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# Preliminary investigation on impact resistance of additive manufactured Ti-6Al-4V

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**Abstract**

Understanding key failure mechanisms and material anomalies is one of the main challenges for an accelerated certification of additive manufactured parts. In this paper, the response to high velocity impact of Ti-6Al-4V printed by direct metal laser sintering was investigated and compared with wrought material. Taylor impact test at different impact velocities were performed with the scope to determine the velocity at onset damage development. Results show that such velocity is 57% lower than that of wrought material. Microscopy investigation on recovered samples reveals that the presence of initial voids in the microstructure, resulting from the printing process, reduces the shear resistance anticipating the formation of shear bands that is the main mechanism controlling fracture at high deformation rates.



*Keywords:* additive manufacturing, impact, Ti-6Al-4V, Taylor cylinder test

## 1. Introduction

Additive manufacturing technologies enable the construction of components in a near-net-shape condition by means of material layer-by-layer deposition using 3D model information. With particular reference to aero-space market, these technologies will drive a significative reduction of raw materials for the production of components in service

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with the reduction of "buy-to-fly" ratio. Innovation is also expected for unmanned aerial vehicles, Herderick (2011). The increasing expectations on such technologies brought out the importance of the "quality", not only intended as dimensional accuracy and lack of defects, but also in terms of effective mechanical properties, as a critical factor. At present, published studies on the correlation between the production process, part shape and effective properties are limited and not systematic. Lewandowski and Seifi (2016), in a detailed review of mechanical properties of additively manufactured materials, concluded that published data on standard samples are limited while papers addressing fundamental issues such as fracture resistance, response to impact, creep and multiaxial fatigue are missing. In the case of AM, the printing process in association with the shape of the component, leads to peculiar microstructure and residual stress/strain fields that determine the performance in service. The role of the microstructure not necessary becomes particularly evident in traditional quasi-static characterization testing, where the uniform stressed material volume is significantly larger than the microstructural length scale. Alternatively, high strain rate testing provides a unique mean to probe the role of microstructure on the material strength. In this work, additively manufactured Ti-6Al-4V, printed using direct metal laser sintering process was tested under high velocity impact conditions. The scope of the work was to investigate at which impact velocity ductile damage initiates, in comparison to that of wrought material, by means of Taylor impact tests. Preliminary results showed that the onset damage velocity is significantly lower for the AM material. This behavior is probably due to the presence of microvoids resulting from the printing process that seems to trigger anticipated formation of shear bands.

## 2. Material and methods

### *2.1. Material*

The material under investigation is commercial Ti-6Al-4V. This is an alpha-beta titanium alloy with a high strength-to-weight ratio and excellent corrosion resistance. It is one of the most commonly used titanium alloys, widely used in aerospace and biomechanical applications. Additively manufactured (AM) Ti-6Al-4V was printed using direct metal laser sintering (DMLS). This process is a rapid prototyping, AM technique designed to use a high power-density laser to melt and fuse metallic powders together. DMLS has many benefits over traditional manufacturing techniques. Since components are built layer by layer, it is possible to design internal features and passages that could not be cast or machined otherwise, Fig. 1. Cylinders 10.8 mm in diameter and 54 mm long were 3D printed. Each batch included samples oriented along x, y, z and xy 45° and xz 45° directions to investigate possible anisotropy effect due to the printing direction. After printing, each batch was heat treated at 800°C (1470°F) for 4 hours in argon inert atmosphere. At the end of this process, the microstructure has a lamellar structure of primary α and β phase and α grain boundary. Microscopy investigation revealed that the microstructure is also characterized by the presence of distributed microvoids of variable shape and size, ranging from few up to hundreds microns. The presence of such voids was also confirmed by X-ray CT scan, Fig. 2.

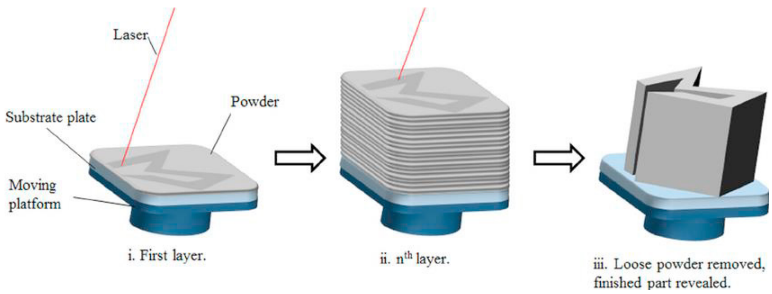
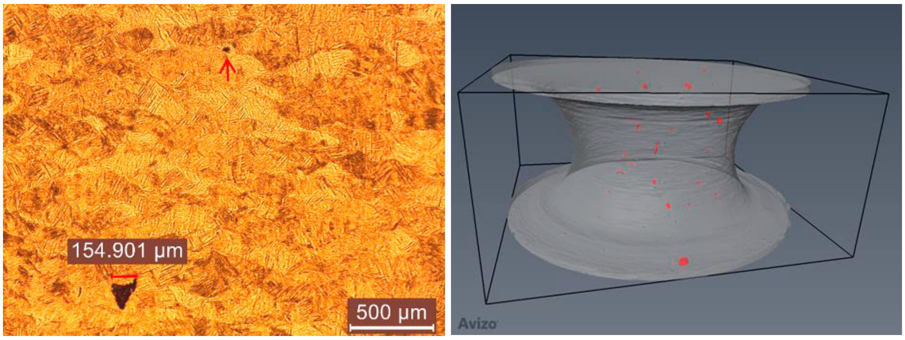



Fig. 1 Sketch of direct metal laser sintering process.




a) b)

Fig. 2 a) Microstructure of AM Ti-6Al-4V showing typical lamellar primary α (lighter) and β (darker) phases; b) X-ray CT scan result showing in red distributed microvoids resulted from the printing process.

### *2.2. Taylor cylinder impact test*

The Taylor impact test was initially introduced by Taylor (1948) to investigate the effect of impact velocity on the material yield stress. Today, this test is mainly used to validate constitutive models, (Bonora et al. (2012), Iannitti et al. (2014), Ruggiero et al. (2014)). The test consists in launching a cylinder of the material of interest at prescribed velocity against a rigid anvil. The cylinder impacts normally to the anvil surface and deforms radially while plastic deformation progresses axially. If the material is extremely ductile, radial deformation can be accommodated without the possibility for ductile damage to develop, (Bonora et al. (2015), Iannitti et al. (2017a)). For less ductile materials, damage in forms of radial cracks, starting at the outer edge of the impact surface, may occur while brittle materials fail by fragmentation. The formation of radial cracks is usually assumed as limit condition since for a further increase of the impact velocity these cracks may propagates leading to the fracture, split off and fragmentation.

In the present work, Taylor cylinder impact tests were performed with the gas-gun available at the University of Cassino and Southern Lazio. The gun is a single-stage gas gun with helium as propeller gas. The maximum pressure in the gas reservoir is 300 bar. Firing is performed by breaching a Mylar foil by means of a thermo-resistance. This solution ensures a full control of the firing pressure and high-test repeatability. The system allows the use of barrels with different bores ranging from 6 mm up to 40 mm. Projectiles can be launched with or without sabot. For the Taylor cylinder impact tests, an anvil made of C40 gas nitriding steel, is used. The gun and the anvil surface are accurately cleaned before each test. The anvil is located in a vacuum chamber that works also as containment. The velocity of the projectile is measured by means of laser photodiodes. Measurement stations are located inside the gun at the proximity of the gun mouth. Tests are monitored by means of high-speed video camera (up to 500 kfps).

In this work, Taylor impact tests were performed reducing progressively the impact velocity from 280 m/s to identify the threshold velocity at the onset damage. Such upper bound velocity value was estimated to be sufficiently high to cause damage by means of finite element simulation (Bonora et al. (2018)). Tests were performed on samples differently oriented with respect to the printing direction. Microscopy investigation analysis was carried out on recovered samples.

## 3. Results

At all velocities investigated in this work, Taylor cylinders showed a limited deformation in the radial direction. The “mushrooming” was always very contained consistently with the limited ductility of the material. In Fig. 3 the sequence of fracture development and separation for 153 m/s impact, of sample oriented along x-printing direction, is shown. Here, the mechanism of fracture is clearly visible. The crack starts at the cylinder outer surface and propagates radially causing the split-off of a portion of the cylinder approximately equal to one diameter in the axial direction. Once the crack is formed the cylinder slides along the crack plane that acts as a wedge. At higher velocity, the crack has less time to propagate: once the crack is initiated, the forming wedge is crushed under the pressure exerted by the rear portion of the cylinder.

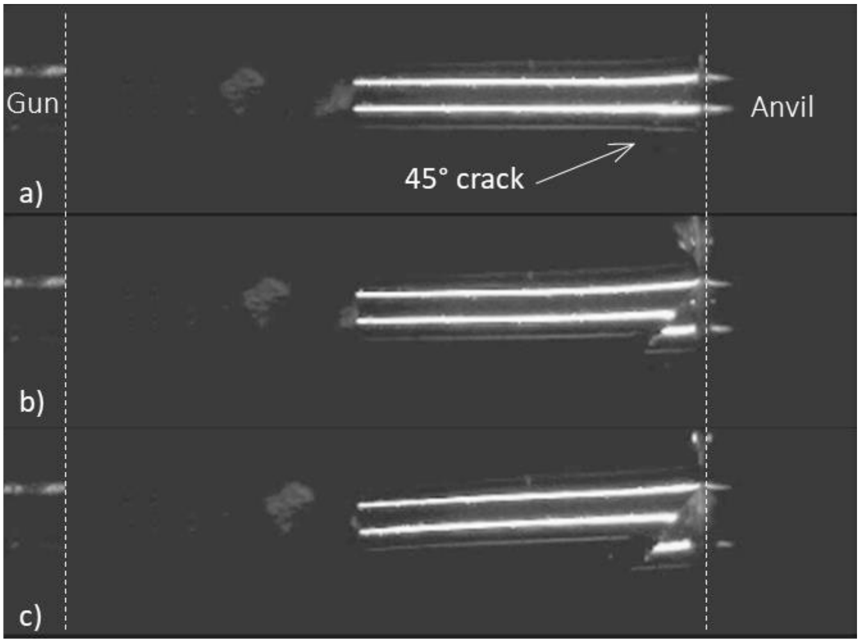



Fig. 3 Sequence of 45° crack formation at the impact with the anvil for AM Ti-6Al-4V at 153 m/s

In Table 1, the summary of the results of Taylor cylinder impact tests is given.

Table 1. Summary of impact tests results.

| Impact velocity [m/s] | X | XY | XZ | Y | Z | Wrought Ti-6Al-4W |
|---|---|---|---|---|---|---|
| 120 | Deformed | - | - | - | - | |
| 145 | Deformed | Deformed | Deformed | Deformed | Deformed | |
| 155 | Split-off | Split-off | Split-off | - | Shear cracks | |
| 170 | Split-off | - | - | - | - | Deformed |
| 220 | Split-off | - | - | - | - | Shear crack |
| 244 | | | | | | Split-off |
| 280 | - | Split-off | Split-off | Split-off | Split-off | Split-off |

Here, it is evident that in AM Ti-6Al-4V split-off starts to occur approximately at 155 m/s and higher. No appearance of shear cracks was observed for almost all printing directions at lower velocity (145 m/s). These have been observed only for the Z-direction at 155 m/s indicating that probably the impact resistance of the material, printed along this direction, is slightly higher. These results have been compared with those of similar experimental investigation carried out by Yu et al. (2011) on wrought Ti-6Al-4V which showed an impact velocity for split-off 57% higher than that of AM.

Such difference in the dynamic fracture resistance can be probably ascribed to the presence of preexisting voids resulting from the 3D printing process. In situ X-ray CT scan during quasi-static tensile tests on round notched bars, see Iannitti et al. (2017b) and Iannitti et al. (2017c), revealed that these voids do not grow and have no effect on the resulting fracture strain which in these sample geometry is controlled by stress triaxiality. On the contrary, Da Silva and Ramesh (1997) reported a reduction of 50% of shear fracture strain in porous Ti-6Al-4V (7.6% porosity) with respect to fully dense material. Under high strain rate loading, this reduction of shear resistance may promote the anticipated development of shear bands, as indeed observed in the post-mortem microscopy investigation, which is precursory to fracture development.

## Conclusions

In this work, preliminary results of an experimental investigation on the impact resistance of additively manufactured Ti-6Al-4V are presented. The dynamic fracture resistance was investigated performing Taylor cylinder impact test at different impact velocity to determine the damage threshold velocity. This value was found 57% less than that of wrought material. Microscopy investigation of recovered samples confirmed that fracture was caused by the extensive development of shear bands in the material. The presence of preexisting microvoids in the printed material seems to anticipate the formation of such bands, resulting in lower impact velocity necessary for damage development. Interestingly, these voids, the dimensions of which may vary from a few microns to hundreds, do not affect the failure strain under quasi-static deformation process dominated by stress triaxiality. In Taylor impact tests, these voids seem to act as weak spots that drive the development of shear bands.

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