

Article

Fabrication of Electron Beam Melted Titanium Aluminide: The Effects of Machining Parameters and Heat Treatment on Surface Roughness and Hardness

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Abstract: Titanium aluminide alloys have gained attention for their lightweight and high-performance properties, particularly in aerospace and automotive applications. Traditional manufacturing methods such as casting and forging have limitations on part size and complexity, but additive manufacturing (AM), specifically electron beam melting (EBM), has overcome these challenges. However, the surface quality of AM parts is not ideal for sensitive applications, so post-processing techniques such as machining are used to improve it. The combination of AM and machining is seen as a promising solution. However, research on optimizing machining parameters and their impact on surface quality characteristics is lacking. Limited studies exist on additively manufactured TiAl alloys, necessitating further investigation into surface roughness during EBM TiAl machining and its relationship to cutting speed. As-built and heat-treated TiAl samples undergo machining at different feed rates and surface speeds. Profilometer analysis reveals worsened surface roughness in both heat-treated and non-heat-treated specimens at certain machining conditions, with higher speeds exacerbating edge cracks and material pull-outs. The hardness of the machined surfaces remains consistent within the range of 32–33.1 HRC at condition 3C (45 SFM and 0.1 mm/tooth). As-built hardness remains unchanged with increasing spindle and cutting head speeds. Conversely, heat-treated condition 3C surfaces demonstrate greater hardness than condition 1A (15 SFM, and 0.04 mm/tooth), indicating increased hardness with varying feed and surface speeds. This suggests crack formation in the as-built condition is considered to be influenced by factors beyond hardness, such as deformation-related grain refinement/strain hardening, while hardness and the existence of the α_2 phase play a more significant role in heat-treated surfaces.

Keywords: titanium aluminide (TiAl) alloys; additive manufacturing; post-processing; microstructure; hardness; machining



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1. Introduction

Titanium aluminide (TiAl) alloys are of particular interest and are increasingly gaining global interest within the academic community and various industries, including the aerospace and automotive sectors. This is due to the fact that TiAl alloys are lightweight and exhibit excellent dimensional stability. Additionally, they possess a high melting point and offer superior strength and stiffness at elevated temperatures. These alloys

also exhibit remarkable resistance to oxidation and creep, particularly at moderately high temperatures [1,2]. Until very recently, the applications of TiAl alloys have been limited to small and simple configurations. Examples include turbocharger turbine wheels [3,4] and automotive engine valves [5,6], which have traditionally been fabricated using conventional manufacturing techniques such as casting, forging, and/or rolling. For example, TiAl creates some disadvantages such as ease of crack formation at highly stressed locations, low ductility of product, problems related to poor fluidity, high reactivity, and challenges in welding type repairments when the casting is preferred for fabrication [7,8]. Another handicap of the method is that the surface oxide and contamination layer from the casting mold is required to be removed when the manufacturing task is carried out [9]. The production of complex parts from rolled, thin plates also poses challenges. Designing plates with variations in thickness or creating large-scale 3D structures is still not feasible. Furthermore, difficulties may arise during the assembly process, particularly when welding is involved. These factors make the goal of producing complex parts using rolled thin plates less realistic [7]. The manufacturing of TiAl alloy-based large components with complex shapes and high dimensional accuracy is still an unmet criterion using conventional methods. TiAl alloys, despite the challenges faced in their forming procedures, hold the potential to partially replace the usage of Ni-based alloys and heavy steels in various industrial applications. This is particularly applicable to fields such as gas turbines, where the possession of the aforementioned desirable material characteristics is crucial [10,11]. Given the current circumstances, the adoption of novel solutions for the production of TiAl alloy parts to be used in various applications can provide valuable support to both industry and academia.

One of the most recent advancements in the field of metal and alloy manufacturing is the widespread adoption of additive manufacturing (AM). This innovative technique has garnered significant attention, particularly from the aerospace industry, due to the numerous advantages it offers over conventional manufacturing processes [12,13]. AM improves the manufacturing cycle time of complex parts in a cost-effective manner since it eliminates the need for excessive machining and the utilization of expensive tooling [14–17]. Moreover, composite materials, complex structures, or parts that were conventionally impossible to manufacture, such as lattice structures or those with complex and intricate internal features, can be easily produced using AM processes [18–21]. By leveraging the production ease offered by additive manufacturing (AM) technology, the challenges encountered during the production procedure of large and complex parts based on TiAl alloys can be avoided. Compared to other additive manufacturing (AM) techniques, the fabrication process of Ti alloy-based parts is carried out at temperatures around 1000 °C. This temperature range minimizes or eliminates temperature gradients, thereby facilitating the production of stress-relaxed parts [22]. Similar to other additive manufacturing (AM) processes, such as selective laser melting (SLM) [23–26], electron beam melting (EBM) [27] is a powder-bed fusion technique used to directly manufacture complex-shaped geometries from a 3D CAD file; the other most popular metal additive manufacturing method is directed energy deposition (DED), where the metal powder is blown through a carrier gas and the transferred metal powder on the substrate is melted using a high energy source such as a laser beam [28–30]. During the entirety of the EBM fabrication process, which operates under a vacuum environment, the powder material is fed and fused by scanning a focused laser or electron beam as a heat source. This implies highly reactive materials can be produced using the EBM method, whereas oxidation and contamination of the parts are avoided through the process [8].

Rough surface formation is a natural occurrence in any type of AM process, although the degree of surface roughness may vary depending on the specific AM method employed for production. There is an inverse correlation between surface quality and the degree of surface roughness, which significantly impacts the mechanical properties of additively manufactured parts [31]. While there are some minor cases that do not apply to this assumption [32], such as parts with larger internal defects. The necessity of surface quality

improvement motivates us to find post-processes methods such as machining [33], electrochemical treatments [34], electron-beam irradiation [35], and multi-jet hydrodynamic cavitation abrasive finishing [36] to remove the undesirable surface characteristics and fix the surface morphology. Machining is still one of the easiest ways to improve the surface quality since it does not require hazardous chemical acids such as acetic/perchlorate, sulfuric, phosphoric, nitric, or hydrofluoric acids or requires less rare equipment that is hard to access when compared to machining equipment [37–39].

While there have been numerous studies on machining techniques for conventionally manufactured metallic parts [40], there is relatively limited research on machining methods specifically tailored for additively manufactured metals and alloys [41–43]. The existing studies in the literature mainly concentrate on Inconel 718 alloys [43], Ti6Al4V alloys [44], various steels [25,41], and aluminum alloys [26] for additively manufactured materials and machining of additively manufactured materials. Due to factors such as availability, cost, and commercial confidentiality, the research focus on TiAl alloys has been limited, resulting in a relatively small number of studies conducted on this particular material. Beranoagirre et al. investigated the machinability (end milling) of a variety of γ -TiAl alloys using an AlTiN-coated tungsten carbide tool. They correlated the influence of cutting speed with the end milling tool wear and durability [45]. Hood et al. focused on surface integrity and residual stress when the TiAl was subjected to the slot milling procedure using a small-diameter AlTiN-coated tungsten carbide end milling tool [46]. Klocke et al. investigated the effect of cooling liquids regarding the machining (turning) of cast TiAl alloy and discovered the significant influence of cryogenic cooling on the prevention of tool wear and sub-surface defects [47]. Similarly, Bentley et al. also concentrated the effect of turning parameters and cooling liquid on the strain hardening, surface quality, and microstructure simply by checking the microscope images while the cast TiAl was subjected to machining [48]. Zu and Chen studied the effect of tool material and lubricant choice on tool wear during the machining (hole drilling) operation of TiAl alloy [49]. Furthermore, these limited number of earlier studies are solely focused on conventionally manufactured TiAl alloys, which have different microstructural characteristics [50,51]. To the best of our knowledge, there is a dearth of inclusive and enthusiastic research in the literature regarding the machining of TiAl and machined-TiAl surfaces. Upon additive manufacturing, the microstructure is observed to evolve into a complex state, exhibiting finer grain structure, preferred orientations, etc., compared to the TiAl manufactured by conventional methods. This means the effect of machining on the final part may be different, for which the initial condition is not the same as that of conventionally produced TiAl alloys, motivating researchers to investigate the effect of machining parameters on the surface and hardness properties of TiAl alloys. The current study will help other scholars and industry to avoid crack-related machining failures and time loss.

The main goal of our current study is to inspect how machining parameters affect the surface structure's evolution and the hardness properties of additively manufactured TiAl parts. We hypothesize that the changes that occurred during the machining of AM parts will advance the replacement of conventional manufacturing methods with AM processing. For this reason, rectangular-shaped TiAl parts have been fabricated by means of the EBM process. Subsequently, a set of the TiAl parts is subjected to a heat-treatment procedure. The fabrication of TiAl parts and heat-treated conditions has been the motive to explore in detail the effect of machining parameters on the surface characteristics and mechanical properties of the additively manufactured part.

2. Materials and Methods

2.1. Production of TiAl Samples with E-PBF

An Arcam A2X electron beam melting (EBM) machine with an accelerating potential of 60 kV as energy carried within a vacuum environment was used to produce Ti-48Al-2Cr-2Nb alloy specimens (Figure 1). Briefly, 1333 K preheating temperature and 90 μ m layer thickness were kept in the productions where 0.200 mm line offset, 12 mA current, and

1600 mm/s scan speed variables were performed. TiAl powder (Praxair S.T. Technology, Inc., Indianapolis, IN, USA) has a particle size ranging from 56–127 μm , and its chemical composition is given in Table 1. The parameters were selected based on previously reported work [52,53]. Subsequent to the EBM fabrication, 20 mm $\times$ 20 mm $\times$ 40 mm-sized rectangular samples are cut off from the base plate and are referred to as “as-built” conditions. Some of the as-built specimens are heat-treated at 1473 K for 2 h under an argon atmosphere and are hereafter denoted as “heat-treated” conditions.

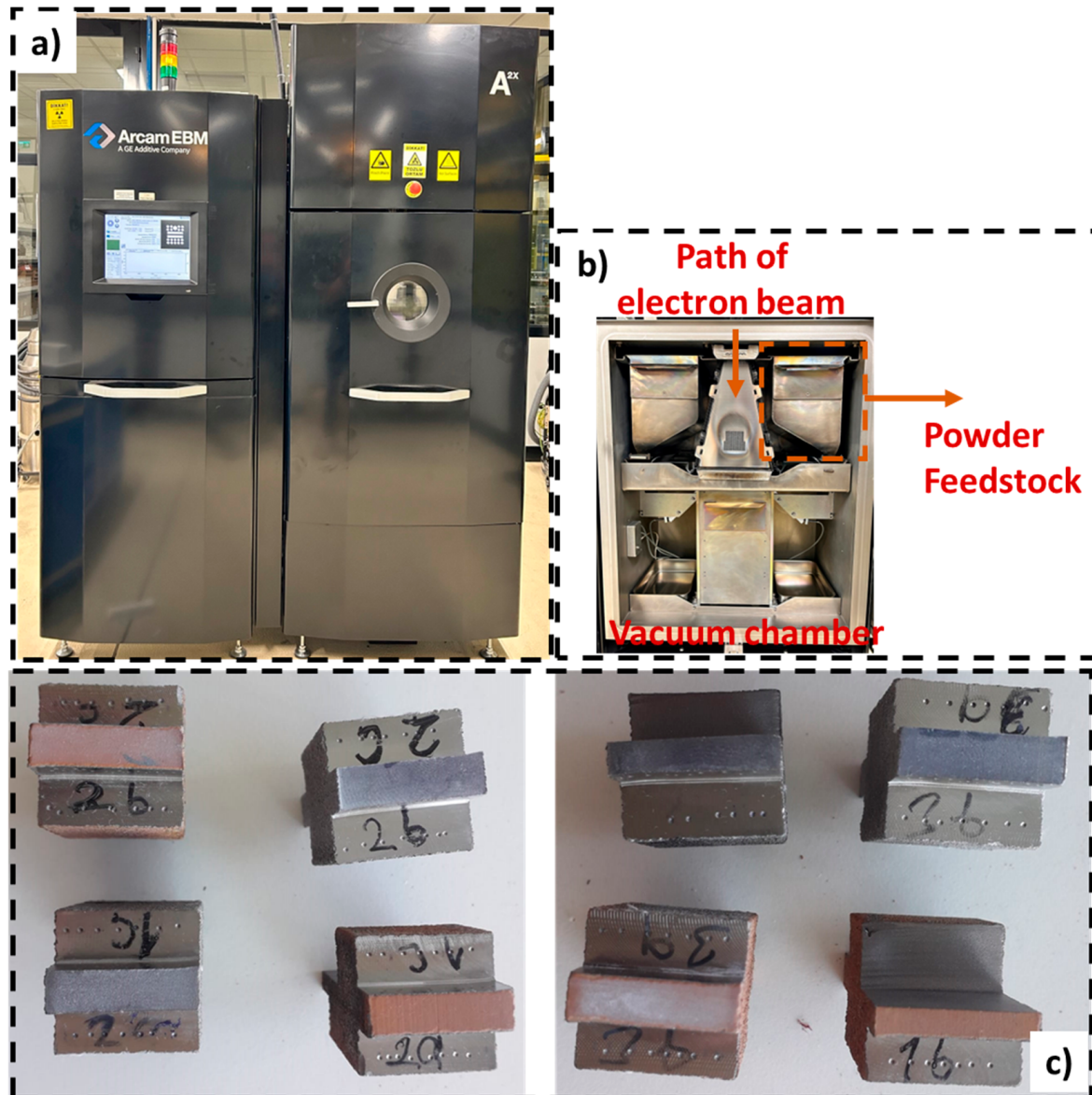


Figure 1. (a) The Arcam A2X machine used to fabricate TiAl samples in the current study; (b) illustration of EBM vacuum chamber; (c) machined surfaces of the fabricated EBM TiAl samples.

Table 1. Chemical compositions of TiAl powder (in weight percent, wt%).

	Al	Cr	Nb	Fe	C	O	N	H	Ti
Element wt%	33.4	2.9	4.7	0.06	0.01	0.01	0.01	0.005	Bal.

2.2. Microstructural Characterization

Microstructural characterization of the TiAl samples is conducted on the cross-section of the samples. In the case of optical microscopy (OM, Clemex LVN100ND) and a 15 kV focused ion beam scanning electron microscope (FIB-SEM) examination of the as-built conditions, which are not subjected to any machining process, 1 cm × 1 cm × 1 cm cuboidal microstructural analysis specimens are sectioned from the fabricated parts via wire electrical discharge machine (EDM) [54]. The regions near the top surface of the specimens are selected for microstructural observation. The surfaces and cross-sections of the samples are polished with 1 µm Al₂O₃ colloid for the OM analyses to observe porosity. The roughness measurements of the sample surfaces are conducted using a MarSurf M 300 C mechanical profilometer.

2.3. Machining and Hardness Tests

To remove the rough surfaces inherited from the additive manufacturing process, a carbide cutting material coated with TiAlN via PVD is used (CoroMill® Plura solid carbide end mill for medium roughing, 16 mm). To further enhance the surface of the additively manufactured TiAl, the TiAl material is surface finished using an NXT-coated (a kind of patented TiAlN coating) tool (Seco, solid carbide end mill, 16 mm). The machining of the EBM samples was conducted using the DMG Mori Seiki Lasertec 65 3D Hybrid Process Machine. Machining of the TiAl material is conducted using the cutting parameters shown in Table 2.

Table 2. Machining parameters used for TiAl samples and the labels (from 1A to 3C, shown in Figure 1c) that are referred to surfaces machined with selected parameter.

		Surface Speed					
		15 SFM		30 SFM		45 SFM	
		Spindle Speed RPM		Spindle Speed RPM		Spindle Speed RPM	
Feed	0.04 mm/tooth	298 (1A)	0.4768 m·min ^{−1}	596 (1B)	0.9536 m·min ^{−1}	895 (1C)	0.1432 m·min ^{−1}
	0.07 mm/tooth	298 (2A)	0.8344 m·min ^{−1}	596 (2B)	0.16688 m·min ^{−1}	895 (2C)	0.2506 m·min ^{−1}
	0.1 mm/tooth	298 (3A)	0.1192 m·min ^{−1}	596 (3B)	0.2384 m·min ^{−1}	895 (3C)	0.358 m·min ^{−1}

Some of the machined EBM samples are shown in Figure 1c. Hardness measurements are carried out using an AFFRI 206 EX/206 EXS hardness tester on the as-built, heat-treated, and machined surfaces. The mechanical properties of the EBM samples are also determined using tensile tests. Four tensile test specimens are used to calculate an average value. The corresponding data were expressed as the mean.

3. Results and Discussion

3.1. Microstructural Characterization

Figure 2 presents FIB-SEM micrographs of the TiAl sample following the EBM fabrication. The low-magnification image in Figure 2 clearly reveals the presence of local cracks, which are commonly observed in EBM-manufactured samples and are influenced by process parameters [55]. Additive manufacturing processes inherently generate a rapid solidification phenomenon (a production temperature of 953–993 °K for EBM and a cooling rate of 10³–10⁵ K/s [55]) motivating the formation of a high thermal gradient, thermal stresses, and crack formation [56]. The EBM is more resistant to thermal stresses than any other L-PBD process [57]. Another possible explanation for this occurrence is the presence of an inherited β phase in the TiAl powder prior to the EBM manufacturing

process. This inherited β phase can promote crack formation during machining, as observed and reported in prior studies [58]. To address this issue, one possible solution is to improve the development of processing parameters. By optimizing these parameters and combining them with the utilization of thermal and residual stress models created through finite element analysis, it is possible to achieve crack-free microstructures in the TiAl alloy. The general microstructure of the TiAl alloy consists of lamellar colony grains, whereas some of the equiaxed γ grains also exist. The majority of the grains are lamellar colonies, and this is indicative of what the microstructure can be referred to as “nearly fully lamellar γ/α_2 microstructure”. The conducted XRD analysis also confirms that EBM TiAl is predominantly composed of the γ phase, as the majority of the peaks correspond to the γ phase. Figure 3 exhibits SEM electron backscattered diffraction (EBSD) inverse pole figure images and energy dispersive spectrometry (EDS) elemental mapping for the Al, Ti, and O elements, respectively. The IPF maps in Figure 3 demonstrate that a significant portion of the grains are predominantly oriented along the $\langle 101 \rangle$ direction, while the majority of the remaining grains are oriented along the $\langle 001 \rangle$ direction. The EDS maps further support the SEM images in Figure 2, indicating that the primary microstructure constituent is the γ TiAl phase. This conclusion is corroborated by the dominance of the Al and Ti elements in the elemental map images. The evaporation of Al during the EBM process is a common concern [56]; however, the EDS Al map in the current study reveals the successful printing of Al and its presence in the samples. The EBSD images also indicate that the majority of the grains are around 5 μm in size and even finer. As reported previously, conventionally manufactured TiAl exhibits a significantly larger grain size, typically around 200 μm [59]. In contrast, the EBSD images show that the TiAl produced through EBM has much finer grains. In various metal additive manufacturing processes, it is possible to achieve finer microstructures compared to conventionally manufactured metals, such as those obtained through casting.

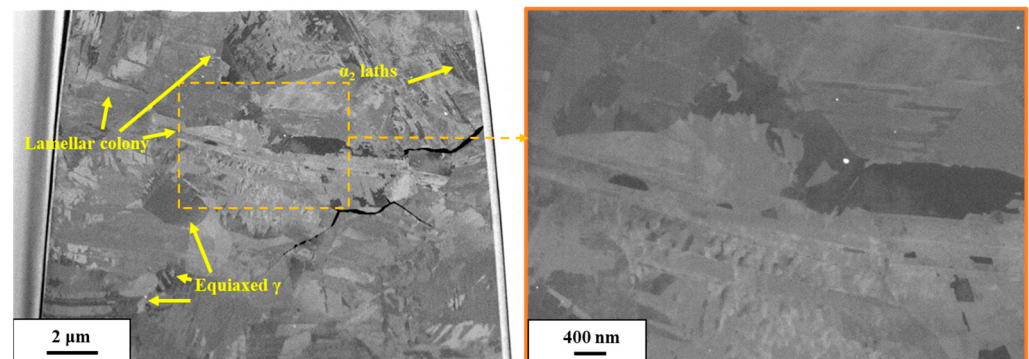


Figure 2. Low and high magnification SEM micrographs of the TiAl specimen.

It is already a widely witnessed phenomenon that porosity originates in any kind of additive manufacturing process for any type of metal or alloy [60]. The formation of porosity during AM fabrication is closely related to the process parameters and porosity of the initially used metallic powders caused by atomization [61]. The porosity has significant importance in both the microstructure and mechanical properties of the metallic materials, which creates enough motivation to examine them. In order to achieve this goal, the morphology and extent of porosity in as-built TiAl samples were investigated using an optical microscope (OM). Figure 4 presents the optical microscopy images, revealing the prevalence of spherical-type porosities in the TiAl samples. Contrarily, no lack of fusion or shrinkage porosity was observed in the OM investigations conducted. The porosity level is found to be around $0.71 \pm 0.56\%$ for the as-built EBM TiAl alloy, and this value is consistent with the findings of previous studies conducted by different researchers, which reported porosity levels ranging between 1% and 3% [62,63].

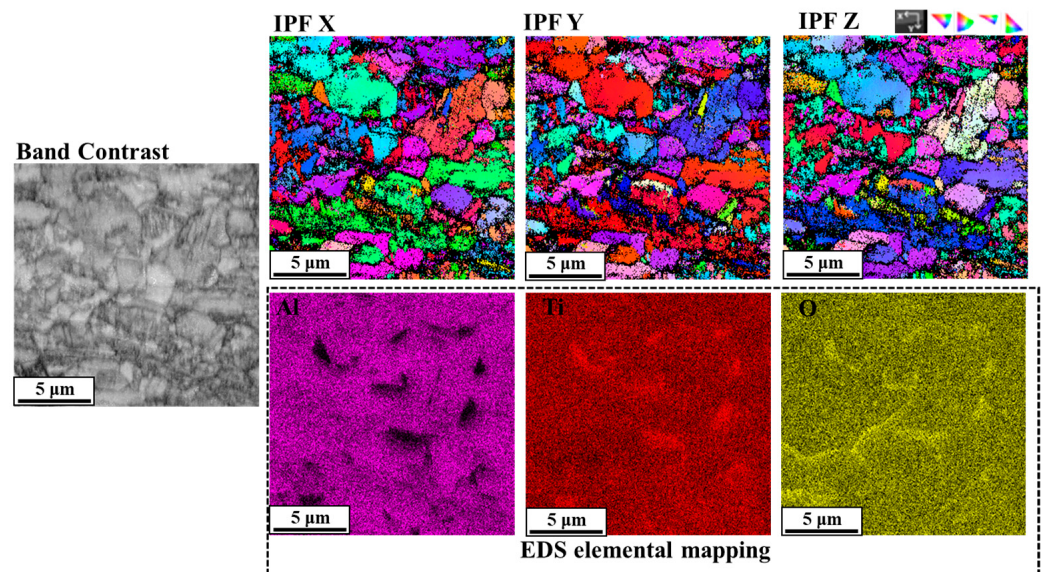


Figure 3. SEM electron backscattered diffraction analysis (EBSD) band contrast, IPF images and energy dispersive spectrometry elemental mapping for Al, Ti, and O, respectively.

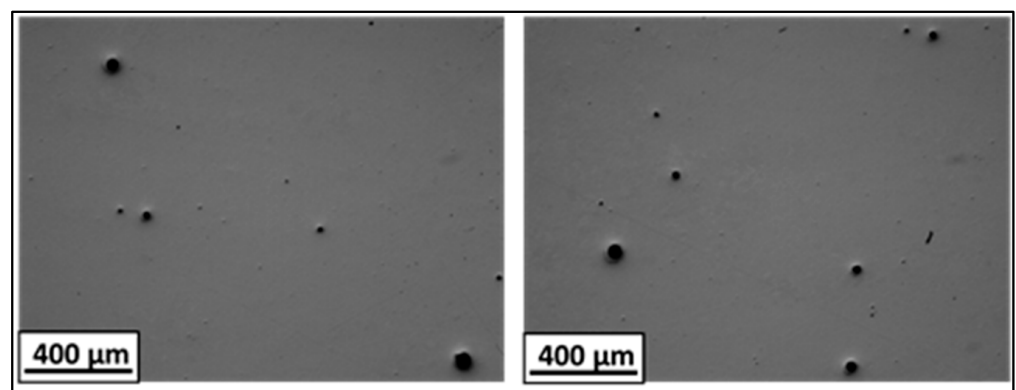


Figure 4. The optical microscopy (OM) images of the EBM-fabricated TiAl samples depict the presence of porosities.

Figure 5 shows the X-ray microcomputed tomography (CT) images of the as-built TiAl specimens following EBM fabrication. Figure 5 provides a comprehensive visualization of the entire porosity structure, where the larger and less frequent porosities, ranging from $2\text{--}5 \times 10^6 \mu\text{m}^3$, are highlighted in red. The majority of the porosities have a volume ranging between $0.5 \times 10^6 \mu\text{m}^3$ and $0.01 \times 10^6 \mu\text{m}^3$. The data presented in Figure 5 indicate an inverse correlation between the frequency of occurrence and the volume of porosity. In other words, smaller porosities are more frequently observed compared to larger porosities. The extent of porosity formation during the EBM manufacturing of the specimen is found to be around 0.4% based on X-ray CT measurements, which validates the results obtained by OM analyses (around 0.71%), as also shown in Figure 4. Stress–strain curves of the as-built samples are given in Figure 6. The ultimate tensile strength (UTS) and 0.2% proof stress values are $500 \pm 3.7 \text{ MPa}$ and $456.5 \pm 7.5 \text{ MPa}$, respectively, whereas the elongation and Young's modulus are $1.45 \pm 0.9\%$ and $172.7 \pm 0.2 \text{ GPa}$, respectively.

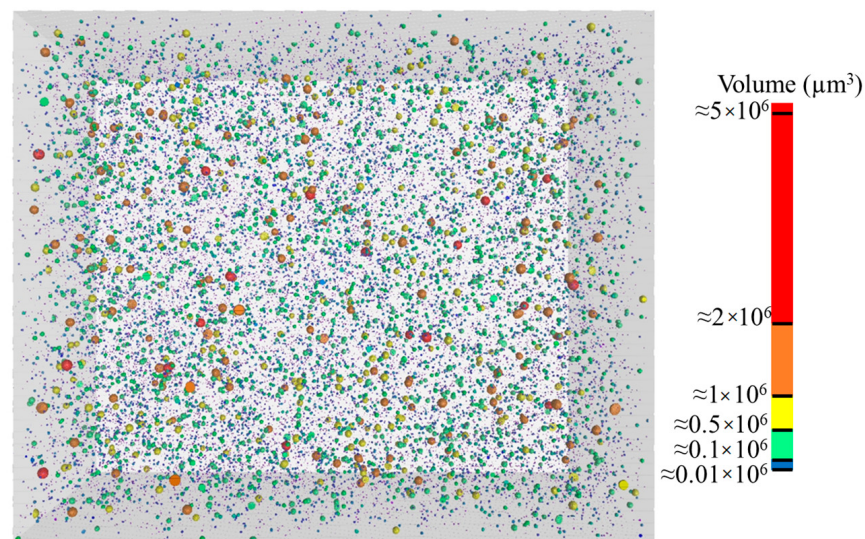


Figure 5. Micro CT images of the EBM-fabricated TiAl samples demonstrating porosity map.

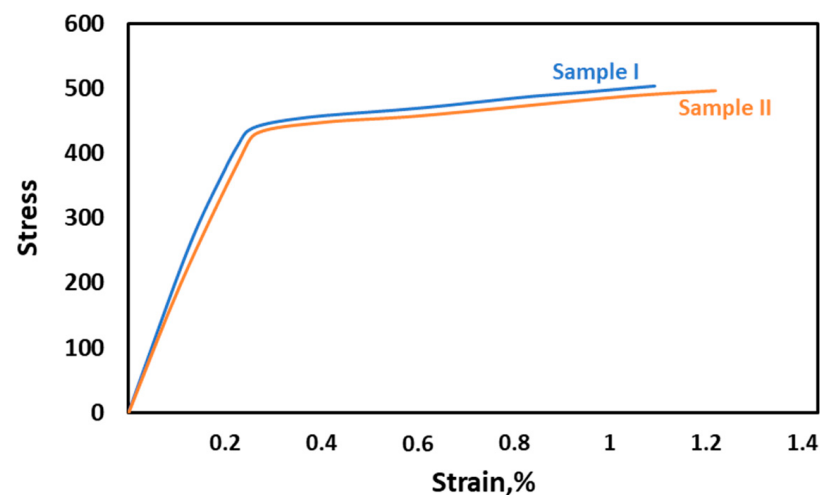


Figure 6. Stress–strain curve of the EBM-fabricated as-built TiAl samples.

Figure 7 illustrates the surface roughness of machined surfaces using different cutting parameters. The surface roughness for as-built 1A, 1B, 1C, 2A, 2B, 2C, 3A, 3B, and 3C are $0.66 \pm 0.1 \mu\text{m}$, $0.33 \pm 0.1 \mu\text{m}$, $0.49 \pm 0.1 \mu\text{m}$, $0.42 \pm 0.1 \mu\text{m}$, $0.45 \pm 0.05 \mu\text{m}$, $0.48 \pm 0.1 \mu\text{m}$, $0.59 \pm 0.05 \mu\text{m}$, $0.51 \pm 0.16 \mu\text{m}$, and $1.5 \pm 0.7 \mu\text{m}$, respectively, as also shown in Table 3. The surface roughness, Ra, value slightly decreases at the surface 1B prior to its rise at 1C and then almost saturates up to 3C for the as-built condition. Unlike the surfaces machined with the other parameters, the surface machined with 45 SFM surface speed and 0.1 mm/tooth feed demonstrates greater Ra value and variation.

Table 3. Surface roughness, Ra, values of the TiAl samples that are machined using various parameters.

	Surface Roughness, Ra (μm)								
	1A	1B	1C	2A	2B	2C	3A	3B	3C
As-built	0.66 ± 0.1	0.33 ± 0.1	0.49 ± 0.1	0.42 ± 0.1	0.45 ± 0.05	0.48 ± 0.1	0.59 ± 0.05	0.51 ± 0.16	1.5 ± 0.7
Heat-treated	0.90 ± 0.24	0.82 ± 0.27	0.96 ± 0.2	0.96 ± 0.25	1.04 ± 0.42	0.99 ± 0.2	0.99 ± 0.24	0.96 ± 0.22	1.3 ± 0.2

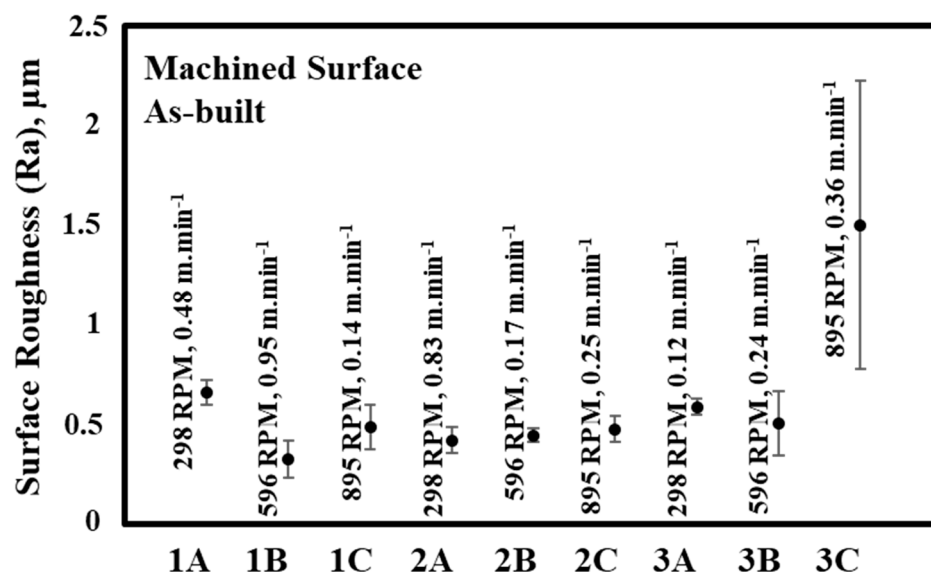


Figure 7. Surface roughness (R_a) at the surfaces machined via different cutting parameters from 1A to 3C, which are also explained in Table 2 in detail, for as-built and heat-treated TiAl samples.

In the case of the heat-treated condition, the surface roughness for 1A, 1B, 1C, 2A, 2B, 2C, 3A, 3B, and 3C are $0.90 \pm 0.24 \mu\text{m}$, $0.82 \pm 0.27 \mu\text{m}$, $0.96 \pm 0.2 \mu\text{m}$, $0.96 \pm 0.25 \mu\text{m}$, $1.04 \pm 0.42 \mu\text{m}$, $0.99 \pm 0.2 \mu\text{m}$, $0.99 \pm 0.24 \mu\text{m}$, $0.96 \pm 0.22 \mu\text{m}$, and $1.3 \pm 0.2 \mu\text{m}$, respectively. As for the heat-treated condition, the surface roughness does not significantly differ when the surface speed and feed value are enhanced, as shown in Figure 8. This tendency remains the same, including condition 3B; however, the surface roughness value pertained to at 3C is higher than those of the surfaces referred to as 1A, 1B, and 1C. When comparing 1A to 3C, an increase in the surface roughness is obvious, and it is independent of the heat treatment procedure. An increase in the surface roughness is attributed to originating from higher temperatures induced by higher cutting speeds, thereby promoting tool wear and expectedly damaging the surface quality. Conventionally fabricated TiAl alloy has been reported to have a surface roughness of $0.8\text{--}2.95 \mu\text{m}$, whereas optimized cutting speed is known to range from $7\text{--}10 \text{ m}\cdot\text{min}^{-1}$ for the reported study [64]. The optimized cutting speed values discovered in this study are even lower than what is recommended for the milling procedure of γ -TiAl alloy, which is usually 2–3 times lower compared to those of regular titanium and nickel-based alloys [64]. The obtained surface values of our current study are much lower, even for the 3C with the worst results arising, when compared to what is already reported by Aust et al. [64]. The obtained results are also much lower compared to what is obtained by Tetsui et al., ranging from $5\text{--}10 \mu\text{m}$ [7]. However, much higher cutting speeds were employed for this study, where the TiAl was machined using a parameter set of $10\text{--}40 \text{ m}\cdot\text{min}^{-1}$. One of the highest cutting speeds for cutting TiAl attempted by Hood et al. [46] in the literature was reported to use a cutting speed of $88 \text{ m}\cdot\text{min}^{-1}$ with 0.05 mm/tooth and obtained surface roughness values ranging from $0.8\text{--}1.2 \mu\text{m}$, which is greater than that of the as-built but comparable with that of the heat-treated condition of the current study. Still, a range of cutting speeds from $10\text{--}40 \text{ m}\cdot\text{min}^{-1}$ even $88 \text{ m}\cdot\text{min}^{-1}$ was reported to be much slower when compared to the values used for other alloys in the industry, such as $100\text{--}300 \text{ m}\cdot\text{min}^{-1}$ for the low alloy steels, $50\text{--}100 \text{ m}\cdot\text{min}^{-1}$ for stainless steel, and comparable with that of Ni-based superalloys around $20\text{--}40 \text{ m}\cdot\text{min}^{-1}$ [4,46]. On the other hand, these cutting speeds are still far from being realistic for the industrial applications of TiAl since, for example, in the turning procedure, the tool life is reported to be below 10 min upon the introduction of a cutting speed of around $25 \text{ m}\cdot\text{min}^{-1}$ [51]. Though the cutting speed employed was much slower compared to industrial-scale machining values, the main target of the current study was to illustrate the effect of changing

machining parameters and heat treatment on the surface quality and hardness of TiAl alloys and elucidate the evolution.

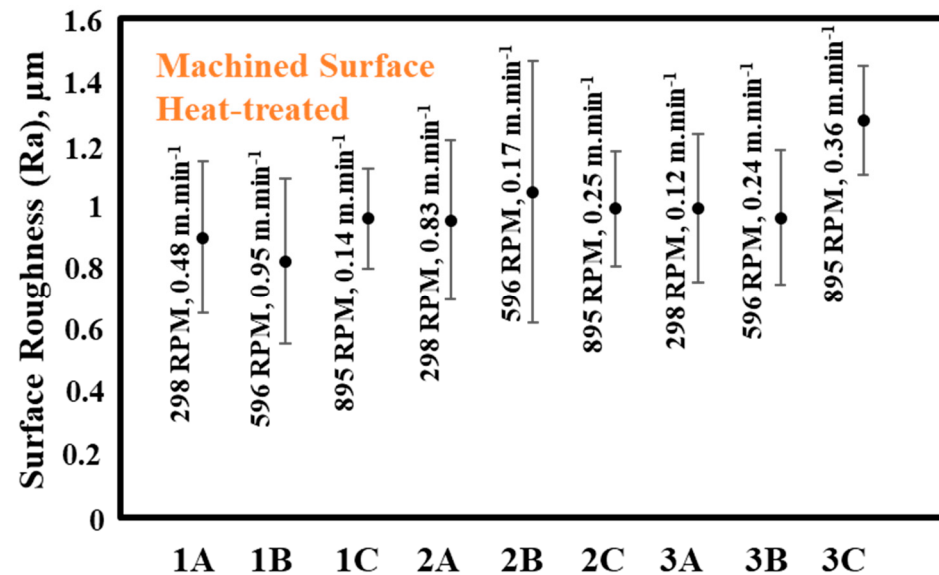


Figure 8. Surface roughness (Ra) at the surfaces machined via different cutting parameters from 1A to 3C (detailed explanation referred in Table 2) for heat-treated TiAl samples.

Figure 9 shows the optical microscope images of the surface following the machining of as-built and heat-treated EBM samples under different machining conditions. The analyses of the machined surfaces establish a correlation between the machining parameters and the quality of the machined surface. None of the samples show any debris remaining from the machined material. However, feed lines are apparent for all machining conditions. However, in the case of 3C, the feed lines are observed to have larger intervals and exhibit deeper wear tracks. It has been previously reported that the severity of cutting conditions and the progression of flank wear lead to a more pronounced presence of feed marks on the machined surface [65]. Regardless of the application of heat treatment, the 1A samples display a superior surface quality compared to the 3C samples, which is also consistent with the surface roughness graphs in Figures 7 and 8. There are no observable cracks on any of the machined surfaces in the samples. Furthermore, almost every condition exhibits the presence of microporosities in their machined surfaces. These porosities can also be attributed to the nature of the additive manufacturing process, where the presence of micron-sized porosities is possible. This idea is further supported by the porosity map illustrated in Figure 5.

Figure 10 displays the XRD patterns of both as-fabricated and heat-treated additive manufacturing parts following different machining feed and speed strategies. From the XRD patterns, it is evident that all samples exhibit a strong γ (111) TiAl texture. Additionally, XRD analysis confirmed that both the EBM TiAl conditions consisted of the γ phase and the α_2 phase. The previous findings in EDS maps further support the XRD findings in Figure 10, indicating that the primary microstructure constituent is the γ TiAl phase. A peak shift is noticeable following the EBM process and heat treatment application, respectively. In heat-treated and machined conditions, the α_2 phase becomes more prominent and noticeable. The presence of the α_2 phase is also substantiated by XRD analysis, as depicted in Figure 10. The α_2 phase is known to be finer and can also act as a nucleus in the microstructure [59]. One possible attribution for the increased brittleness and decreased surface quality during machining in heat-treated conditions is thought to be the underlying cause because α_2 phase structure would yield a finer microstructure in heat-treated conditions. The α phase is recognized for its hexagonal close-packed (hcp) crystal structure, which inherently possesses a limited slip system, leading to difficulties in accommodating deformation. Moreover, there are some studies showing that machining would yield some phase changes

in TiAl alloys, supported by EDS analysis [66]. In certain cases, an increase in cutting speed can lead to thermal softening of the material, which may result in improved surface quality during the machining process [66]. However, it is expected that increasing the cutting speed excessively in the heat-treated condition would lead to adverse effects in the machining process, resulting in a poorer surface compared to the as-built conditions. Moreover, the presence of a higher proportion of the α_2 phase in the heat-treated condition could further contribute to these adverse effects. The slightly broader peak of the heat-treated 1A condition with greater peak intensity could be indicative of what heat-treated 1A is expected to have finer grains than other conditions following the machining process. The refinement of the grains and increase in dislocation density are quite common phenomena in machined metals [65,67]. However, with the application of different machining parameters, no other peak changes or formation of textures were observed.

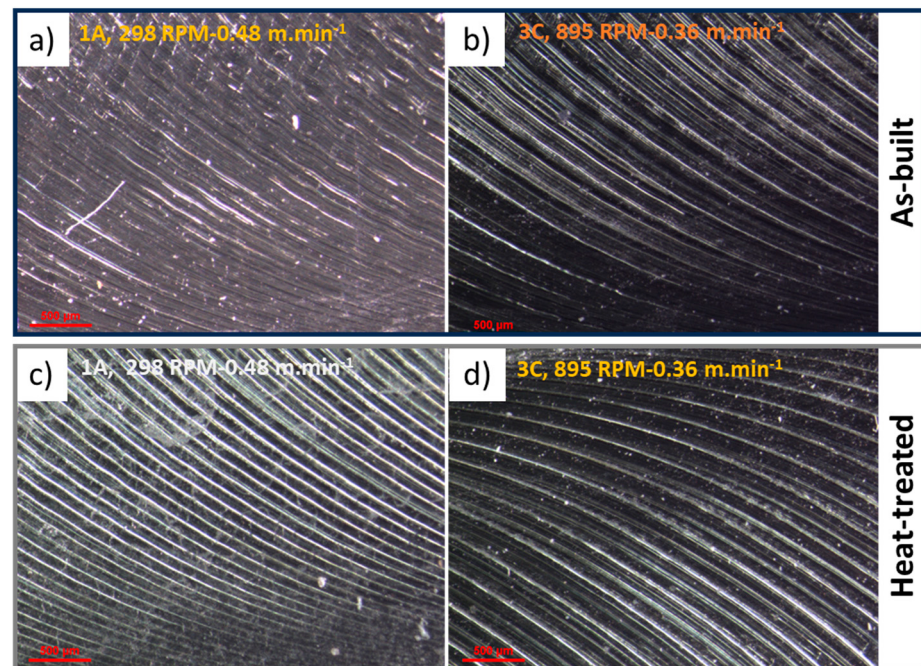


Figure 9. Optical microscope images of machined as-built and heat-treated EBM TiAl samples.

3.2. Hardness Measurements

Hardness measurements were conducted for both non-machined and machined surfaces. A hardness value of around 32.25 ± 1.24 HRC is observed for the as-built condition. On the other hand, the hardness value pertained to heat-treated conditions is determined to be 29.91 ± 1.84 HRC. The heat treatment influenced hardness behavior, where a decrease in overall hardness was observed subsequent to the heat treatment. The obtained hardness values, which are obtained via measuring along the machined surfaces of the as-built and heat-treated conditions, are represented in Figures 11 and 12.

In the case of the heat-treated condition, the hardness of the samples with 1A and 1B parameters is similar. In general, there is a correlation between the hardness of the machined surfaces and surface integrity, characterized by features such as pull-out of the material, crack generation, deformed lamellae, and surface drag [51,69]. The hardness of the machined TiAl surface is even reported to be double that of the bulk alloy prior to the machining procedure, and this hardness increase is attributed to the strain hardening, thereby reducing the ductility of the surface [47,48]. This has been observed and reported previously; the occurrence of severe strain hardening is attributed to excessive tool wear, which promotes an increase in the thermal and mechanical load along the sub-surface [48] and can be prevented by using efficient lubricants such as cryogenic cooling [70]. On the other hand, some of the cases with similar hardness do not apply to this generalization [71].

Upon the machining introduction of the as-built and heat-treated TiAl alloys at 3C, cracks originate at the surface of the part and also damage the surface integrity when processed using the $0.358 \text{ m} \cdot \text{min}^{-1}$ value. The majority of the literature about the machining of TiAl validates the challenges for maintaining the workpiece integrity [51,72], which is also experienced in the current study at 3C, except for the turn-milling of cylindrical geometries and high-speed milling in some cases [51]. It is widely recognized that processing the edges of TiAl alloys is more challenging compared to other titanium alloys [51]. Our current work confirms this observation, as we have observed the removal of material chunks at the top edges of TiAl parts in both as-built and heat-treated conditions. This finding aligns with the reports in the literature regarding the behavior of other TiAl parts. The hardness of heat-treated and machined surfaces at 3C is almost comparable to that of as-built and machined surfaces at 3C, and the pull-out of the material is promoted in each case. As expected, the samples with decreasing hardness from 3B to 1A at the heat-treated condition do not demonstrate any material removal during the machining. In contrast to this phenomenon, even though the hardness remains almost the same under conditions changing from 1A to 3C, any of the material pull-out events are not observed except for 3C. This is indicative that there should be another reason for pull-out besides the hardness increase at conditions 3C for both as-built and heat-treated; this could be the effect of the α_2 phase, where it is observed for all heat-treated conditions. As shown by and demonstrating this argument, an increase in the hardness always does not correlate with an increase in the material pull-out/surface integrity in the TiAl alloys; the hardness of the TiAl alloy is reported to be reached at 700 HV, where the deformed lamellae and a 50–100 μm deep hardened zone were observed following the grinding procedure. In the case of the 3C surface, there appears to be an additional contributing factor that leads to cracking and material removal compared to other surfaces machined with different parameters (1A to 3B) in the as-built state, which is attributed to the refinement of the grains and increasing dislocation density with the severity of the machining conditions. Right after the machining of 3C conditions for as-built and heat-treated states, residual powders were observed and could possibly be attributed to the machining process since powders from the EBM procedure were already entirely cleaned following the fabrication of the blocks. This was reported and observed previously by Tetsui et al. [7]; the observed brittle behavior of the TiAl alloy during cutting, even after heat treatment, indicates that the material did not exhibit sufficient ductility to be effectively machined using the parameter set corresponding to 3C. This result is attributed to the α_2 phase and increased feed and cutting speeds in the 3C heat-treated sample. The tensile tests are also conducted on as-built EBM specimens. The ultimate tensile strength (UTS), 0.2% proof stress, and elongation were determined to be 565.5 MPa, 501 MPa, and 1.4%, respectively, whereas the Young's modulus was found to be around 173 GPa.

In the case of the as-built condition, the hardness values for 1A, 1B, 1C, 2A, 2B, 2C, 3A, 3B, and 3C are $33.6 \pm 3.2 \text{ HRC}$, $34.1 \pm 1.6 \text{ HRC}$, $33.9 \pm 0.9 \text{ HRC}$, $33.2 \pm 1.3 \text{ HRC}$, $33.3 \pm 0.9 \text{ HRC}$, $33.8 \pm 0.9 \text{ HRC}$, $32.9 \pm 1.3 \text{ HRC}$, $32.7 \pm 1.2 \text{ HRC}$, and $32.0 \pm 2.6 \text{ HRC}$, respectively, displayed in Table 4. Upon comparing the hardness values of the as-built machined surfaces with the non-machined surface hardness (around 30 HRC), it is observed that machined surfaces have slightly greater hardness, which exhibited a hardness of approximately 32–34 HRC. The increase in hardness is about 25 HV (almost 3 HRC compared to the as-built's hardness of around 30 HRC) which is much lower when compared across the previously reported literature. For example, Zhang et al. reported a 150 HV to 275 HV hardness increase at a depth of 10 μm from the surface subjected to machining with a cutting speed of $20 \text{ m} \cdot \text{min}^{-1}$ [68]. Furthermore, the hardness value further increased up to 700 HV when grinding was applied to the TiAl alloy at a speed of $50 \text{ m} \cdot \text{s}^{-1}$ [51]. When the samples with increased surface speed and feed are observed, their hardness is observed to be almost constant. On the other hand, greater hardness values are observed in the samples with increased surface speed and feed when in the heat-treated samples, especially in 1A and 1B conditions compared to those in 3C. The obtained hardness values of 1A, 1B, 1C, 2A, 2B, 2C, 3A, 3B, and 3C are $30 \pm 1.1 \text{ HRC}$, $30 \pm 0.8 \text{ HRC}$, $31.3 \pm 0.9 \text{ HRC}$,

31.4 ± 1.0 HRC, 31.0 ± 0.9 HRC, 31.1 ± 1.1 HRC, 31.2 ± 1.9 HRC, 31.4 ± 0.6 HRC, and 33.1 ± 1.1 HRC, respectively.

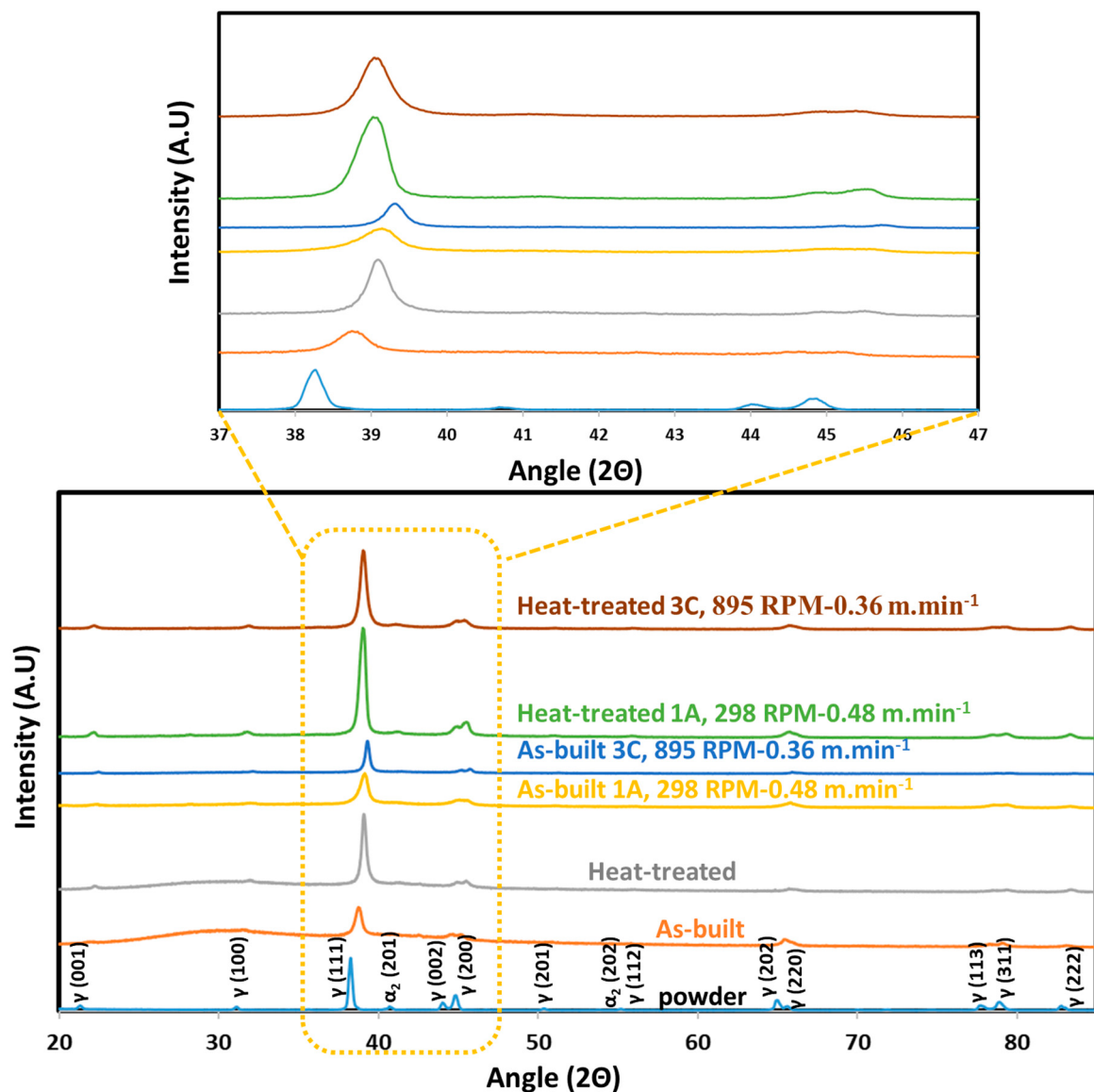


Figure 10. X-ray diffraction spectra of TiAl powder, as built EBM TiAl, heat-treated EBM-TiAl, and machined as-built and heat-treated EBM TiAl samples; black, orange, grey, yellow, blue, green and brown colors denote to powder, as-built, heat-treated, as-built 1A, as-built 3C, heat-treated 1A and heat-treated 3C conditions, respectively.

Table 4. Hardness values of the TiAl samples that are machined using various parameters.

	Hardness, HRC								
	1A	1B	1C	2A	2B	2C	3A	3B	3C
As-built	33.6 ± 3.2	34.1 ± 1.6	33.9 ± 0.9	33.2 ± 1.3	33.3 ± 0.9	33.8 ± 0.9	32.9 ± 1.3	32.7 ± 1.2	32.0 ± 2.6
Heat-treated	30 ± 1.1	30 ± 0.8	31.3 ± 0.9	31.4 ± 1.0	31.0 ± 0.9	31.1 ± 1.1	31.2 ± 1.9	31.4 ± 0.6	33.1 ± 1.1

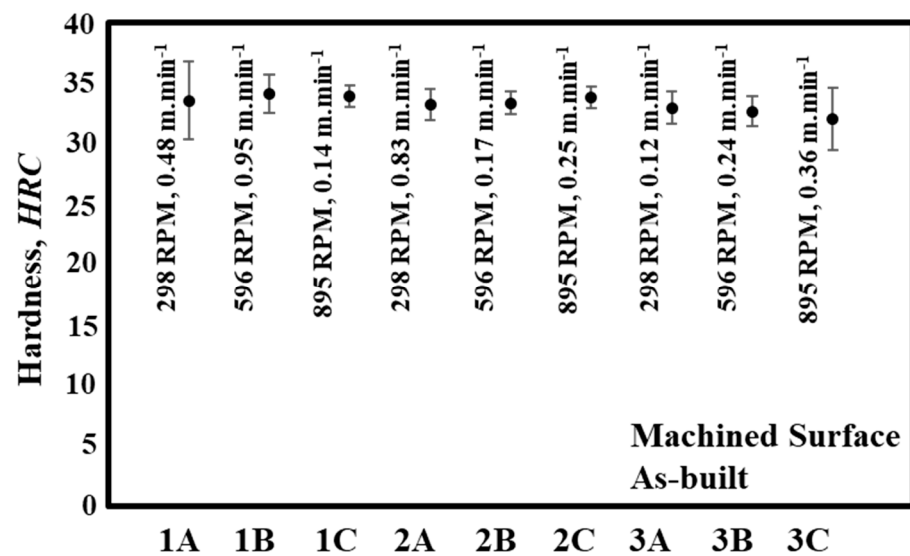


Figure 11. Hardness values at the surfaces machine via different cutting parameters from 1A to 3C (detailed explanation referred in Table 2) for as-built TiAl samples.

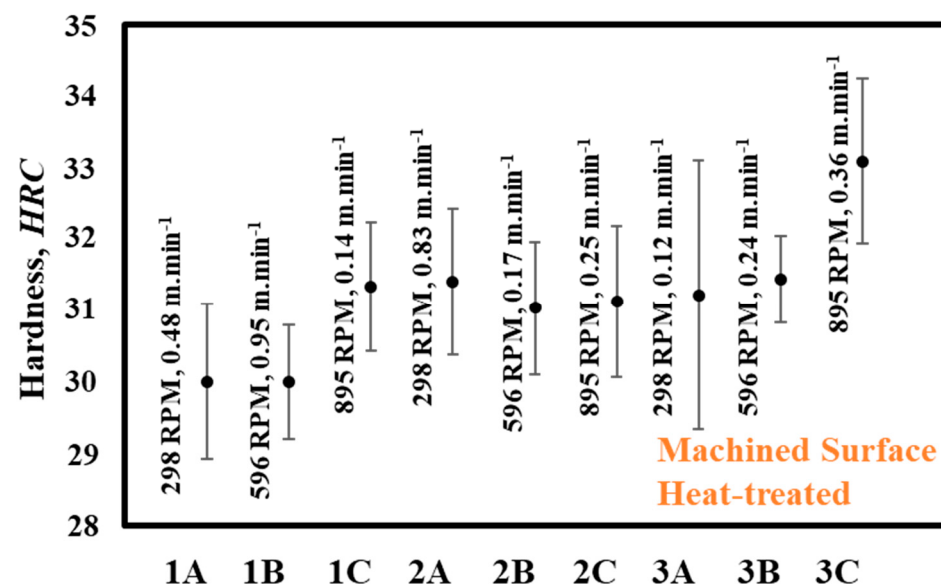


Figure 12. Hardness values at the surfaces machine via different cutting parameters from 1A to 3C (detailed explanation referred in Table 2) for heat-treated TiAl samples.

4. Conclusions

In the current study, the impact of machining parameters, specifically cutting speed (surface speed) and feed rate, on the surface roughness of the EBM TiAl alloy was investigated. In addition, the effect of machining on the microstructure and the relationship between microstructure and hardness were studied. Surface roughness drastically increases with increasing surface speed and feed. Hardness is almost constant in samples with increased machining parameters such as surface speed and feed. Contrary to expectations, the hardness of the heat-treated samples increased with higher feed rates and surface speeds. This is attributed to the α_2 phase presence and finer grains in the 3C specimen with enhanced cutting speed and a possible temperature effect. The sample integrity suffers from crack formation at 3C's ($0.358 \text{ m} \cdot \text{min}^{-1}$ and 0.01 mm/tooth) for both as-built and heat-treated conditions with the almost same hardness values. However, any kind of material pull-out phenomenon was not observed for the conditions ranging from 1A to 3B for the as-built sample set. These findings suggest that there are factors and microstructural

dynamics such as phase composition (α_2 phase), grain refinement, and strain hardening related to severe machining conditions that affect the brittle behavior of the TiAl alloy during machining rather than the solely hardness increase.

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