is of concern. In this case, the knowledge of the microstructure characteristics under LMD processing conditions as well as their responses to different heat treatment regimes are necessary for a deep understanding of the performance of LMD components.
Titanium alloy Ti-6Al-4V is widely used in a broad range of applications, including aerospace thanks to the properties like high strength, low weight and outstanding corrosion resistance.
A number of studies have been undertaken to investigate the material properties of Ti-6Al-4V processed by laser based additive manufacturing processes like LMD and Selective Laser Melting [1]-[7].
The work reported here is part of a larger investigation to understand the microstructure, static and dynamic mechanical properties of Ti6Al4V processed by LMD. Preliminary findings of this study on static tensile properties and microstructure of LMD parts are described in [1]. In this work first results on dynamic mechanical material properties are presented. This study will be completed in a future work with all results of samples loaded in 3 different orientations, in 2 stress states (as-built and stress relieved) and build up at 2 different travel speeds.

2. Experimental setup

The experiments were carried out using a 7 kW IPG fiber laser with out-coupling fiber of a diameter of 600 µm. The use of a focal lens with a focal length of 250 mm and a collimator lens with a focal length of 125 mm results in a laser spot diameter of 1200 µm on the substrate. The laser spot has a top-hat energy distribution and the powder was transported through a coaxial nozzle (Fraunhofer-Institut für Lasertechnik). Blocks were built up using a raster deposition pattern, encompassing an in-plane rotation of the fill tracks with 90 degree between each layer. The neighbouring scans within one layer have an overlap of 50% and a layer thickness of 0,5mm was applied. Samples

have been built up using optimal processing conditions at two different travel speeds. These are designated in the following text as ‘slow’ (1 m/min) and ‘fast’ (3 m/min). The ‘slow’ scanning parameters are used by default.
All samples have been built up in an inert chamber filled with argon.
Stress relieving (SR) heat treatment at 550°C for 4 hours with furnace cooling is performed after LMD (AB).
The microstructure was studied by optical microscopy and the texture and phase constitution were obtained by X-ray diffraction (XRD). The specimens were etched by a solution of hydrochloride acid, nitric acid and hydrofluoric acid, for microscopic analysis.
The tensile static properties tests were performed on Instron 5582 with an extensometer according to ASTM E-8M standard (see Figure 1). Samples for fracture toughness (FT) and fatigue crack growth (FCGR) have been built up in different orientations (Figure 2(a)). Using a similar nomenclature as the one used in ASTM Standard E399, the specimens are named as follows: first the direction normal to the notch and second the direction in which the crack is expected to grow (see Figure 2). For the FT specimens, pre-cracks are introduced by cyclic loading, with the frequency of 10Hz and R=0.1. All FCGR tests are performed with R=0.1 and a frequency of 5Hz. In order to record the comprehensive crack growth rate vs. stress intensity range curve, three load levels are selected during the fatigue loading on each particularly oriented group of LMD Ti6Al4V samples, P_{max} = 4kN, 3.2kN and 2.5kN.
Electric discharge machining (EDM) has been used to extract samples from the large blocks. The notch in the FT and FCGR samples has been machined mechanically.



(a) (b)

Figure 1: Static tensile samples (a) orientations and (b) dimensions.

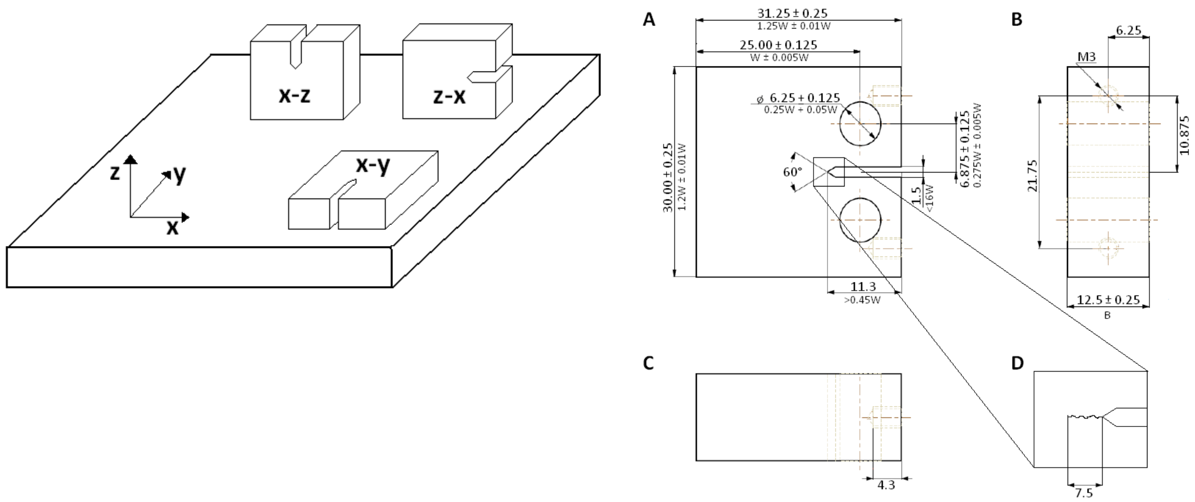


Figure 2: (a) Fracture toughness and crack growth rate sample orientations. (b) Dimensions of fracture toughness samples. Fatigue crack growth rate samples have a thickness B equal to 6.25 mm instead of 12.5mm. The remainder of the dimensions are identical.

3. Results

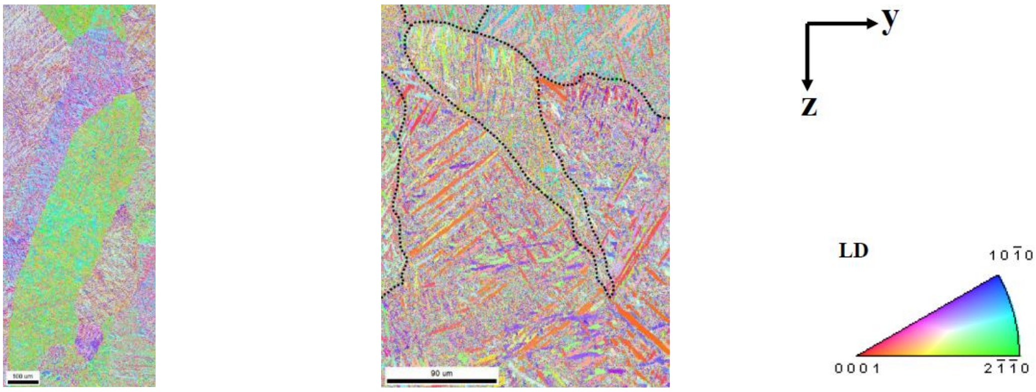
3.1 Microstructure, texture and interstitial element contents

Instrumental Gas Analysis has been performed to evaluate the content of oxygen, nitrogen and hydrogen in the LMD parts (see Table 1). The results show that the material after LMD fulfils the requirements for Grade 23 titanium alloy (Ti-6Al-4V ELI).

Table 1: Contents of oxygen, nitrogen and hydrogen for Ti6Al4V LMD part as measured by Instrumental Gas Analysis compared to materials specifications

Elements	**Oxygen (wt%)**	**Nitrogen (wt%)**	**Hydrogen (wt%)**
LMD parts	0,08	0,013	0.003
Material specifications Grade 5	$\leq$ 0,2	$\leq$ 0,05	0.0125
Material specifications Grade 23	$\leq$ 0,13	$\leq$ 0,03	0.0125

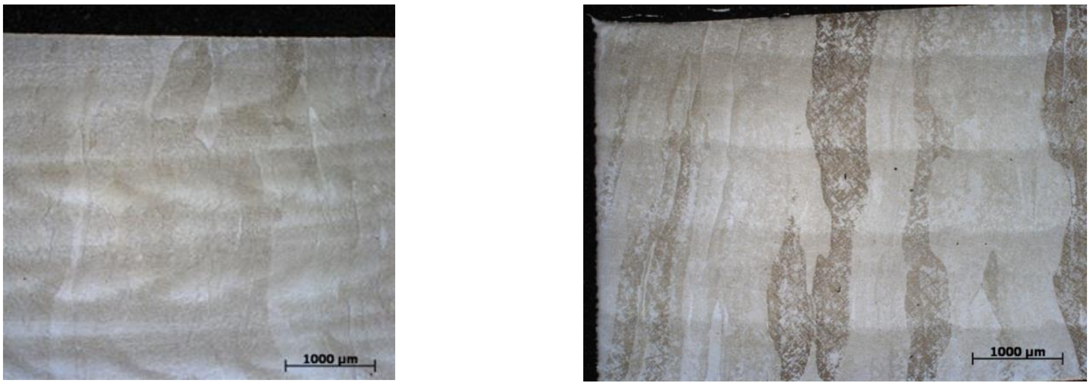
No defects apart from a few small, spherical pores are present in the LMD material (see Figure 4).
The microstructure consists of elongated prior β grains along the building direction (see Figure 4). The width of the grains seems larger at the top than at the bottom.
Electron backscatter diffraction images (EBSD) shows the relative high misorientation between the prior β grains in the slower scanned sample compared to in the faster scanned sample.



(a) (b)

Figure 3: Electron backscatter diffraction of side section of LMD material produced at relatively (a) slow and (b) fast travel speed of the laser.

Within the prior β grains, mainly a hexagonal martensitic α’ phase is present. XRD reveals the presence of also a bcc β phase in the vertical oriented parts at the top and the bottom regions (see Figure 5).
XRD has been performed to evaluate the crystallographic texture of the LMD material. In general, a significant crystallographic texture is detected for the LMD material processed at a slow travel speed, being characterised by <-12-10> preferentially along build direction and <0001> parallel to scanning directions as illustrated in Figure 6.



(a) (b)

Figure 4: Side view micrograph of (a) bottom and (b) top region of LMD part built in vertical orientation (see Figure 1(a)).

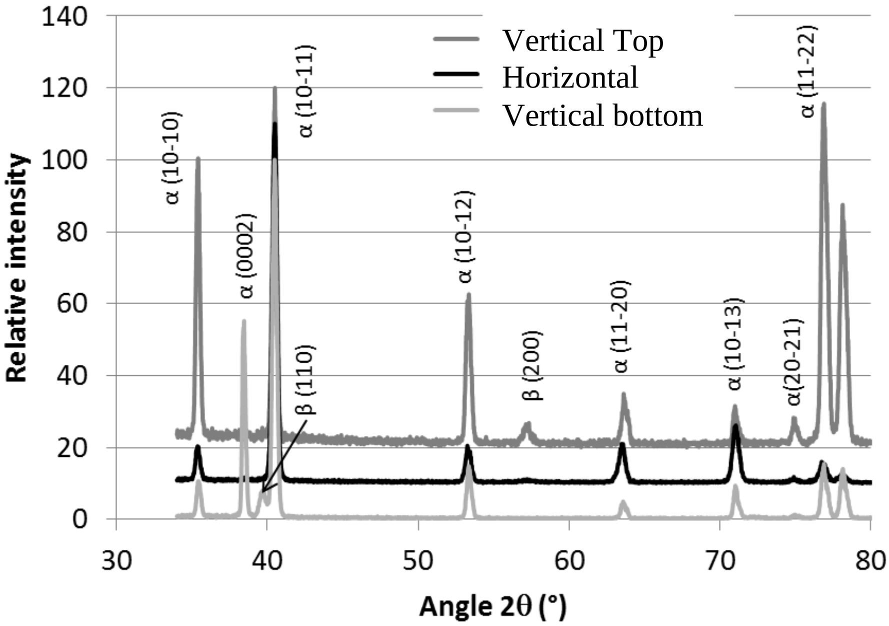


Figure 5: X-Ray Diffraction data for LMD parts built in horizontal and vertical orientations (see Figure 1(a))

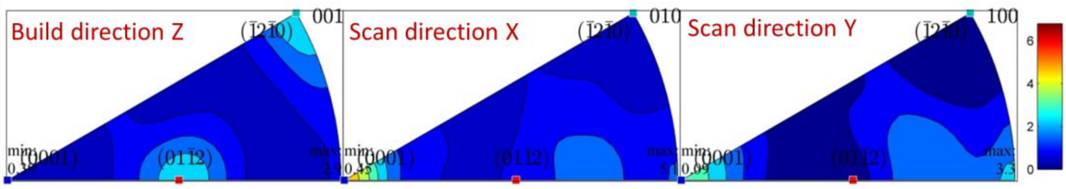


Figure 6: Inverse pole figures aligned along the building and the two scanning directions for LMD material produced at relatively slow travel speed for vertical oriented sample.

3.2 Static tensile properties

Figure 7 shows both the effect of building orientation of the sample relative to the loading direction and of the travel speed on the strength and elongation. As a reference also the literature values of the properties of conventional wrought Ti6Al4V are included. The strengths of the horizontal oriented parts are larger while the strengths of the vertical oriented part are equal compared to conventional processed Ti6Al4V. The part produced in vertical orientation is significantly weaker in strength and more ductile in terms of elongation. A higher travel speed does not significantly affect the strength, but results in a higher elongation at fracture.

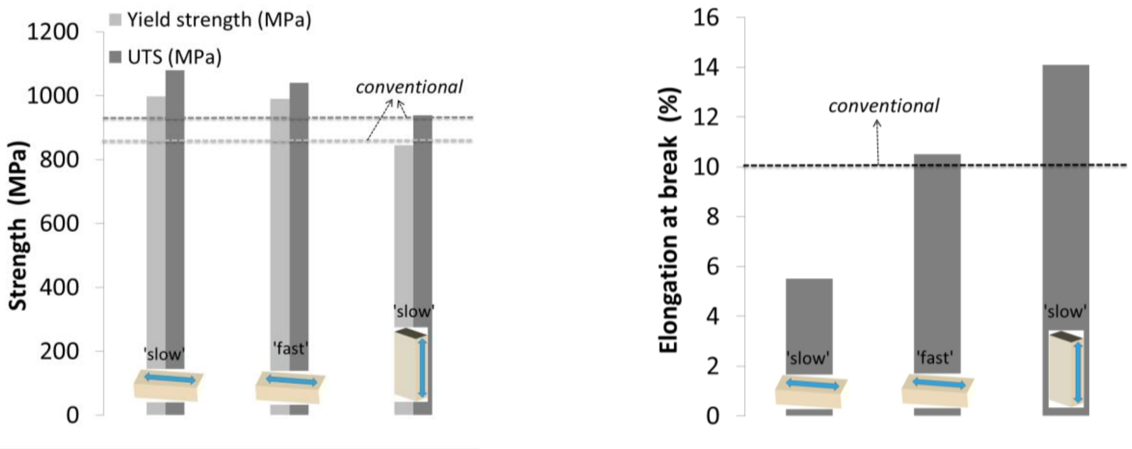


Figure 7: Static tensile test results for LMD samples built in 2 orientations at slower and higher travel speed of the laser compared to conventional wrought Ti6Al4V.

3.3 Dynamic mechanical properties

The fracture toughness of the Ti6Al4V LMD samples are in the range of 45-53 MPa*m$^{1/2}$. Higher scanning speed during LMD does not have a significant impact on the fracture toughness for the specimen with x-z orientations. Other orientations have not been tested yet. From the results up to now, a stress relieve heat treatment does not seem to influence the fracture toughness to a significant extent. There is no large scatter in results for samples built in same conditions and subjected to same loading conditions.

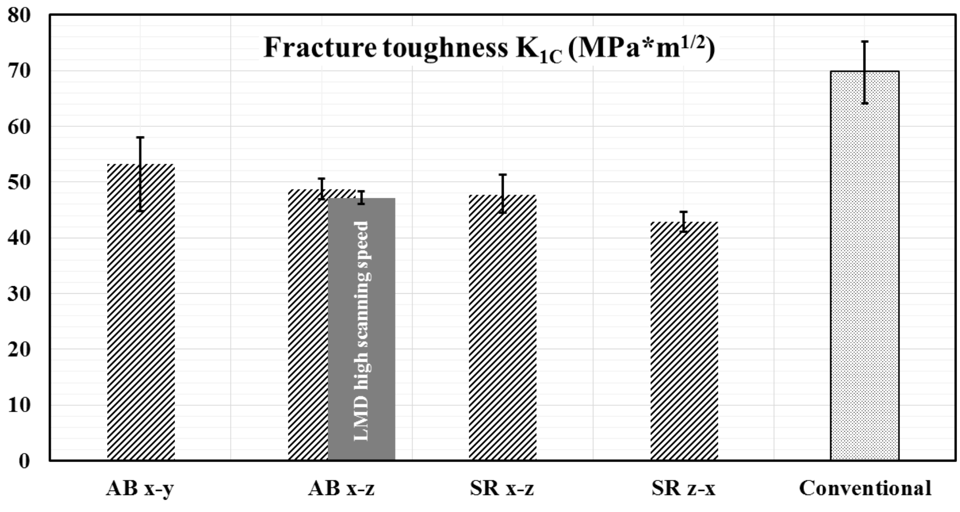


Figure 8: Fracture toughness values K_{IC} of as-built (AB) and stress-relieved (SR) LMD Ti6Al4V compared to conventional wrought Ti6Al4V.

Fatigue crack growth rate data of as-built and stress-relieved LMD Ti6Al4V for 3 different orientaions are shown in Figure 9. There is a small scatter in results for samples built at same processing conditions and loaded in same conditions. Between the stress intensity range of 10 to 50 MPa*m$^{1/2}$, all samples obey the Paris' law. The Paris' relationship parameters are listed in Table 2.

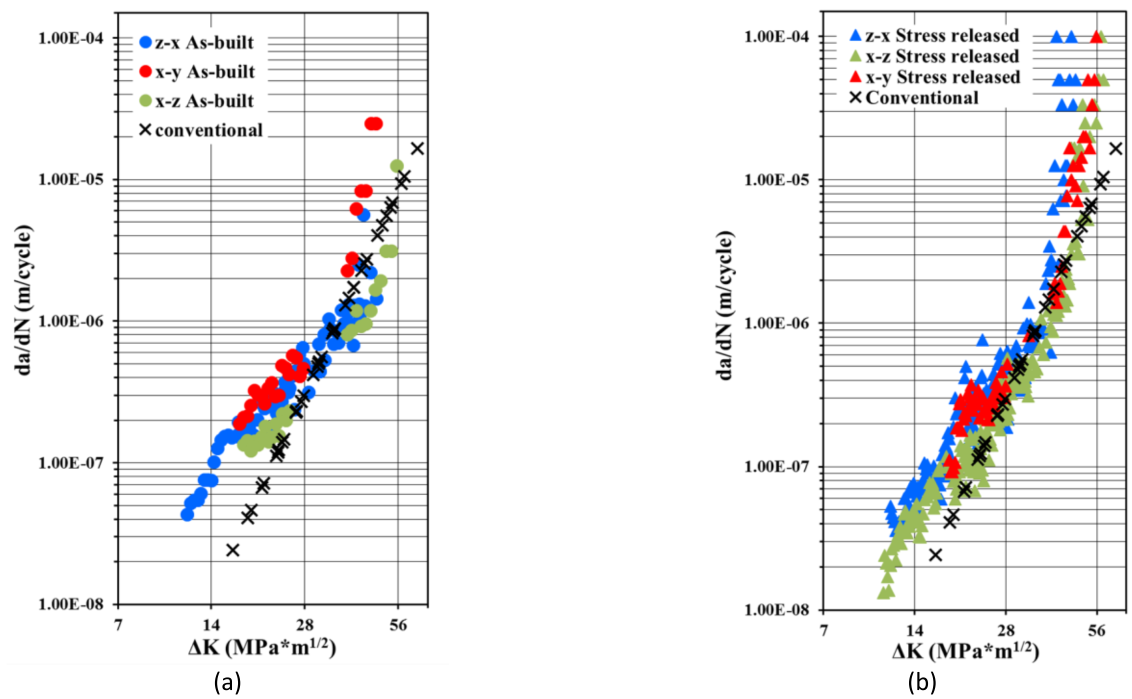


Figure 9: Crack growth rate da/dN versus stress intensity range ΔK for (a) as-built and (b) stress-relieved Ti6Al4V samples built in 3 orientations by LMD (see Figure 2) compared to conventional processed Ti6Al4V.

	m, crack growth exponent	C, crack growth coefficient	R^2
x-y AB	4.409	$4.385*10^{-13}$	0.9016
x-y SR	3.475	$4.950*10^{-12}$	0.8785
x-z AB	2.840	$2.805*10^{-11}$	0.9682
x-z AB high speed scanned	2.759	$4.989*10^{-11}$	0.8838
x-z SR	3.106	$1.064*10^{-11}$	0.8808
z-x AB	2.444	$1.388*10^{-10}$	0.9425
z-x SR	3.110	$1.524*10^{-11}$	0.8591

Table 2: Paris parameters and relevant correlation factors.

Stress relieving heat treatment results in slower crack propagation just after crack initiation, but doesn't show strong influence just before the final fracture at higher ΔK values. After stress relieving, x-y oriented specimen has a lower FCGR, while x-z and z-x oriented samples show no obvious change. Despite of both the earlier crack initiation and final breaking, stress-relieved specimen x-z shows equal or even lower crack growth rate during the crack propagation period (25-50 MPa*$m^{1/2}$).

3. Conclusions

The microstructure, texture and static and dynamic mechanical properties of a range of LMD Ti6Al4V samples have been tested. The effects of building orientation, travel speed and stress relieve heat treatment are included in this study. The work is still on-going but from the results presented in this work following conclusions can already be drawn:

- The microstructure after LMD is characterised by elongated prior β grains consisting of mainly martensitic α' phase. Dependent on the geometry and position within the component difference in phase constitution as well as in microstructural scale are observed.
- Vertical oriented Ti6Al4V samples show a significant lower static tensile strength and higher elongation than horizontal oriented samples. Apart from the difference in orientation between build direction and

- loading direction, differences in material characteristics caused by changing heat flow attribute to this observation.
- LMD Ti6Al4V has a fracture toughness in the range of 45-53 MPa*$m^{1/2}$.
- Only for the x-y oriented specimen the fracture toughness and fatigue crack growth rate properties of LMD Ti6Al4V seem to be significantly influenced by a stress relieving heat treatment.

Acknowledgement

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