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Research Article

The Experimental Research Of The Additively Manufactured Ti4Al4V Parts With The Perspective Of Mechanic Features

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Abstract

This study aims to generate research data on basis of engineering evidences in terms of validation tests for Additively Manufactured (AM) Ti4Al4V parts. It is known that Ti6Al4V alloy is broadly used for highly-engineered air vehicles and in compliance with the aviation-grade specifications. For validation, the test parts were manufactured using EOSM290 DMLS (Direct Metal Laser Solidification) machine under argon inert gas. The raw powder was inspected before the manufacturing process with the "better size brand" particle size evaluation machine. The composition of the Ti6Al4V is determined as 90% Ti, 5,48% Al, 4,22% V, 0,369% C, 0,112% Fe, 0,0625% Sn, 0,00386% Nb, 0,0099% Cr in accordance with ASTM F1472 and ATFM 2924 standards and the average diameter size is evaluated as 30 µm. Since the elongation, yield-strength and tensile strength values are the key indicators of mechanical features the stress-strain analysis was performed for 30 test parts. The aim of the analysis is to have information about the mechanical properties such as ductility, brittleness, toughness from the experiments. Analysis results indicate that construction direction, heat treatment, turning, and finishing operations such as sandblasting directly affect the mechanical properties of Ti6Al4V parts.

Keywords: Additive Manufacturing, Aviation-Grade, Ti6Al4V Alloy, Validation

Eklemeli Üretim İle Üretilen Ti6Al4V Parçaların Mekanik Özellikler Perspektifinden Deneysel Araştırması

Öz

Bu çalışma, Eklemeli Olarak Üretilen (AM) Ti4Al4V parçaların doğrulama testleri açısından mühendislik kanıtlarına dayalı araştırma verileri üretmeyi amaçlamaktadır. Ti6Al4V alaşımının, havacılık sınıfı üretim spesifikasyonlarına uygun olarak yüksek mühendislik ürünü hava araçları için yaygın olarak kullanıldığı bilinmektedir. Doğrulama için test parçaları, argon asal gaz altında EOSM290 DMLS (Direkt Metal Lazer Sinterleme) makinesi kullanılarak üretilmiştir. Toz, üretim sürecinden önce "bettersize marka" partikül boyutu değerlendirme makinesi ile incelenmiştir. ASTM F1472 ve ATFM 2924 standartlarına göre uygunluğu değerlendirilen Ti6Al4V alaşımının içeriği %90 Ti, %5.48 Al, %4.22 V, %0.369 C, %0.112 Fe, %0.0625 Sn, 0,00386% Nb ve %0.0099 Cr olarak belirlenmiştir. Uzama direnci, akma dayanımı ve maksimum çekme dayanımının, mekanik özelliklerin belirlenmesinde anahtar belirleyici değerler olması sebebiyle 30 adet test parçasına gerilme-uzama testi yapılmıştır. Analizin amacı, deneylerle süneklik, kırılganlık, tokluk gibi mekanik özellikler hakkında bilgi sağlamaktır. Analiz sonuçları, inşa yönü, ısıl işlem, torna işleme ve kumlama gibi bitirme işlemlerinin Ti6Al4V parçalarının mekanik özelliklerini doğrudan etkilediğini göstermektedir.

Anahtar Kelimeler: Eklemeli Üretim, Havacılık Seviyesi, Ti6Al4V Alaşım, Validasyon

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1. Introduction

The aviation industry is a meticulously regulated industry like medical and aerospace industries. Stiff aviation regulations require using high-tech materials such as Titanium and Aluminum alloys. Ti6AL4V is one of them. It is a broadly known light alloy, characterized by having high endurance mechanical features and corrosion resistance with satisfactorily low weight. From manufacturing perspective, the additive manufacturing is a high-tech method that converts the conventional methods. This method provides the opportunity for manufacturing lighter and more durable aircraft structures [1]. Allowing the more complex part is another benefit of additive manufacturing. For catching up with the newest industrial developments, engineers are changing the way they design a part, as they shift from legacy method "subtracting material" to the novel method of adding material in layer-wise in order to manufacture the parts especially the complex ones [2].

Additive manufacturing is a layer-wise production technique that permits generating 3D parts that have complex shapes. Besides, it has advantages such as; reducing material wastage, minimizing the manufacturing consumables such as coolant and cutters, providing opportunities for weight reduction and topology optimization.

The applications like flight-critical parts and engine parts like LEAP engine fuel nozzle shown in Figure 1 can be achieved by additive manufacturing technologies.

Figure 1. LEAP engine fuel nozzle that is additively manufactured [3]

Reportedly, the mentioned fuel nozzle was an assembly consists of 20 parts converted to a single part that is 5 times durable and %25 lighter than its predecessors [4]. LEAP engines power the Airbus, Boeing, and Comac companies' new generation commercial passenger airplanes [5] and every LEAP engine includes 19 fuel nozzles [6]

Undoubtedly, the aviation-grade parts are designed for extraordinary working conditions. In this manner, the aviation-grade materials are similar to medical-grade parts. There are some remarkable studies that provide information about the high-tech industries. For example; Gastineau et al [7] examined the similarity between the medical and aviation industry in terms of relevant authorities' regulation framework. In the mentioned study, it was highlighted that in the medical industry, establishing an international regulation system like the aviation industry would be more effective. In another study, Murr et al [8] investigated human tissue manufacturing via additive manufacturing technologies. In the mentioned study, it was highlighted that, with the help of know-how transfer from the aviation industry to the medical sector, producing basic human tissue would be possible although there are some considerable challenges in these emerging technologies. Additionally, there is another study provides information about the production and testing of the Ti6Al4V parts in the aviation field. It has been observed that the studies are generally focused on the relationship between mechanical features of the additively manufactured Ti6Al4V and structure particularly. For example; Kaya et al [9], investigated the efficiency of textured cutting tools in orthogonal cutting of Ti6Al4V alloy. Conclusionally, no study was found that focuses on the First Article Inspection (FAI). It is noteworthy that, this is the first paper for an aviation-grade and medical-grade FAI. The FAI is an essential step for prototyping and initial acceptance activities of a system or machine though not a must through mass production [10]. While the testing environment was preparing for FAI activities, DIN 50125 Standard was taken into account. After investigating the above-mentioned scientific papers, it was observed that this study is the first one making tests for the parts which are the most closely to aviation-grade parts.

For a prompt manufacturing process to have a desired tensile strength and surface roughness, there are four main key parameters that should be optimized. These are; the layer thickness laser power, scan speed, and hatch distance. In Figure 2 the process mechanism of the AM DMLS is shown.

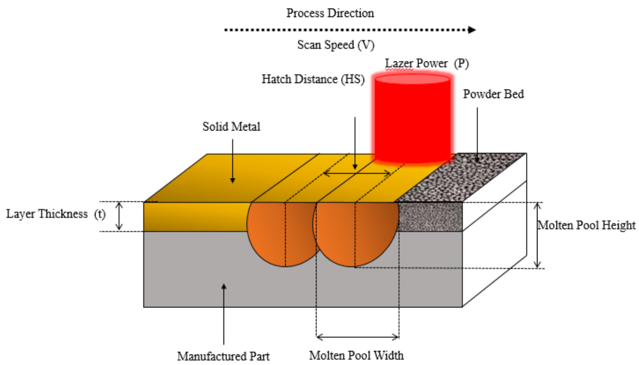

Figure 2. Laser-based machining process in DMLS [11]

1.1. Layer Thickness

In additive manufacturing, a part is produced in through build direction with equal slices. The height of the distance between slices called as layer thickness. As it is shown in Figure 2, there's a positive correlation between layer thickness and surface roughness while there's a negative correlation between layer thickness and tensile strength.

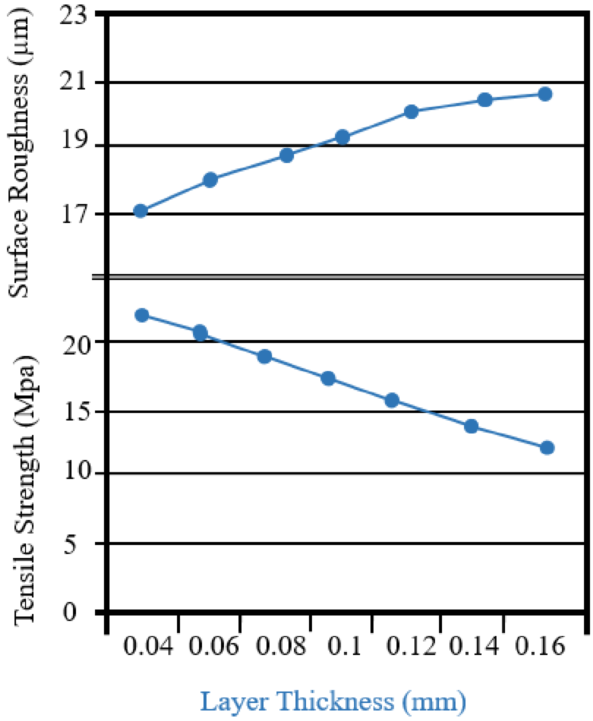

Figure 2. Layer thickness effect on the surface roughness and tensile strength [12,13]

1.2. Laser Power

For DMLS manufacturing, for sintering the required energy is obtained by laser power. EOSM290 machine's maximum laser power is 400 Watt. As shown in Figure 3, with the increasing power of laser surface quality increase up to a certain point. Besides, tensile strength increases with the increasing laser power.

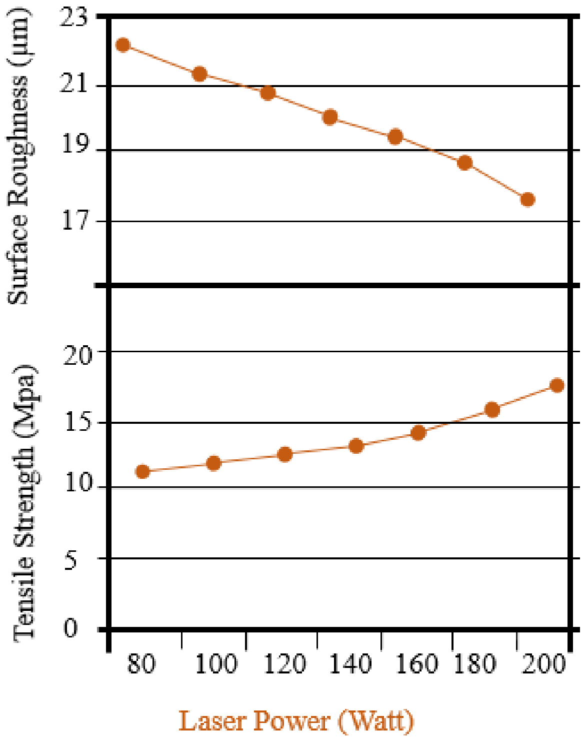

Figure 3. Laser power effect on the surface roughness and tensile strength [12,13]

1.3. Scan Speed

Mainly, scan speed determines the amount of the molten particles simultaneously. If it is slower than the desired speed then the laser beam will spend a longer time on the particles which can conclude with unwanted keyholes on the material. However, if it is faster than the desired speed then the particles are not sintered and this phenomenon concludes with incontinuities. In Figure 4, the scan speed effect over the Surface Roughness and Tensile Strength is shown. In accordance with the increasing scan speed the surface roughness increases, while tensile strength dramatically decreases

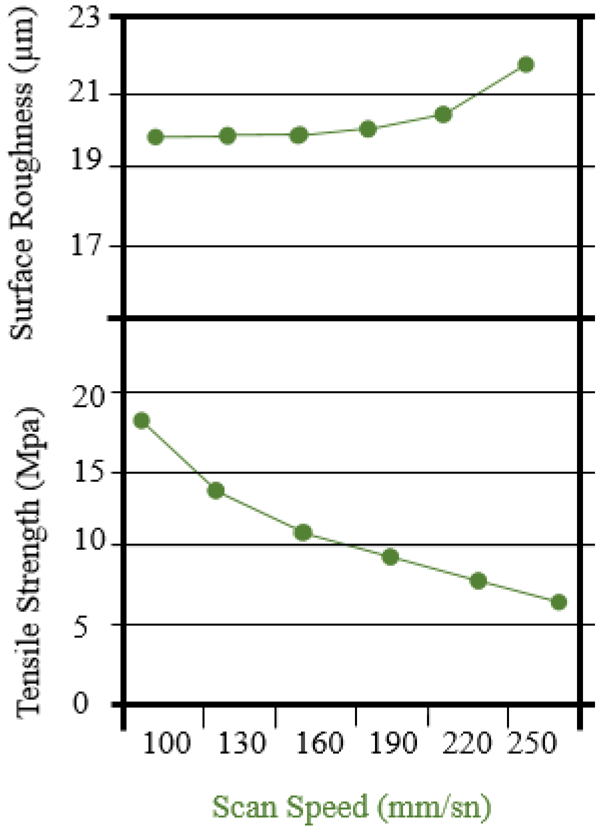

Figure 4. Scan speed effect on the surface roughness and tensile strength [12,13]

1.4. Hatch Distance

It is the distance between scanning lines while producing the layers. If the distance is wider than the desired distance then the laser beam cannot cover the desired area in terms of handling the entirely sintered particles. In the open literature, there are four types of hatch patterns. In Figure 5, the relation between hatch distance and surface roughness, and tensile strength is provided. It can be claimed that with the increasing hatch distance the tensile strength decreases whereas the surface roughness increases.

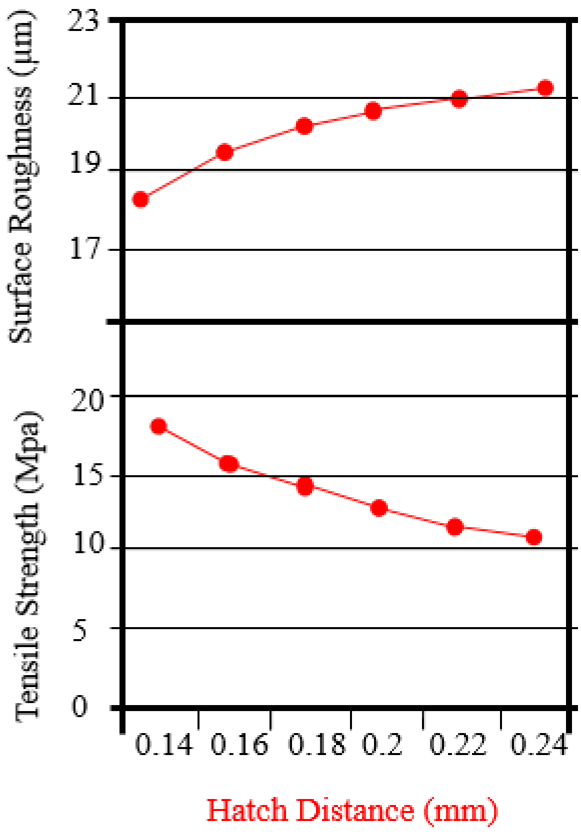

Figure 5. Hatch distance effect on the surface roughness and tensile strength [12,13]

Other than distance, the hatch patterns also have an impact on the finished part. The hatch patterns are given below;

1.4.1. Bi-Directional Pattern

It is a pattern that the laser is driven in a zigzag route. As it is shown in Figure 6, the beam makes a side movement adjusted by the parameter of the machine.

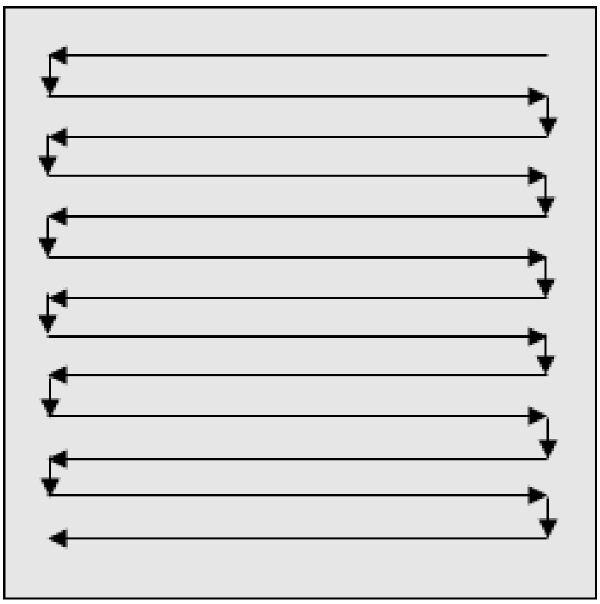

Figure 6. Bi-directional hatch pattern [14,15]

1.4.2. Off-Set In Pattern

In the "Off-Set In Pattern", the laser beam travels from outside to inside with the step of adjusted hatch distance.

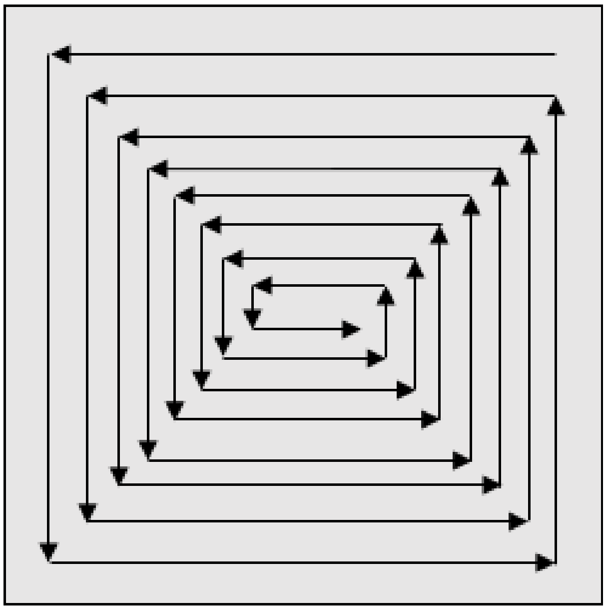

Figure 7. Off-Set in hatch pattern [14,15]

1.4.3. Off-Set Out Pattern

It is the pattern on the opposite of Off-Set in pattern. In this process, the laser beam routes from the outside to inside with the step of hatch distance.

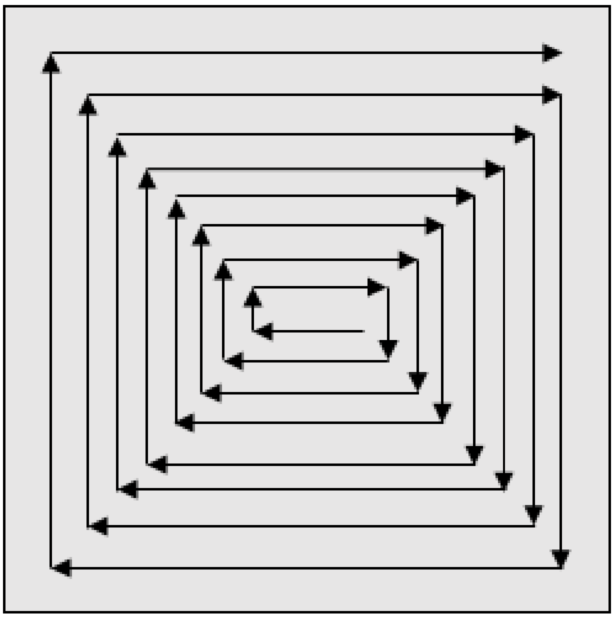

Figure 8. Off-Set out hatch pattern [14,15]

1.4.4 Fractal Pattern

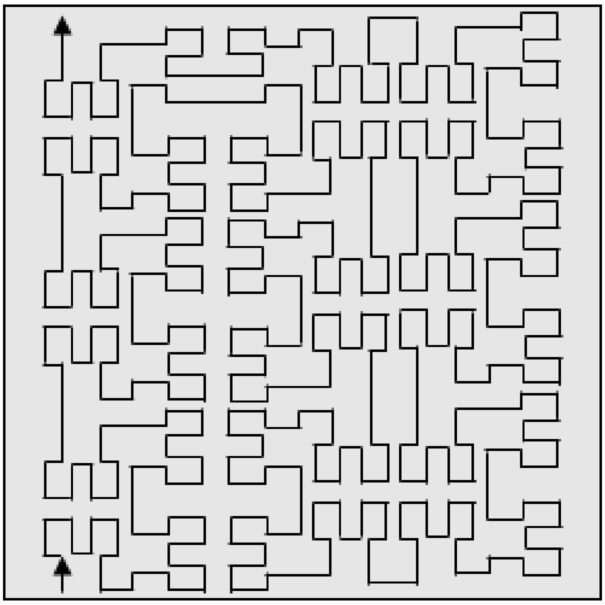

Figure 9. Fractal hatch pattern [14,15]

In this pattern, the laser beam travels through the pattern that has been drawn for providing uniform temperature distribution.

In the overall evaluation, the fractal pattern is the most selected one comparing with the other since it leads to a much more symmetrical temperature which is crucial for having more homogenous structures [16,17,18]

2. Materials and Method

2.1. Manufacturing and tests of the parts

A flow chart was prepared for manufacturing and testing the materials. As it is shown in Figure 10, the test parts were manufactured after approval of the powder quality by an independent test center. Test coupons were produced in accordance with the DIN 50125- C 5X25 Standard.

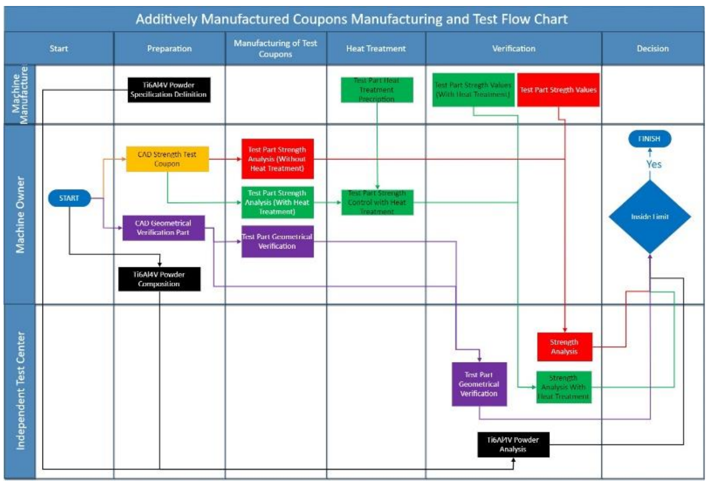

Figure 10. The flow chart of the manufacturing and testing of the additively manufactured test parts.

During the manufacturing process; layer thickness, 60µ, laser power 200 Watt and volumetric energy density 9mm^3 / sec, and fractural hatch pattern were used.

The test parts were prepared in accordance with the specifications of DIN 50125, "Test pieces for tensile testing of metallic materials." In Figure 11, the test parts technical drawing is provided.

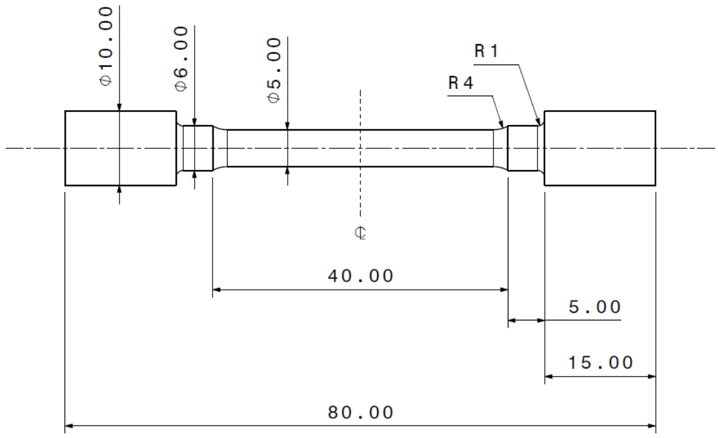

Figure 11. Technical drawing of the test parts

The parts were manufactured as shown in Figure 12.

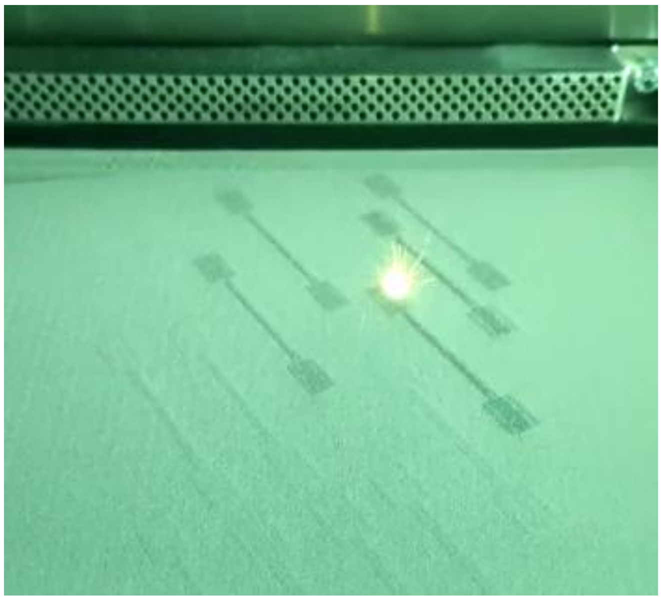

Figure 12. In-Process of the test parts

2.2. Preparation of the test parts

After the manufacturing phase, the parts were prepared for testing as it is shown in Figure 13. In terms of having further information about the surface roughness and strength, the samples were prepared given as follows;

a. The test part after manufacturing without lathe and sand-blasting process,

b. The test part after lathe machining,

c. The test part without any post-process.

It should be highlighted that Rotating machines such as lathe ones are more risky than non-rotating ones in terms of decreasing the mechanical features [19].

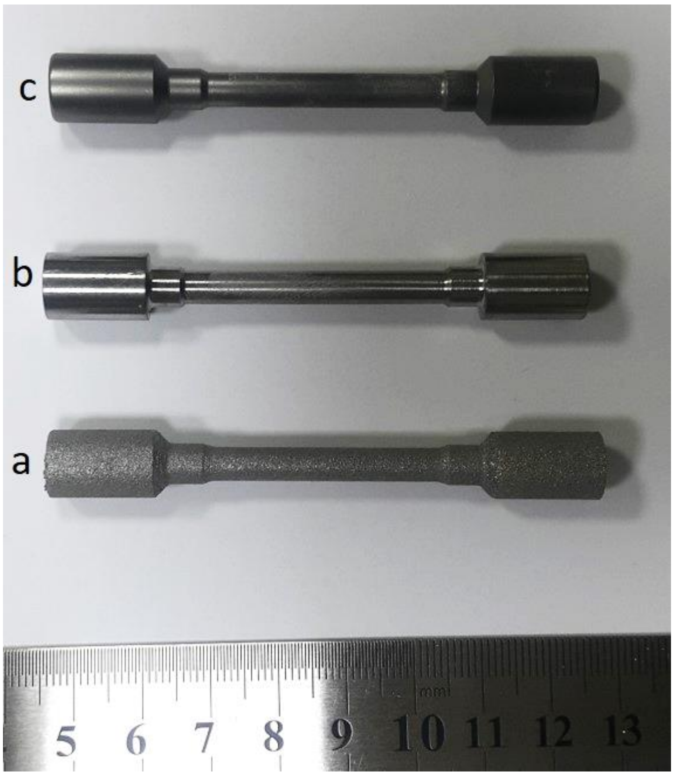

Figure 13. The parts were prepared for surface roughness and mechanical properties. 11.a. The part after manufacturing, 11.b. The part after lathe/turning operation, 11.c. The part after lathe/turning and sand-blasting operation

Some of the under-dimension parts were not chosen for stress-strain tests. In total 30 parts were selected as some of them are shown in Figure 15. For example, the part in the right-end was not used for further test processes. It was observed that all horizontal built parts are bent because of irregular heat distribution.

Figure 14. Some of the test parts

During the study, classification was done for the test parts regarding heat treatment, turn-mill operations, building orientation, sandblasting, and bending conditions. In total 10 groups were established and every group consists of 3 same parts for consistent the result. For test activities, the categorization strategy is given in Figure 14.

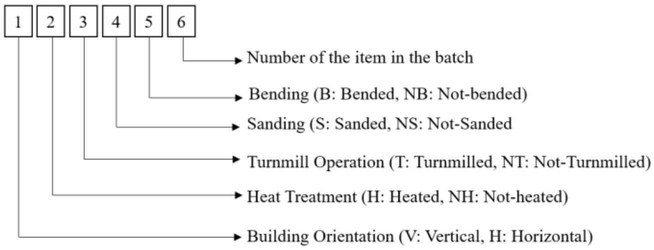

Figure 14. The categorization strategy of the test parts

3. Results and Discussion

After preparation of the parts, they were sent to an independent test center. The parts were analyzed for having information about mechanical properties. The relationship between parts tensile peak load, tensile strength, and yield peak load is given in Table 1.

Table 1. The Relationship between parts tensile peak load, tensile strength, and yield peak

Part Number	Peak Load (kN)	Peak Stress (N/mm²)	Load at Yield (kN)
V-NH-NT-NS-NB-1	22.522	1147.042	20.064
V-NH-NT-NS-NB-2	22.675	1154.843	20.260
V-NH-NT-NS-NB-3	22.458	1143.805	19.825
V-H-T-S-NB-1	20.141	974.142	18.358
V-H-T-S-NB-2	20.241	977.231	18.365
V-H-T-S-NB-3	20.154	978.235	18.585
V-H-T-S-NB-4	20.202	980.963	18.653
V-H-T-S-NB-5	20.171	981.147	18.775
V-H-T-S-NB-6	20.012	982.761	18.854
H-NH-T-NS-B-1	24.478	1246.694	21.383
H-NH-T-NS-B-2	24.606	1253.190	24.033
H-NH-T-NS-B-3	24.650	1255.447	21.662
H-NH-T-NS-B-4	24.895	1267.923	21.563
H-NH-T-NS-B-5	24.643	1255.069	21.373
H-NH-T-NS-B-6	24.434	1244.452	21.501
H-H-T-NS-NB-1	20.169	1027.206	18.384
H-H-T-NS-NB-2	20.555	1046.907	18.706
H-H-T-NS-NB-3	20.306	1034.207	18.529
H-H-NT-NS-NB-1	19.600	998.255	18.152
H-H-NT-NS-NB-2	19.597	998.090	18.100
H-H-NT-NS-NB-2	19.593	997.876	18.074
H-H-NT-S-NB-1	19.625	999.502	18.103
H-H-NT-S-NB-2	19.423	989.227	17.840
H-H-NT-S-NB-3	19.625	999.519	17.956
H-H-T-S-NB-1	20.370	1037.452	18.522
H-H-T-S-NB-2	20.280	1032.895	18.495
H-H-T-S-NB-3	20.232	1030.422	18.346
V-H-NT-S-NB-1	18.961	965.686	17.674
V-H-NT-S-NB-2	19.154	975.522	17.731
V-H-NT-S-NB-3	19.072	971.353	17.672

Also the relationship between parts stress yield, the elongation, and the modulus elasticity is provided in Table 2.

Table 2. The relationship between parts stress yield, the elongation, and the modulus elasticity

Part Number	Stress at Yield (MPa)	Strain at Break Elongation (%)	Modulus Elasticity (kN/mm²)
V-NH-NT-NS-NB-1	1021.882	4.560	99.915
V-NH-NT-NS-NB-2	1031.844	6.378	103.093
V-NH-NT-NS-NB-3	1009.703	6.796	105.068
V-H-T-S-NB-1	971.567	11.149	111.125
V-H-T-S-NB-2	972.458	11.196	111.334
V-H-T-S-NB-3	972.996	11.426	111.821
V-H-T-S-NB-4	974.196	11.556	111.900
V-H-T-S-NB-5	974.689	12.136	112.371
V-H-T-S-NB-6	974.991	12.756	112.494
H-NH-T-NS-B-1	1089.052	6.0033	115.211
H-NH-T-NS-B-2	1224.010	6.834	110.074
H-NH-T-NS-B-3	1103.281	7.230	116.814
H-NH-T-NS-B-4	1098.237	7.510	114.344
H-NH-T-NS-B-5	1088.518	8.295	112.367
H-NH-T-NS-B-6	1095.047	6.379	109.683
H-H-T-NS-NB-1	936.326	9.338	117.437
H-H-T-NS-NB-2	952.733	12.212	117.373
H-H-T-NS-NB-3	943.716	7.328	116.814
H-H-NT-NS-NB-1	924.476	7.963	119.160
H-H-NT-NS-NB-2	921.848	6.420	109.238
H-H-NT-NS-NB-2	920.544	6.854	118.734
H-H-NT-S-NB-1	922.000	8.444	111.474
H-H-NT-S-NB-2	908.588	7.767	111.645
H-H-NT-S-NB-3	914.508	7.225	108.360
H-H-T-S-NB-1	943.336	12.366	116.761
H-H-T-S-NB-2	941.965	11.486	117.154
H-H-T-S-NB-3	934.398	11.6462	116.596
V-H-NT-S-NB-1	900.167	12.483	110.569
V-H-NT-S-NB-2	903.066	13.659	109.438
V-H-NT-S-NB-3	1021.882	12.458	112.358

4. Conclusions and Recommendations

At the end of the experimental studies, the build direction and the heat treatment operations are considered as the major factors that influence the results. Mainly the findings are given as follows;

The vertical building direction provides more precise parts in terms of geometrical accuracy. The horizontal building direction increases the geometrical deviation.

The heat treatment decreases the tensile strength and yield strength of Ti6Al4V alloy parts up to a certain degree. It was observed that Ti6Al4V alloy is sensitive for heat treatment.

The turnmill/lathe operations reduce the strength.

The blast sanding doesn’t affect the mechanical features of the additively manufacture Ti6Al4V parts significantly. Since sandblasting is mainly used for the finishing process as a surface operation, it was evaluated that the mentioned process might be used for improving the surface quality.

In general evaluation, the most powerful influencers are determined as building direction, heat-treatment, machining process respectively while blast sanding has a minor effect on the mechanical features. Besides, bending is a catastrophic phenomenon that cannot be accepted. It is strongly recommended to build the parts in a vertical direction to avoid the machining process other than slight surface operations such as sanding.

For future studies, it would be recommended to change the parameters of scan speed, laser power and apply the stress-strain tests as a complementary study. The result of the mentioned analysis would provide information to determine the more convenient parameter sets and hence produce the parts in a more efficient manufacturing method.

5. Acknowledge

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