Review Article

Fractography and Microstructural Analysis of As-Built and Stress Relieved DMLS Ti6Al4V (ELI) Plates Subjected to High Velocity Impact

Teboho C. Moleko,1 Maina Maringa,2 and Willie B. Du Preez2

1Department of Mechanical and Mechatronics Engineering, Central University of Technology Free State, Bloemfontein, South Africa
2Centre for Rapid Prototyping and Manufacturing, Faculty of Engineering, Built Environment and Information Technology, Central University of Technology Free State, Bloemfontein, South Africa

Correspondence should be addressed to Teboho C. Moleko; moleko_t@yahoo.com

Received 15 February 2022; Revised 22 June 2022; Accepted 21 July 2022; Published 19 August 2022

Academic Editor: Giorgio Pia

Copyright © 2022 Teboho C. Moleko et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

This paper presents fractographic and microstructural analysis of as-built and stress relieved DMLS Ti6Al4V (ELI) plates with thicknesses of 8 mm, 10 mm, 12 mm, and 14 mm, impacted by high velocity projectiles. Fractography was performed through scanning electron microscopy on the surfaces of the projectile holes, while microstructural analysis of specimens extracted from the plates close to and far from the projectile holes was conducted by way of optical microscopy. Fractography revealed brittle behavior at the entry points of the penetration holes and ductile behavior at the exit points of the penetration holes. Microstructural analysis revealed microstructural changes in the alloy and a gradual increase of the $\beta$-phase fraction toward the edge of the projectile holes through all the plate thicknesses.

1. Introduction

In previous work by the authors, testing was conducted on wrought Ti6Al4V as an alternative to aluminium alloy AA 5083 and rolled homogeneous armor steel for high velocity impact applications [1]. Elsewhere, the authors presented justification based on the results in [1], strain energies of deformation, and the advantages of additive manufacturing for ballistic testing of direct metal laser sintering (DMLS) Ti6Al4V (ELI) plates [2]. In the current publication, analyses of the response of as-built and stress relieved direct metal laser sintering (DMLS) Ti6Al4V (ELI) plates to ballistic impact are presented and compared to the results presented in [1].

Impact phenomena can be characterized in numerous ways according to the impact angle, the geometry and material characteristics of the target or projectile, as well as the striking velocity [3, 4]. With reference to the striking or initial velocity ($V_i$), multiple categories of ballistic impact loading can be defined depending on the application [3, 4]. High velocity impact is normally simulated through ballistic testing, which is the firing of a high-speed projectile at a target, followed by investigation of damage to the target [4, 5]. This category of impact is characterized by a projectile traveling in a velocity range of 50 to 1500 m/s [4].

Failure under ballistic impact is due to the interaction of a variety of mechanisms, including fracture due to the initial stress wave, growth of cracks in the radial direction perpendicular to the direction of impact, spalling, scabbing, plugging, discing, dishing, front, and rear petalling, fragmentation in the case of brittle targets and ductile hole-enlargement [4, 6]. It has commonly been observed in ballistic experiments that plugs tend to form in hard thick plates, dishing and petalling in thin ductile plates, and ductile hole-enlargement and spalling in softer, thick plates [4, 6]. The other characteristic feature of a ballistic hole in
metals is an enlarged diameter at the entry, convergence followed by divergence at mid-depth, and continued divergence thereafter till the exit [6].

During high velocity impact, there is an adiabatic temperature rise of the target material [7]. Therefore, it is important to understand whether the temperature rise during impact is significant enough to bring about microstructural changes in the target material [7]. At room temperature, the microstructure at equilibrium of the Ti6Al4V alloy consists mainly of the α-phase (hexagonal close-packed (HCP) with some retained β-phase (body-centered cubic (BCC)) [8, 9]. As the temperature is raised, the alloy undergoes an α to β transformation [8, 9]. The lowest temperature at which a 100% β-phase can exist is called the beta transus and it is about 995°C [8]. It has been found that there is an adiabatic temperature rise in steels, which exceeds 1000 K at an impact velocity of 550 m/s [7].

As the temperature of the Ti6Al4V alloy increases, the percentage of α-grains in the microstructure of the two-phase region decreases [8, 10]. The foregoing statement can be substantiated by the Ti6Al4V phase diagram in Figure 1, which shows the percentage of the α-phase in the microstructure at a 4% volume fraction of vanadium to decrease as the temperature of the alloy increases [8, 10].

Ti6Al4V can exist in four different microstructural morphologies at room temperature as a function of the heat treatment [8, 10]. The four microstructural morphologies are acicular martensitic α, fully lamellar, equiaxed, and duplex or bimodal [8, 10, 11] and are illustrated in Figure 2.

The martensitic α microstructure is distinguishable by its randomly oriented fine needle-shaped morphology [10]. The fully lamellar microstructure compared to the equiaxed microstructure is distinguishable by a greater α/β surface area and more orientated colonies of alternate α- and β-grains that form the lamellae. An equiaxed microstructure has a uniform structure composed of equiaxed α-grains and transformed β-grains at the grain boundaries [8, 10, 11]. Moreover, the bimodal microstructure consists of primary alpha (αp) grains and colonies of α-laths that are separated by ribs of β-grains in the form of lamellae [10].

In the case of through penetration of a target, the projectile leaves a hole with a fracture surface [12]. It is important in this case to determine whether the fracture formed is through a ductile or brittle fracture, or a combination of the two mechanisms, to provide insight into the behavior of the target material [12]. Ductile fracture is characterized by extensive plastic deformation [13–15]. Ductile rupture refers to the failure and complete separation of highly ductile materials. When this type of failure occurs, the material pulls apart through the initial formation of dimples, followed by micro-cavities, and finally voids before failure [12, 14].

On the other hand, brittle fracture is characterized by little or no plastic deformation prior to failure, which is denoted by the formation of cracks and cleavage mark surface features on the fracture surface [12, 15, 16]. Figure 3 shows a scanning electron microscope (SEM) micrograph exhibiting dimple and cleavage rupture features at a fracture zone [14], while Figure 4 is a micrograph showing ductile fracture surface dimples [16].

Adiabatic shear bands (ASBs) are also common in cases of high strain rate and are likely to occur in cases of ballistic impact failure [16, 17]. Figure 5 shows an optical micrograph of an ASB observed in a bimodal microstructure of a Ti6Al4V plate [17].

This research is conducted to investigate if additively manufactured Ti6Al4V (ELI) can be used as an alternative over AA5083 and RHA, given its advantages of high specific strength and hardness and high corrosion resistance and toughness, as well as the advantages of additive manufacturing over traditional methods of manufacture.

### 2. Materials and Methods

#### 2.1. Specimen Preparation

Preparation of the specimens began with building, through DMLS, four sets of plates, all with planar dimensions of 100 mm by 100 mm and different thicknesses. Three plates each of thickness of 8 mm, 10 mm, 12 mm, and 14 mm, were built in an EOSINT M 280 machine at the center for rapid prototyping and manufacturing (CRPM) from Ti6Al4V (ELI) powder supplied by TLS Technik GmbH. The plates were then labeled by punching a numbering system on them to ensure traceability throughout the study. Each plate was allocated its own specific number, for example, 8-1 for the first 8 mm plate and 8-2 for the second one, and so forth.

#### 2.2. Test Setup and Measuring Equipment

The high velocity ballistic impact testing was carried out at Gerotek testing range with the help of ARMSCOR. Figure 6 is a schematic of the test setup on the Gerotek, South Africa, testing range. The projectiles used for the tests were 7.62 × 39 mm armor piercing incendiary (API) bullets.
The chronograph shown in Figure 6 was placed at a distance of 2 m in front of the target and was used to measure the velocity of the bullet at that point. A subtraction of 1.82 m/s on the chronograph reading was done to obtain the actual striking velocity on the target. The value of 1.82 m/s was arrived at from the known distance between the chronograph and the target and the known fact that the bullet experienced a reduction in velocity of 0.91 m/s per meter due to resistance in the air.

A system of 15 mild steel witness plates, each 1 mm thick, were placed in the mounting frame, behind the test plates, for use in determining the residual velocity of projectiles in case of through penetration. The plates were spaced 20 mm apart.
A high caliber rifle was used to propel the projectiles (bullets) towards the target, at approximately 90° to the front face of the target. The outlet of the barrel of the rifle was placed 30 m from the target upon advice of the personnel at the testing range based on their knowledge that at this distance the bullet would have stabilized and would therefore impact the target with little or no yaw.

2.3. Test Procedure. Initially, the test plates were sorted according to their respective thicknesses and labeling to ensure the correct testing order was followed. The next step was to mount a dummy target on the mounting jig and fire a few shots in order to adjust the telescope of the rifle to ensure the best accuracy. During this process, the functioning of the chronograph was also verified. Prior to each test shot, each test piece was mounted on the jig and secured by tightening the clamps of the jig to keep the test plate in place. The witness plates were then placed in their respective slots.

All personnel at the testing range were evacuated from in front of the rifle and located behind the witness protection wall, before shooting proceeded. The first set of shots was fired on the first three 14 mm thick plates, one at a time. With every shot that was fired, the velocity of the bullet from the chronograph was recorded. In the case of through penetration for any target plate, the number of mild steel witness plates that the bullet went through was recorded and the penetration holes in each witness plate were marked clearly. Subsequent sets of tests were carried out on the 12 mm, 10 mm, and 8 mm thick plates in this specific order, following the process explained in the previous paragraph.

2.4. Microstructural and Fractographic Investigation. For microstructural and fractographic investigation, the plates were wire cut through electro-discharged machining into four sections along the lines shown in Figure 7. In the figure, the red arrow indicates the DMLS build direction (BD).

Two of the four sections cut, Sections 3 and 4 in Figure 7, were cut through the projectile hole. The other two sections, Sections 1 and 2 in the same figure, were cut at the furthest points from the projectile hole. Fractographic studies of the projectile holes in Sections 3 and 4 were first conducted and thereafter, all four Sections 1–4 were further cut to produce specimens a, b, c, d, e, and f.

Specimens a, b, c, d, e, and f were then mounted on bases of resin, ground, polished and etched. Specimens e and f were used to confirm the initial microstructure of the target plates prior to testing, while specimens a, b, c, and d were used to study the microstructure of the flat plate surfaces.
radially outwards from the projectile holes. Figure 8 shows specimens a and c mounted on bases of resin.

Using an electric engraving pen, specimens a, b, c, d, e, and f were marked to ensure traceability when conducting microstructural analyses. A Struers CitoPress-1 automatic electro-hydraulic hot mounting press was used to mount specimens a, b, c, d, e, and f in bases of multifast resin. A Struers Tegramin-25 automatic, microprocessor-controlled grinding and polishing machine was used to grind and polish the mounted specimens.

Fractography of the projectile hole surfaces in Sections 3 and 4 was performed in a JEOL JSM-6610 SEM. A ZEISS Axioscope 5 Pol optical microscope was used to conduct microstructural analyses of specimens a, b, c, d, e, and f.

The half sections 3 and 4 from the 8 mm, 10 mm, 12 mm, and 14 mm thick plates of the projectile holes, were placed separately with their fracture surfaces facing vertically upwards in a SEM with the electron beam directed downwards onto them, to study the fracture surfaces formed by through penetration of the projectiles. The mounted, ground, polished, and etched cut-out faces of samples a, b, c, d, e, and f were then studied through optical microscopy to determine the initial, as well as post ballistic impact microstructures.

3. Results

3.1. Fractography. Following are SEM fractography of various sections of the test plates detailed in the preceding section. In the SEM images shown here, the red arrows in the figures indicate the direction of penetration (DOP) of the projectile. Two sets of micrographs are now presented, for the 8 mm thick plates and the 10 mm thick plates.

Figures 9(a) –9(c) are SEM secondary electron image (SEI) micrographs of the surface of a typical penetration hole through an 8 mm thick plate.

Figures 10(a) and 10(b) are SEM SEI micrographs of the same projectile hole shown in Figure 9(b) at different magnifications.

Figures 11(a) and 11(b) are SEM SEI micrographs of the area shown in Figure 9(c) at different magnifications.

For the 10 mm, 12 mm, and 14 mm thick plates, SEM SEI micrographs were taken at the projectile hole entrance, middle, and exit points through the plates. Based on the fact that the micrographs were observed to have similar features, the micrographs for a 10 mm thick plate are presented here as a representative of all these plate thicknesses.

Figures 12(a)–12(c) are SEM SEI micrographs of the surface of a penetration hole through a 10 mm thick plate at different locations of the hole and at different magnifications.

Figure 13(a) is an SEM SEI micrograph of the same area shown in Figure 12(b), while Figure 13(b) is a higher magnification micrograph of the circled area in Figure 13(a).

Figure 14 is a SEM SEI micrograph of the surface at the middle point of the penetration hole through a 10 mm thick plate.

Figure 15(a) is an SEM SEI micrograph of the same area shown in Figure 12(c), while Figure 15(b) is a higher magnification micrograph of the circled area in Figure 15(a).

3.2. Microstructure. This section focuses on the microstructural analyses of specimens a, b, c, d, e, and f extracted from the 8 mm, 10 mm, 12 mm, and 14 mm thick plates.

The first set of micrographs was taken from specimens a and b for all the plate thicknesses. Micrographs were obtained from the edge of the projectile hole and at distances of 2 mm, 4 mm, and 6 mm away from there moving radially outwards, in order to investigate the change in microstructure with distance away from the penetration hole during impact.

Based on the similarities of the microstructures of all the plate thicknesses near the edge of the projectile holes and radially away from them, the key features are represented through micrographs obtained from a plate of 10 mm thickness.

Figure 16(a) is an optical micrograph and Figures 16(b) and 16(c) have higher magnifications of 16(a), all near the edge of the projectile hole through a plate of 10 mm thickness. In the diagram immediately above these micrographs the projectile hole, filled with multifast resin during mounting of the specimen, is shown. The red dots in this
diagram show the locations at which observations were carried out on each specimen, with distances indicated relative to the edge of the projectile hole.

Figure 17(a) is an optical micrograph and Figure 17(b) a higher magnification, both at 2 mm from the edge of the projectile hole through a plate of 10 mm thickness.

Figure 18(a) is an optical micrograph and Figure 18(b) a higher magnification, both at 4 mm from the edge of the projectile hole through a plate of 10 mm thickness.

Figure 19(a) is an optical micrograph and Figure 19(b) a higher magnification, both at 6 mm from the edge of the projectile hole through a plate of 10 mm thickness.
To investigate whether the impact of the high velocity projectile did also affect the microstructure of the alloy at a distance of 25mm away from the edge of the projectile hole, a set of micrographs were taken at mid-span of specimens c and d.

Figure 20(a) is an optical micrograph and Figure 20(b) a higher magnification, both at 25mm from the edge of the projectile hole through a plate of 10mm thickness.

To confirm the microstructure of the as-built and stress relieved DMLS Ti6Al4V plates prior to testing, a set of micrographs was taken at mid-span of specimens e and f. Figure 21(a) is an optical micrograph and Figure 21(b) a higher magnification showing the initial microstructure of the as-built and stress relieved DMLS Ti6Al4V (ELI) plates used. The micrographs were taken at a distance of 40mm from the edge of the projectile hole.
Figure 13: SEM SEI micrographs (a) at the entry point of the penetration hole through a 10 mm thick plate and (b) a higher magnification micrograph of the circled area in (a).

Figure 14: SEM SEI micrograph at the middle point of the penetration hole through a 10 mm thick plate.

Figure 15: SEM SEI micrographs (a) at the exit point of the penetration hole through a 10 mm thick plate and (b) a higher magnification micrograph of the area indicated in (a).
Figure 16: (a) Optical micrograph, (b) and (c) higher magnification optical micrographs, all near the edge of the projectile hole through a 10 mm thick plate.

Figure 17: (a) Optical micrograph and (b) higher magnification optical micrograph, both at 2 mm from the edge of the projectile hole through a 10 mm thick plate.
To support the claim made earlier that the change in the \( \beta \)-phase fraction arises from induced high temperatures, which also led to a lower hardness, microhardness tests were conducted at different distances from the edge of the projectile hole. Using the FM 700 Digital Vickers microhardness tester at a constant load of 300 g for 15 seconds, multiple indentations were made at different distances from the edge of the projectile hole and along the ASBs.

Figure 22 is an optical micrograph showing the position of the indentations resulting from the Vickers microhardness testing of a 10 mm thick plate.

Table 1 shows the Vickers hardness values obtained from an as-built and stress relieved DMLS Ti6Al4V (ELI) ballistic impacted 10 mm thick plate, from the edge of the projectile hole to a distance of 6 mm radially away from this edge. In Table 1 and Figure 23, the symbols Avg and STD stand for mean value and standard deviation, respectively.

Figure 23 is a graph showing values of Vickers hardness of the as-built and stress relieved DMLS Ti6Al4V (ELI), ballistically impacted 10 mm thick plate from the edge of the projectile hole to a radial distance of 6 mm from this edge.
4. Discussion

4.1. Fractographic Analyses. The penetration holes through all the plate thicknesses, exhibit initial convergence at the entry side and divergence at the exit side of the plates, which is typical of ballistically impacted metallic plates. Evidence of this can be seen in Figures 9(a) and 12(a).

For all the plate thicknesses there is bulging and formation of a crater at the entry point of the projectile holes, as evidenced by Figures 9(b) and 12(b). The bulges here resulted from the inability of the target material to deform fast enough in front of the projectile, which caused alternative deformation outward radially from the edge of the projectile hole and backward. Bulging on the sides of the entry hole suggests a ductile deformation on the edges of the hole. The craters formed here, resulted from spalling failure of the material due to impact compression stresses inducing tensile waves in the direction of outward expansion and bulging at the point of impact of the projectile.

At the entry point of the projectile holes, the fracture surfaces show ridges as seen in Figure 10(b) for the 8 mm thick plates and Figure 13(b) representing all the other plate thicknesses. The ridges here are a result of interacting shear steps during impact. These are distinctive feature of a brittle fracture and therefore suggests a brittle mode of failure at the entry point of the penetration holes through all the plate thicknesses.
At the middle point of the projectile holes through the 10 mm, 12 mm, and 14 mm thick plates, represented by the micrographs shown in Figure 14 for the 10 mm thick plate, there are grooves and signs of smearing. Both these two features are thought to have been caused by the twisting and sliding movement of the projectile through the metal. These features make it impossible to identify the mode of fracture prevalent at this point along the penetration holes.

For all the plate thicknesses, dimples are visible at the exit point of the projectile holes as seen in Figure 11(b) for the 8 mm thick plates and Figure 15(b) for all the other plate thicknesses. Figure 11(b) for the 8 mm thick plates and Figure 12(c) for all the other plate thicknesses also show signs of petalling and scabbing left-over surfaces at the exit points of the projectile holes. Petalling and dimples are both indications of a ductile mode of failure. Petalling occurred as a result of the compressive incident stress waves that were reflected at the free exit end of the plates as tensile waves. This caused layers of material to peel off at this end, followed by internal failure and separation of material along a direction perpendicular to that of penetration of the projectile. The result of this was the formation of petals as the projectile exited the material. Based on the foregoing explanation it is clear that, scabbing predated petalling.

### 4.2. Microstructural Analyses

From Figures 16(a) and 16(b) it can be seen that near the edge of the projectile hole, there is a network of adiabatic shear bands (ASBs). The ASBs appear to run more or less parallel to the edge of the penetration hole. The narrow ASB, which is nearer the edge of the penetration hole, runs at an angle to the edge of the penetration hole for part of its length and then joins the large ASB located further away from the edge of the penetration hole.

The inclined ASB is consistent with shear failure of materials along the directions of maximum shear that are inclined to the directions of principal stresses. On the other

### Table 1: Vickers hardness of as-built and stress relieved DMLS Ti6Al4V (ELI), ballistically impacted 10 mm thick plate.

<table>
<thead>
<tr>
<th></th>
<th>At the edge of the projectile hole (A)</th>
<th>Along an ASB (B)</th>
<th>To the right of the ASB (C)</th>
<th>2 mm radially away from the edge of the projectile hole</th>
<th>4 mm radially away from the edge of the projectile hole</th>
<th>6 mm radially away from the edge of the projectile hole</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vickers hardness</td>
<td>304.0 HV</td>
<td>307.9 HV</td>
<td>407.7 HV</td>
<td>344.1 HV</td>
<td>340.7 HV</td>
<td>334.9 HV</td>
</tr>
<tr>
<td></td>
<td>323.2 HV</td>
<td>304.4 HV</td>
<td>326.8 HV</td>
<td>331.9 HV</td>
<td>349.8 HV</td>
<td>355.5 HV</td>
</tr>
<tr>
<td></td>
<td>313.0 HV</td>
<td>292.2 HV</td>
<td>351.4 HV</td>
<td>350.7 HV</td>
<td>358.6 HV</td>
<td>351.4 HV</td>
</tr>
<tr>
<td></td>
<td>331.8 HV</td>
<td>282.5 HV</td>
<td>320.2 HV</td>
<td>350.5 HV</td>
<td>346.1 HV</td>
<td>356.4 HV</td>
</tr>
<tr>
<td></td>
<td>328.1 HV</td>
<td>299.8 HV</td>
<td>310.2 HV</td>
<td>349.6 HV</td>
<td>359.1 HV</td>
<td>357.5 HV</td>
</tr>
<tr>
<td>Avg</td>
<td>320.0 HV</td>
<td>297.4 HV</td>
<td>343.3 HV</td>
<td>345.4 HV</td>
<td>350.9 HV</td>
<td>351.1 HV</td>
</tr>
<tr>
<td>STD</td>
<td>11.4</td>
<td>10.1</td>
<td>30.5</td>
<td>7.9</td>
<td>7.9</td>
<td>9.4</td>
</tr>
</tbody>
</table>

**Figure 23:** Vickers hardness numbers for an as-built and stress relieved DMLS Ti6Al4V (ELI), ballistically impacted 10 mm thick plate.
hand, the orientation of the ASB that is parallel to the direction of penetration can be attributed to tensile fracture as a function of induced circumferential tensile stress parallel to the circumference of the penetration hole. In Figures 16(a) and 16(c), on the right of the large ASB, the microstructure is comprised of a combination of lamellae and basket-weave microstructure within columnar structures. The columnar structures are aligned in the radial direction, which is the direction of induced tensile stress waves. It is not clear what led to the formation of columnar structures, which forms a subject for further research.

Figures 17(a) and 17(b) together with Figures 18(a) and 18(b), show that at 2 mm and 4 mm from the edge of the projectile hole, the microstructure is comprised of a combination of lamellae and basket-weave microstructure within columnar structures, respectively. At 4 mm from the edge of the projectile hole, the fraction of α-phase here is larger than in the previous micrographs at 2 mm and near the edge of the projectile hole. The higher prevalence of the α-phase here implies a lower induced temperature compared to the case at a distance of 2 mm from the edge of the projectile hole. Similarly, Figures 19(a) and 19(b) show that at a distance of 6 mm from the projectile hole, the microstructure is also comprised of a combination of lamellae and basket-weave microstructure within columnar structures. Furthermore, there are fewer incidences of lamellae compared to those at 2 mm and 4 mm from the edge of the projectile hole. In addition, the α-phase fraction is also significantly larger compared to the other distances.

At 25 mm from the edge of the projectile hole, the microstructure is comprised of a basket-weave microstructure within columnar structures. Here the prevalence of the α-phase has increased significantly compared to the previous micrographs at 4 mm and 6 mm from the edge of the projectile hole. The higher prevalence of the α-phase here implies a lower induced temperature compared to the case at distances 4 mm and 6 mm from the edge of the projectile hole. It is clear from Figure 21(b) that the as-built and stress relieved DMLS Ti6Al4V (ELI) had a basket-weave microstructure, prior to high velocity impact. From the micrographs shown in Figures 16–21, there is a variation in the α-phase and β-phase fractions with distance from the ASBs. The highest β-phase fraction occurs nearest to the ASBs. In the areas nearest to the ASBs, the high β-phase fraction is thought to have arisen from induced high temperatures during impact, which led to the formation of a fine lamellar microstructure with a higher content of the β-phase, which has a lower hardness. This claim of the induction of high temperatures is supported by the work done by Chen et al. [7], where it was found that there is an adiabatic temperature rise in steels, which exceeds 1000 K at an impact velocity of 550 m/s. As the average impact velocity of 702 m/s in the current work during ballistic testing is higher, it is suggested that there was heating of the alloy above the β-transus temperature of 995°C.

During the DMLS process, the alloy is cooled within an environment of static argon gas, while during the ballistic testing it experienced cooling in the open air at an ambient temperature of 25°C. The significant factor in the two cases is different starting temperatures of 3000 K and more than 1000 K for the DMLS process and ballistic testing, respectively. The cooling rate in the DMLS process is very rapid, varying between 10^5–10^6 K/s and thus leads to the formation of martensitic α-grains, while the cooling rate in the air during high velocity impact is much lower, thus leading to the formation of α and β lamellae.

From Figure 23 the microhardness of the as-built and stress relieved DMLS Ti6Al4V (ELI) ballistically impacted plate was lowest along the ASB at a value of 297.4 HV. This can be attributed to the fact that extreme deformation and therefore, temperature rise, took place along ASBs, which resulted in thermal softening. Consequently, the effect of transformation from the original microstructure to the fully β microstructure and then the evolution of the α and β lamellae is highest here, thus resulting in the lowest values of hardness.

Furthermore, the microhardness of the alloy had an average value of 320.0 HV at the edge of the projectile hole, which increased beyond the values at the ASB with increasing distance radially away from the projectile hole to a maximum value of 351.1 HV at a distance of 6 mm from the edge of the projectile hole. The trend in the values of microhardness observed in this study is indicative of a heating effect that diminished away from the edge of the projectile hole, accompanied by equivalent changes in the content of the β-phase fraction.

5. Conclusions

Although Ti6Al4V is classified as a ductile metal under normal loading conditions, the tests conducted here on DMLS Ti6Al4V (ELI), showed that under conditions of high velocity impact the alloy exhibits brittle and ductile behavior at the entry and exit points of the penetration holes, respectively.

During high velocity ballistic impact, the high strain rate imposed on the plates led to microstructural changes in the alloy. The impact of ballistic projectiles on the plates brought about an increase of the β phase fraction towards the edges of the projectile holes. The increase in the β phase fraction arose from induced high temperatures, which also led to lower values of hardness close to the edges of the projectile holes.

The high strain rate and rise in temperature arising from high velocity impact were enough to cause the formation of ASBs, whose incidence dissipated with distance away from the edge of the projectile hole.

Data Availability

The primary data can be made available upon request, subject to limitations of the service providers (ARMSCOR) data access rules and regulations.

Conflicts of Interest

The authors of this article declare that there are no conflicts of interest.
Acknowledgments

The authors would like to express their gratitude to the Centre for Rapid Prototyping and Manufacturing (CRPM) of the Central University of Technology, Free State (CUT), for manufacturing the as-built and stress relieved DMLS Ti6Al4V (ELI) plates used for the tests. Furthermore, Dr. Thyiwill Dzogbewu is thanked for his guidance and assistance in the metallographic laboratory of CUT. Lastly, the authors express their gratitude towards Flamengro, a Division of Armscor SOC Ltd, in collaboration with Armour Development, for their guidance and assistance in the testing phase of the project. This research was funded by the South African Department of Science and Innovation (DSI) through the Council for Scientific and Industrial Research (CSIR), for the Collaborative Program in Additive Manufacturing, Contract No.: CSIR-NLC-CPAM-18-MOA-CUT-01.

References


