Failure of WC$_p$/Ti-6Al-4V layer prepared by laser melt injection

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Abstract

Metal Matrix Composite layers consisting of WC particles (~ 80 µm diameter) incorporated into a Ti-alloy matrix by the so-called Laser Melt Injection process were mechanically tested. Standard tensile tests as well as in-situ scanning electron microscope observations of tensile stressed surfaces were performed. Crack initiation and crack propagation processes were observed at initial and final stages of failure. Cracks initiate always in the ceramic particles. Intergranular brittle fracture of the central part of the WC particles or brittle decohesion along the WC/W$_2$C interface form the initial failure. The crack propagates further inside the Ti matrix through brittle fracture of individual TiC dendrites and induces new cracks in the ceramic particles in the front of the main crack tip. Ductile fracture of the metal matrix, that creates the resulting fracture surface, is the final stage of the failure process. Internal tensile stresses formed during the laser processing are superimposed on the external tensile stress, which causes that local failure of the MMC layer starts at a relatively low external stress. The toughness of the Ti matrix makes the final failure process ductile.

1 Introduction

Laser surface alloying techniques attract interest for practical application. A promising process is the Laser Melt Injection (LMI), where a high power laser beam scans the metal surface with the aim to melt it locally. At the same time ceramic reinforced particles are injected into the melt [1, 2]. The Metal Matrix
Composite (MMC) layers with a thickness of about 300 – 800 μm on the metal surface are formed after solidification. Usually steels and light metal alloys are used as substrate and appropriate carbides or borides as reinforced particles.

In the case of Ti and its alloys, the formation of such a surface layer may be an elegant way to improve wear or corrosion properties [3, 4] without affecting the bulk properties. On the other hand, investigations of the fracture characteristics of ceramic particle reinforced metals have shown that particle addition usually lowers the fracture toughness. The effect of microstructure on failure characteristics is significantly affected by the details of the microstructure and the particle/matrix interface characteristics.

In the presented paper a WC/Ti-6Al-4V MMC layer was formed by the LMI process. Standard tensile tests as well as in-situ tensile tests inside a Scanning Electron Microscope (SEM) were performed with the aim to reveal the weakest structural components from the mechanical point of view. The crack nucleation process and further progress of the fracture were observed during testing and by conventional fractographic analysis after failure.

2 Experimental procedures

Spherically shaped, fused granular WC particles with a typical size of 80 μm were injected in 5mm thick slices of Ti-6Al-4V alloy by using a 2 kW Nd:YAG laser. Single laser tracks were made with a length of 20 mm, width of 1.5 and injection depth of about 1 mm. A more detailed description of laser injection process and particular parameters used may be found elsewhere [5, 6].

Flat tensile specimens with thickness of 1 mm were cut from the alloy substrate surface by spark erosion. Laser cutting was used to form V-type notches in the middle of 10 mm wide samples intended for in-situ observations. The direction of the specimen loading corresponds to the moving direction during the laser injection, i.e. in the longitudinal axis. The laser track with injected WC particles lay in this longitudinal axis and V-notches touched it from both sides to form a 1 mm wide region of stress concentration. The surface of the “in-situ specimens” was mechanically ground and polished.

Flat specimens with the width of 1.5 mm were cut using laser cutting to form a “standard” tensile specimen with an approximately working length of 15 mm. For the sake of comparison in which way the remelting by laser beam changes the tensile properties of the Ti-6Al-4V alloy, samples with the same dimensions were cut also from the substrate material and from the laser track without injected WC particles.

In-situ tensile test samples were loaded by a special stage (Kammrath & Weiss) inside a FEG-E-SEM Philips XL30 (field emission gun – environmental – scanning electron microscope), which allows observing deformation of the specimen surface simultaneously with the sample loading.

Standard tensile test were performed using a INSTRON 1195 tensile test machine with strain rate of $4.2 \times 10^{-4}$ Si. Sample deformation was measured by a non-contact video-extensometer Messphysik ME-46 using the sampling frequency of 100 Hz. The video-extensometer enables to observe an elongation...
of several sample segments simultaneously and therefore to study the deformation homogeneity along the sample length. Typically 4-6 surface markers were used to indicate 3-5 segments of the sample.

Optical microscopy, SEM, TEM and XRD methods were used to study the microstructure of the tested MMC layer.

3 Results

3.1 Microstructure

Processing and microstructure of laser melt injected WC particles in a Ti-6Al-4V alloy have been studied in detail and results of this study are published elsewhere [5, 6]. The final results are summarized in Fig. 1a,b. The width of a laser track is about 1.8 mm, the injection depth is about 1 mm and the volume fraction of WC particles inside the track lies in the range of 0.25 to 0.30. It is important to note that the particle distribution is homogeneous and the particles are injected over the whole depth and width of the melt pool. Figure 1b shows the detailed microstructure in the area around a WC particle. A W<sub>C</sub> layer surrounds the WC particle and then a TiC reaction layer is present, which is itself surrounded by W and TiC grains. Finally, further in the Ti matrix randomly oriented TiC dendrites are present.

![SEM micrograph of a cross section of laser track](image1.png) ![SEM micrograph (back scattered electron mode) of a WC particle and reaction zone](image2.png)

Fig. 1: a) SEM micrograph of a cross section of laser track. b) SEM micrograph (back scattered electron mode) of a WC particle and reaction zone.

3.2 Tensile properties

Figure 2 summarizes the tensile properties observed during the standard tensile test of the substrate Ti-alloy; the substrate material is re-melted by laser beam and finally the MMC layer is prepared by laser melt injection. The Ti-6Al-4V alloy shows a large decrease of ductility together with a strength increase of about 15% after re-melting by the laser beam. Such a behavior is not a surprise, because the substrate microstructure is optimized by thermal treatment to reach the best mechanical characteristics. Microstructure formed after laser beam re-
melting is more close to microstructures formed during the rapid quenching and therefore reduces plasticity and increases the strength.

![Stress-Strain Curves](image.png)

**Fig. 2:** Strain-stress curves for Ti-6Al-4V alloy substrate, laser re-melted substrate and WC/Ti-alloy MMC prepared by LMI process (left side and insert on left side). Right side: video-extensometer view of tensile test sample (a) before and (b) after the tensile test with slightly slanted markers for video-extensometer. The distance between markers before the test was 16 mm.

The WC/Ti-Al-V MMC layer shows that the tensile properties are much worse than the properties of the original Ti alloy or the laser re-melted samples. Fracture stress does not exceed 500 MPa and ductility is only on the level of 0.5%. As the insert in Fig. 2 demonstrates, the non-linear behavior from the beginning of loading process indicates a formation of local cracks and localized plastic deformation. At an external stress level of about 250-300 MPa ragged strain-stress curves prove the formation of macrocrack, which finally leads to the fracture at stress slightly above 400 MPa. Fracture occurs randomly along the sample length but is always localized inside the segment in which the ragged strain-stress curve was observed at the stress of about 250-300 MPa. The fracture surface is macroscopically oriented perpendicularly to the tensile axis.

### 3.3 In-situ failure and fractographic observations

Figure 3 shows the crack propagation path from the notch situated at the very left side. It was the rule, that cracks were already present inside WC particles.
situated close to the notch before applying a tensile stress. During the increase of the applied stress these cracks initiate cracking of the WC particles, which lie deeper in the sample. Cracks inside WC particles are often branched and their propagation is temporarily stopped at the particle/matrix interface. Particle cracking was observed in two distinguishable modes: as an intergranular cleavage (often branched) in the central part of the particle or as a cleavage along the WC/W\(_2\)C interface near the particle border, which is shown in Fig. 4. Fracture surfaces formed during the intergranular cleavage of the central part of ceramic particle and along the WC/W\(_2\)C interface are shown in Fig. 5.

A further stress increase leads to the cleavage of TiC dendrites inside the matrix area between the fractured particles. Macroscopically the cracks are oriented perpendicularly to the external tensile stress, but because of random orientation of in the matrix, the crack may locally deviate from this direction, as Fig. 6 clearly demonstrates. A lot of longitudinal fracturing of TiC dendrites,
observable on the fracture surface (Fig. 7), indicate that the failure process minimizes the deformation work through the cleavage of TiC dendrites along their longitudinal axes. In the case when the TiC layer around a particle is thicker, we also observed cleavage inside this layer (Fig. 8), but decohesion between TiC and W₂C is never observed. Finally, when all TiC dendrites on the

Fig. 5: Two mechanisms of failure inside ceramic particle: intergranular cleavage - left side and WC/W₂C interface decohesion - center. (fractographic observation).

Fig. 6: Crack propagation through cleavage of TiC dendrites that are randomly distributed in the matrix (in-situ observation).

path between two cracked particles are already broken and when the local stress concentration exceeds the strength of Ti-alloy matrix a macrocrack is formed through the ductile fracture of the Ti matrix. Considerable traces of plastic deformation are presented in Ti-alloy matrix in the inter-dendrite areas in Fig. 7. The macrocrack forms a new stress concentration at its tip and thus the cracking of the near embedded particles appears and the whole process is repeated and accelerated, until final fracture of the sample. Usually, two or a few main cracks propagate between notches and final failure occurs, either when they join or
when one of them reaches the opposite side of the sample. Figure 9 demonstrates two main cracks at a moment shortly before final fracture.

Fig. 7: Cleavage of TiC dendrites and ductile failure of Ti-alloy matrix between them (fractographic observation).

Fig. 8: Cleavage from the center of WC particle propagates through the thick TiC reaction layer (in-situ observation).

Fig. 9: An overview of main crack propagation at a moment close to final fracture (in-situ observation).
4 Discussion

The fact that cracks inside WC particles near the notch were observed even before an external stress was applied, reveals an important role of internal stresses introduced by laser processing. Internal stresses originated from the mismatch of the thermal expansion coefficient between Ti matrix and WC particle may be estimated for a spherical particle shape using Eshelby’s equivalent inclusion approach [7]. Inside the particle a hydrostatic compression is present. The value of hydrostatic pressure component depends on elastic modules of particle and matrix and linearly increases with the difference in thermal expansion coefficients of a particle and the surrounding matrix. The size of the hydrostatic pressure component does not depend on the particle size. Outside the particle both: radial compression and tangential tension stress components rapidly decrease ($\sim 1/r^2$) with the distance from the particle center [7].

Our estimation of this compression component gives a value from an interval 250 -350 MPa, using the difference in temperatures $\Delta T = 700-1000$ K, when particle is elastically stresses during the cooling and neglecting the presence of thin TiC layer. However, these internal stresses cannot lead to the WC particle cracking itself, because of their hydrostatic compression character inside the particle.

Both compressive and tensile residual stresses were observed by X-ray measurement in laser surface melted Ti-6Al-4V alloy [8]. The distribution of the residual stresses is tensile within the centre of the track and compressive toward the edges. Although, this result characterizes laser track made by a CO$_2$ laser with a different beam energy distribution, the maximum values of residual internal stresses ($\pm 200$ MPa) may be an indication for our laser process. Phenomenological analysis of residual stresses induced by laser coatings shows [9], that the longitudinal and transverse components of the residuals stresses are nearly equal inside as well as outside the laser track. When we situate a notch from the side of laser track (as Fig. 3 demonstrates), than the longitudinal residual stress component is amplified because of the notch stress concentration. This destroys an approximate stress symmetry state around the particle located closely to the notch and its stress state is not in a hydrostatic compression anymore. Now formation of brittle cracks inside the WC particles is possible and relatively easy, if the strength of a boundary between individual WC grains is low.

The same effect will be later induced by each crack, which will propagate through the MMC layer. We showed this by a statistic observation of surfaces of already in-situ cracked samples. We found, that approximately 85% of WC particles in the main crack surrounding are cracked. On the other hand, only 20% of particles in areas far away from main crack were cracked.

Once sharp crack in the sample is formed inside WC particle, further crack propagation through the surrounding TiC layer does not need a substantial
increase of external tensile stress. From the fracture toughness of TiC (2-3 MPa m$^{1/2}$) [10] and from the initial crack length equal to the maximal size of WC particle (~ 80 μm) we may calculate that a tensile stress of 190 MPa is required for the cleavage of TiC layer or TiC dendrites. Indeed such estimation is valid in the most ideal case, when the initial crack is straight, perpendicular to the external tensile stress, and propagates through the whole WC particle size. In reality, higher tensile stress for cracking of TiC components inside the laser track may be expected. This corresponds to our observation of ragged strain-stress curves at stress of about 250-350 MPa (see Fig. 2). Nevertheless, excellent bonding between particle and the surrounding TiC layer is achieved in contrast to the bonding observed in SiC/Ti-alloy MMC prepared by LMI [2].

Post failure fractographic observation of fracture surfaces confirmed that all fracture mechanisms observed on the polished surface during in-situ observation were realized also in the sample bulk. Needless to say is that the amount of cleaved TiC dendrites decreases with the distance from the polished surface. This is caused by a microstructural characteristic inside the laser track, where the density of TiC dendrites decreases with the depth inside the melt pool [5, 6].

The above analysis leads us to the prediction that the right way to improve the tensile the properties of the WC/Ti-alloy MMC layer prepared by LMI is based on the injection of single crystal WC particles and on the suppression of formation of TiC dendrites in the melt pool. The first choice suppresses the formation of brittle cracks inside the WC particles, because of the high strength of non-fused WC phase (1550 MPa) [10]. To realize the second assumption one has to minimize the contact between injected particles and laser beam to a necessary minimum. This will minimize the amount of carbon available for reaction with the titanium matrix as well as the formation of W2C layer on WC particles.

5 Conclusions

Intergranular cleavage inside the WC particle and brittle decohesion along WC/W2C interface are two predominant failure initiation mechanisms observed during in-situ tensile test of WC/Ti-6V-4Al metal matrix composite layers formed by the laser melt injection process. These pre-cracks are formed at a relatively low external stress or may be even induced by acting of internal stresses introduced during laser processing.

Failure proceeds into the matrix through the cleavage of randomly distributed TiC dendrites, mainly along planes laying along the longitudinal dendrite axis. The main crack propagates by the coalescence of these pre-cracks through the ductile fracture of the Ti-alloy matrix.
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References


