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TECHNICAL NOTE

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High-rate characterization of additively manufactured Ti-6Al-4V using Taylor cylinder impact test: Experiments

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Abstract
Fracture behavior of additively manufactured (AM) Ti-6Al-4V has been investigated under quasistatic and impact loading. Taylor cylinder impact tests, on material printed along different directions, have been performed at various velocity to determine high-rate material deformation and impact velocity for damage initiation. Test results revealed that, although the AM material under quasistatic loading condition shows better characteristics than the corresponding wrought material grade, under impact condition, fracture in AM material occurred at an impact velocity almost half of that of wrought grade and at a strain 10 time less of the quasistatic uniaxial fracture strain. Microscopy investigation seems to indicate that pre-existing microvoids produced by the AM process promote shear band development under impact loading causing fracture at much lower strain.

KEYWORDS
additive manufacturing, impact, high strain rate

1 | INTRODUCTION

Additive manufacturing (AM) technology is evolving rapidly. Major advantages of AM, for aerospace and defense applications, are the possibility to print on-demand replacements and spare parts, with a reduction in holding cost and lead time and in maintaining the operational readiness in remote areas difficult to be supplied, and to manufacture primary structural components able to withstand stress and to ensure structural integrity. At present, main limitations for such use of the AM are the lack of robust and mature inspection, quality control and quality assurance techniques and an incomplete knowledge of the relationships between process, part shape, microstructure, and properties, which makes extremely difficult to anticipate the resulting material resistance to different failure modes, such as fracture, impact, creep, and multiaxial fatigue.[1] These limitations currently reflect in an extremely long and costly certification process for parts acceptability.[2] In order to develop reliable criteria for structural integrity assessment of AM parts, the role of process-induced defects must be understood. Several types of defects, which are peculiar of the AM process (such as lack of fusion, balling, gas porosity, cracks and interlayer delamination, and surface roughness), are introduced in the 3D printed parts. Because of their characteristic sizes, these flaws are highly localized in the material microstructure.[3] Classical low-rate characterization tests, such as uniaxial tensile test, may not be sufficient to reveal the effective role of such defects on the material damage tolerant capability since the sampled material volume is much larger than the defect characteristic length. Alternatively, high strain rate testing can be more appropriate because the size of the material volume stressed in fast dynamic load transients is of the same order of the microstructural length scale, which, in turn, enhance the effect of microstructural features. Scope of the work is to investigate the behavior and fracture initiation of additively manufactured Ti-6Al-4V under dynamic impact conditions.

2 | MATERIAL AND METHODS

Among all available materials for AM, Ti-6Al-4V is of primary interest for aerospace industry.[4] In recent years, this material has been the subject of numerous experimental investigations that have focused mainly on the characterization of the mechanical response in uniaxial stress regime (UTS, ductility, hardening, etc.), fatigue behavior, and in some cases on the correlation between the microstructure and macroscopic mechanical properties.[5–9] As far as we know, the literature on AM material behavior under impact loading is scarce with very few exceptions. Among these, the work of Jones et al.,[10] who investigated spall resistance in additively manufactured Ti-6Al-4V performing plate impact experiments,[11] is of particular relevance. They observed that flaws weaknesses resulting from the selected laser melting (SLM) manufacturing process were much more pronounced in the dynamic tests compared with the quasistatic tests. In fact, they found that although in quasistatic tensile tests, the difference in elongation between the vertical and through-thickness loading was about 20%, the difference in the spall-strength was about 40% underlining the importance of rate-dependent studies when characterizing new materials and manufacturing techniques. In the present work, Ti-6Al-4V was additively manufactured by means of direct metal laser sintering (DMLS) with EOSINT M280 power bed machine. The laser power was 260 W with a diameter of 0.1 mm (± .002 mm) and a scan speed of 1200 mm/s. The hatch spacing was 100 μm with a build layer thickness of 30 μm. The printing process was performed in argon atmosphere to minimize oxygen uptake and to avoid oxidation. Printed test samples were heat treated inside the printing chamber at 650°C for 3 h in argon atmosphere followed by furnace cooling. Final composition, average of three print batches given in weight percent, was 91.19 (±0.455) Ti, 3.98 (±0.35) Al, and 4.83 (±0.105) V. Sample geometry is a square cylinder with 13 mm in diameter and 80 mm long. A total of 93 cylinders were printed in three subsequent print batches. In each batch, samples were printed along the reference axis (x,y,z) and at 45° along xy and xz directions in order to investigate possible anisotropy. Final microstructure has a lamellar structure of primary α and β phases and α grain boundary. Samples were inspected with X-ray CT scan, which revealed the presence of isolated microvoids with variable shape and size, ranging from few up to hundreds of microns, Figure 1.

Quasistatic tensile tests have been performed machining uniaxial test samples from 3D printed cylinders in accordance with ASTM E8 standard. Impact resistance was investigated by mean of Taylor cylinder impact test. This test, initially introduced by Taylor,[12] was originally devised as a means of determining the dynamic yield strength of solids. The test involves the impact of a flat-nosed cylindrical projectile on a hard target, usually referred to as "anvil," at normal incidence. Today, the test is used to validate constitutive models and to probe material resistance to impact loading.[13–15] At the impact, the section in contact with the anvil expands radially while the rear part of the cylinder pushes axially and shortens. If the material is ductile, radial deformation is accommodated by plastic deformation that can occur without the damage development. For less ductile materials, voids may nucleate and grow along the cylinder axis immediately below the impact surface.[16,17] For materials exhibiting limited ductility, shear cracks may develop

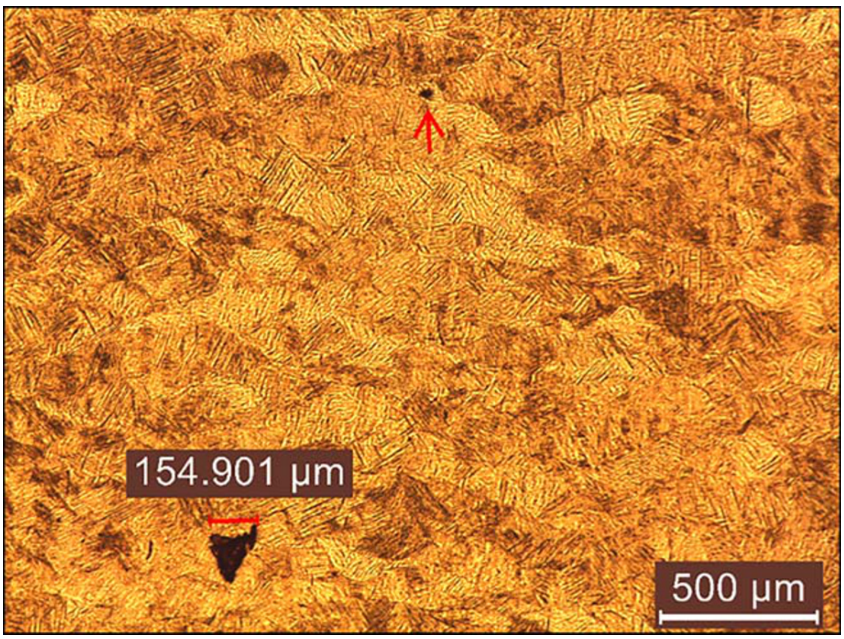

FIGURE 1 Microstructure of additively manufactured Ti-6Al-4V showing lamellar feature (ligher: α hexagonal close-packed (HCP), darker: β body centered cubic (BCC)) and microvoids of different size

radially starting at the edge of the impact surface. In general, the velocity at which these cracks start to can be assumed as the material limit condition since for a further increase of the impact velocity, these cracks propagate leading to cylinder split off and fragmentation. In this work, Taylor impact tests have been performed at different impact velocity to determine the velocity at which damage initiates. Taylor cylinders were machined from raw printed cylinder with 10.95 mm in diameter and 54.75 mm long. Tests were performed with a single-stage gas gun using helium as propeller gas. The firing system, which allows a full control and high repeatability, consists in beaching a Mylar sealing membrane by means of a thermo-resistance at desired gas reservoir pressure. Tests were performed in a vacuum chamber that also acts as containment. The projectile velocity is measured both in the gun, at the exit bore by means of three laser photodiodes, and in air using high-speed video recording. Recovered samples were polished and sectioned for microscopy analysis.

3 | RESULTS

Results of uniaxial quasistatic tensile tests are summarized in Table 1. At least three tests for each printing direction have been performed to check the repeatability of the measured material response. The anisotropy is very low with the z-direction being the weakest, as expected, although specimen printed along z showed the largest ductility in terms of Bridgman's strain. These results are in agreement with those reported also by Keist and Palmer.[18] All specimens, printed along the three normal directions, showed a significant necking prior ductile fracture. All uniaxial tensile test results exhibited relatively consistent behavior for all print batches and exceeded wrought Grade 5 Ti-6Al-4V minimum ASTM B348 requirements[19] although the ductility, given as Bridgman's strain, is 18% lower for the x-direction and ~7% for the z-direction.

Taylor tests were performed at different impact velocity starting from 280 m/s and then progressively reduced. At all velocities, cylinders showed a limited deformation in the radial direction. At higher velocity, cracks were observed to form at the cylinder outer edge starting at the impact surface and then propagating at 45° causing the separation of a fragment along the axis of the size approximately of one diameter. This is shown in Figure 2 where the frame taken with high-speed video recording shows the formed crack. This behavior was observed for specimens printed along all different directions for an impact velocity higher than 150 m/s with the only exception of the z-direction cylinders, which shown at 155 m/s, the initiation of a shear crack not followed full fragment separation. Below 150 m/s, all samples did not show evidence of crack initiation at the edge. This fracture behavior was reported also for wrought Ti-6Al-4V. Yu et al.[20] performed Taylor cylinder impact tests on wrought Ti-6Al-4V using cylinder of similar size (7.8 mm in diameter 25 mm long). They reported similar fracture behavior with the substantial difference that split off at higher velocity occurred as a result of multiple shear cracks starting at the sample periphery for an average strain (Bridgman) at the impact surface of ~0.49, which is very close to the uniaxial fracture strain, in contrast with the very low strain value ~0.034 measured for AM material at 150 m/s (for which the nominal strain rate is approximately $1.3 \cdot 10^4$/s). Taylor cylinders used in this work have twice the mass of those used in Yu et al.[20] However, the pressure wave generated at the impact, which drives fracture process in the material, depends only on the impact velocity, for given material density and velocity sound speed, that can then be used to compare present results with those of wrought Ti-6Al-4V. Interestingly, results of Yu et al.[20] show that the impact velocity at the onset damage development in wrought Ti-6Al-4V (~220 m/s) is 47% higher than that for AM material. Microscopic analysis of near fracture region revealed that localized shear bands developed starting at the pre-existing voids, which did not grow but acts as initiators for shear localization, which is probably the responsible for anticipated fracture at lower impact velocity, Figure 3.

TABLE 1 Summary of quasistatic tensile test along three normal printing directions

ID	YS (MPa)	UTS (MPa)	ε_n	σ_f (MPa)	ε_f
QsXJ1	1067.1 ± 19.28	1141.23 ± 5.68	0.041 ± 0.0015	926.9 ± 26.06	0.398 ± 0.0349
QsYJ1	1081.9 ± 6.56	1143.7 ± 6.24	0.040 ± 0.002	930.8 ± 11.01	0.396 ± 0.0475
QsZJ1	1057.26 ± 18.85	1124.83 ± 7.29	0.043 ± 0.002	926 ± 23.53	0.355 ± 0.0531

Note: YS is the yield stress at 0.2%, UTS is the ultimate tensile stress, ε_n is the strain at the onset necking, σ_f is the fracture stress, and ε_f is the fracture strain using the Bridgman's formula.

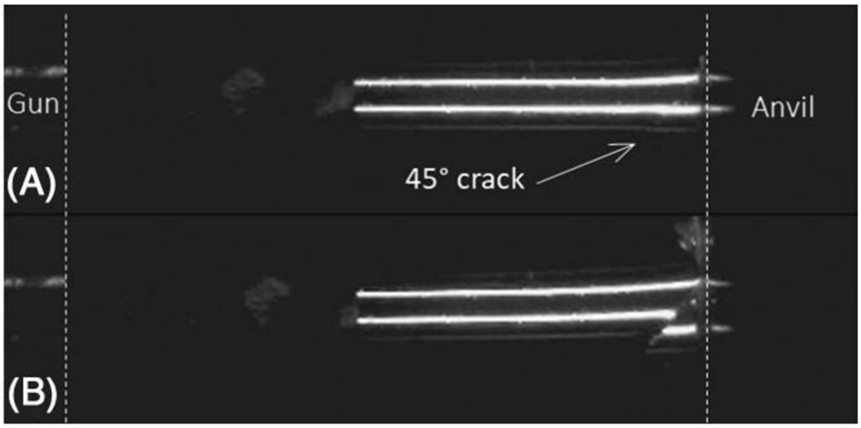

FIGURE 2 Fracture of additively manufactured (AM) Ti-6Al-4V impact at 155 m/s showing 45° crack formation and sample split off at subsequent time instant

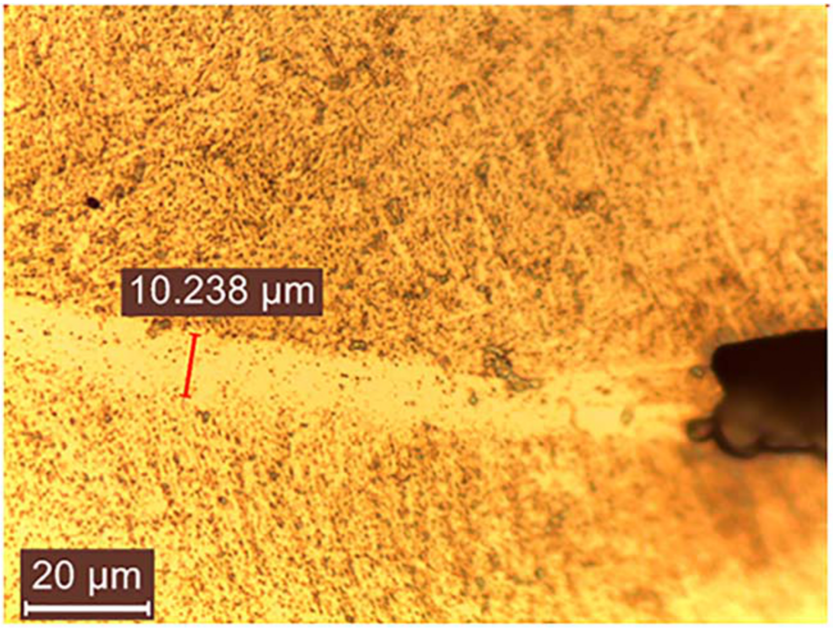

FIGURE 3 Localized shear band starting from a preexisting void in Taylor cylinder impact tests of additively manufactured (AM Ti-6Al-4V)

4 | CONCLUSIONS

In this work, the fracture resistance of additively manufactured Ti-6Al-4V has been investigated performing both quasistatic and impact tests. Under quasistatic loading, the 3D printed material shown mechanical properties exceeding those of wrought Ti-6Al-4V Grade 5. Under impact conditions, test results shown the opposite: the impact velocity at which damage, in form of 45° shear cracks starts in Taylor cylinder impact tests, is almost half of that of wrought material for which the fracture strain is approximately equal to that for quasistatic loading, while, for the AM material, the strain at which damage starts to occur is reduced by a factor of 10. These results confirm that for AM materials, dynamic testing seems to be more suitable to reveal weaknesses of flaws resulting from additive manufacturing process.

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