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COMPARATIVE STUDY OF MACHINABILITY OF ADDITIVE MANUFACTURED AND WROUGHT TITANIUM ALLOY USING ABRASIVE WATERJET MACHINING

Ashwin Polishetty[1*], Guy Littlefair[2]
[1,2]Faculty of Design and Creative Technologies, AUT University, Auckland, New Zealand
*ashwin.polishetty@aut.ac.nz

Abstract— Titanium alloys are popular and used in a wide range of design applications in aerospace and biomedical industry due to its advantageous material properties. This paper attempts to explore the hole making ability using abrasive waterjet machining. Exploring non-traditional hole making operation such as abrasive water jet machining is an important factor to decide failure or success in a design application. Especially in materials having poor machinability characteristics such as titanium alloys. The main objective of this project is to perform a hole making operation on additive manufactured and wrought titanium alloy, Ti-6Al-4V with standard cutting parameters such as abrasive size, feed rate, traverse speed and standoff distance. A comparative study is carried out in terms of kerf taper angle, Material Removal Rate (MRR) and surface roughness. The paper concludes by identifying the factors responsible to produce a superior hole quality and to evaluate the machinability characteristics.

Keywords- Abrasive water jet machining; Kerf taper angle; Machinability; Wrought titanium alloy Ti-6Al-4V; Selective laser melting;

I. INTRODUCTION

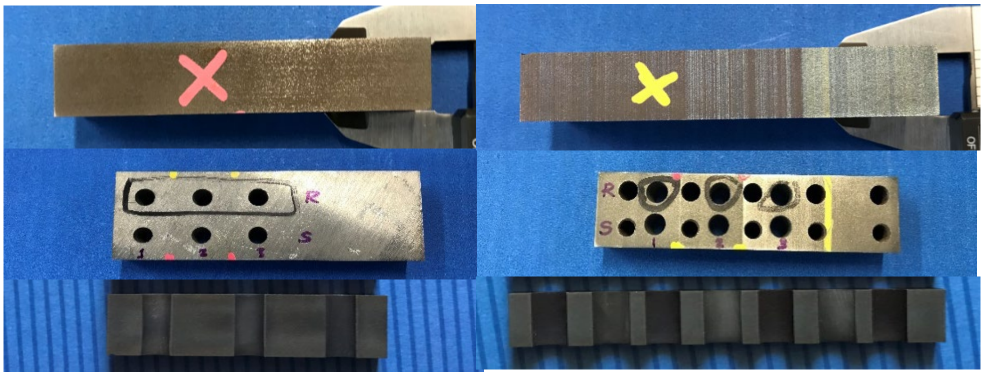
Titanium alloys are used to manufacture components, where the requirements of design reliability and superior material properties such as high corrosion and thermal resistance, high robustness and high strength to weight ratio is a priority [1]. The higher melting point of titanium alloy makes it a superior alloy on comparison to other metals. Titanium alloys have wide verity of applications such as automobile, aerospace and biomedical industry. Contrary, some of the material properties of titanium such as low thermal conductivity and high chemical reactivity leads to poor machinability characteristics [2-4]. Abrasive Water Jet Machining (AWJM) is a non-traditional machining process used for cutting of materials which are difficult to machine. In this technique, the material is removed by projecting a high-pressure water jet with the abrasive particles on a workpiece. One of the major advantages of AWJM is the heat build-up due to friction in the workpiece is minimised during the operation. Any type of complex shapes/cuts can be easily achieved by AWJM [5].

The Water Jet Machining (WJM) process exists from 1970. After ten years, the concept of AWJM was introduced which is an extended and modified version of WJM. The difference in AWJM and WJM is the use of abrasive particles to assist in the hole making process. These technologies work on a common principle that the water and abrasive particles mix pass through the small opening called orifice at extremely high-pressure. The water with inlet pressure between 20000 to 60000 psi is passed over an orifice of diameter .007’ to .005’ which results in a high velocity beam of water. In case of AWJM, the similar water jet is used to rush the abrasive particles to carry out the machining process [6].

M.A. Azmir, A.K. Ahsan carried out an AWJM experiment to find the influence of six process parameters such as types of abrasive, standoff distance, flow rate, traverse rate, cutting orientation on the surface roughness and kerf taper ratio. The outcome was that better quality of cut can be achieved by the increase in the kinetic energy [7]. The performance of various abrasive materials during machining was analysed through the research work of A.A Khan, M.M.Haque. Mahabalesh Palleda examined that influence of various chemical environs like phosphoric acid, acetone and a polymer which is in ratio of 30% to 70% of water. The highest material removal is achieved by addition of slurry with the polymer compared to the other two slurries [8].

A. *Selective Laser Melting (SLM) Technology*

Selective Laser Melting (SLM), is a type of AM technique, which involves layer by layer manufacturing using a micrometer sized particle powder and laser beam as source of heat to melt and bind the powder [1]. SLM 125 metal printer manufactured, supplied, and technology patented by SLM solutions GmbH was used in this research. To prevent oxidation of the metal powder, it is recommended that the SLM process takes place in an inert atmosphere. To achieve this, a vacuum chamber with a nitrogen or argon atmosphere with minimal amount of oxygen is maintained. An initial layer of powder is distributed over an electronically controlled platform and is melted with the help of laser by scanning through the layer. To begin with, a complete 3D model of the specimen is made using CAD software.

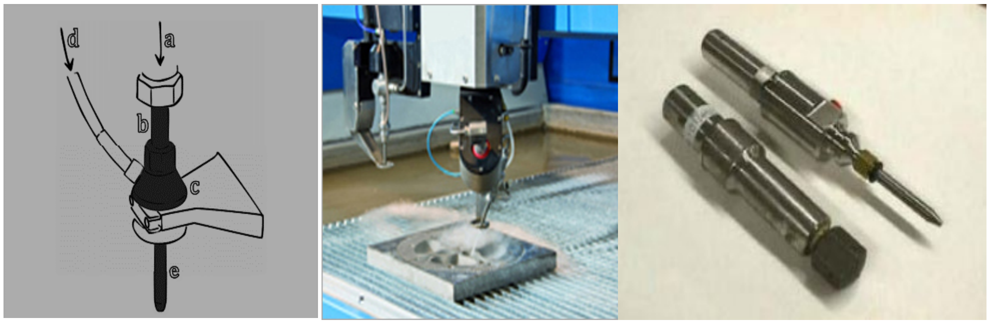

Wrought titanium

SLM titanium

Figure. 1. Wrought and SLM titanium alloy Ti-6Al-4V, machined and cross-section samples

TABLE I. AWJM MACHINING PARAMETERS

Machining	Abrasive size	Flow rate	Abrasive index	Pressure
Parameters	80 mesh	0.33 kg/min	0.97	550000 psi(high) 20000 psi (low)



Schematic of AWJM

Experimental setup

Cutting head

Figure 2. AWJM schematic diagram, set up and cutting head

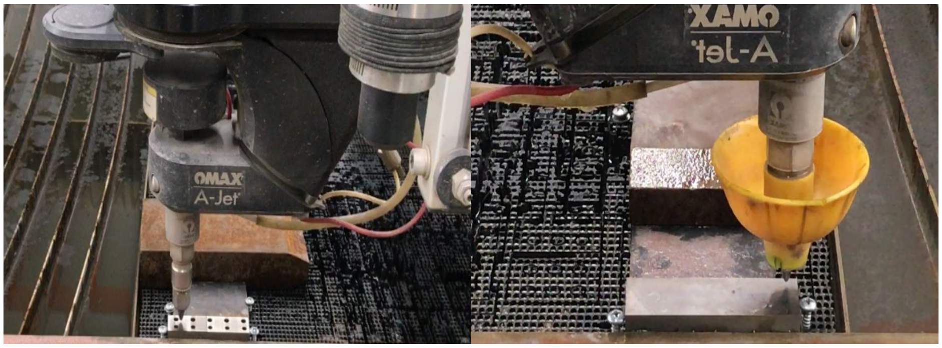
TABLE II. MATERIAL PROPERTIES OF SLM TITANIUM ALLOY

Material Properties	Density, lb/in^3	Yield strength, MPa	UTS, MPa	Vickers hardness
SLM Titanium	0.16	880	950	349

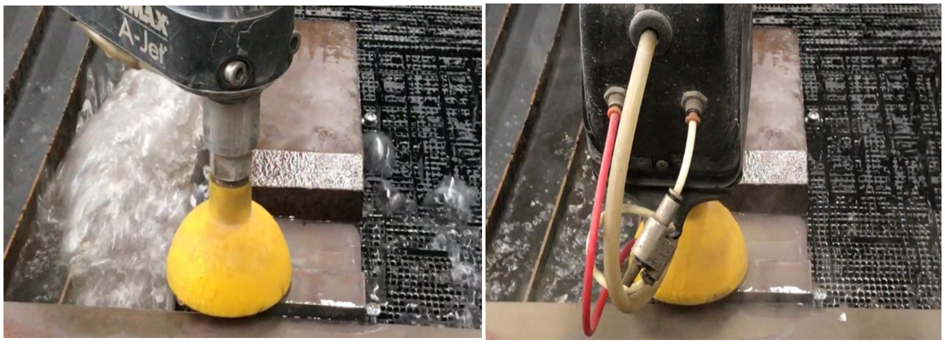
The model is then divided into various layers of micrometer thickness with the help of a customized AM software [9]. A fresh layer is spread over the melted powder and fuse with the previous layer. The process repeats till the entire component is finished as per the CAD data. The process of material forming goes in the same direction of laser beam scanning. Sequentially, elongated lines of molten powder are filled in every cross-section of the part. The quality of the specimen manufactured by SLM method will depend on the layer thickness, powder size, power of the laser beam, scanning speed, hutching, the orientation and build-direction [9]. Hence, SLM manufacturing process is parameter sensitive process. SLM manufactured specimens show high tensile, compression, hardness, and part density as compared to wrought materials, this is because the parts are subjected to high cooling rates during manufacturing process which results in a short grain microstructure. Though, they are reported with low fatigue strengths, caused by the defects during production like porosity, inclusions and anisotropy [10].

II. EXPERIMENTAL DESIGN

The aim of this project is to carry out the comparative study of performance parameters such as surface roughness, material removal rate and kerf tapering angle during hole making operation using AWJM on Selective Laser Melting (SLM) and wrought titanium alloy Ti-6Al-4V as shown in fig 1. The SLM titanium specimen used in this experiment was printed using a SLM125 AM printer as shown in fig 1. The machined and cross sectioned sample for SLM and wrought titanium is also shown in fig.1. SLM and wrought titanium alloy Ti-6Al-4V are subjected to the hole making operation using Omax 55100 jet machining centre using the machining parameters as tabulated in table 1. The material properties of SLM titanium alloy is given in table 2. The standard rotational speed of the machine during a rotary setting was 10,000 steps/revolution and clockwise direction. The standard torque is estimated to be around 15 N-m.



Constant head setting (S)



Rotary head setting (R)

Figure 3. Constant and rotary head setting of AWJM

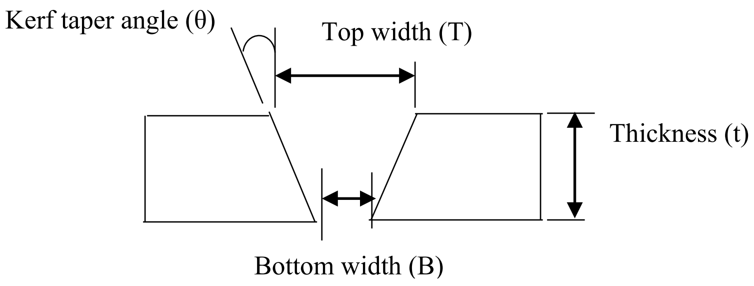


Figure 4. Diagram in support of kerf taper angle calculation.

The components of abrasive water jet machining (as shown in fig. 2) consists of a) Pressurized water from pump, b) Pressure tube, c) Mixing chamber, d) Abrasive feed and e) Focusing tube. The schematic diagram, experimental set up and cutting heads are also shown in fig.2. The experimental procedure consists of conducting hole making operation using two different setting – constant head (S) and rotary head (R) as shown in fig. 3. The first hole represents a rough cut, the third hole represent a fine cut and second hole is a balance between rough and fine cuts. The definition of a rough and fine cut is based on the water pressure as the abrasive size and flow rate remains constant. The result for all trials is a through hole of 6mm diameter. Further, the generated holes are cross-sectioned and subjected to evaluation of factors such as surface roughness (Ra), Kerf taper angle (θ) and Metal Removal Rate (MRR). The surface roughness measurement is done using Alicona optical profilometer. The definition of kerf taper angle is illustrated in fig.4. The kerf taper angle is calculated using the formula given in eq. 1.

$$\theta = tan^{-1}\left(\frac{T-B}{2t}\right) \tag{1}$$

where T = top width, B = bottom width and t = thickness, (all dimensions in mm).

MRR is calculated using the formula as shown in eq. 2.

$$MRR = \frac{w_i - w_f}{m_t} \tag{2}$$

Where wi = initial weight (Kg), wf = final weight (Kg) and mt = machining time (secs).

III. RESULTS AND DISCUSSION

The vickers microhardness hardness results for SLM and wrought titanium Ti-6Al-4V was measured to be 392 and 327 Hv respectively. The quality of the holes generated using AWJM under constant and rotary head setting in wrought and SLM titanium alloy Ti-6Al-4V is evaluated, analysed and presented in graphical format in this section.

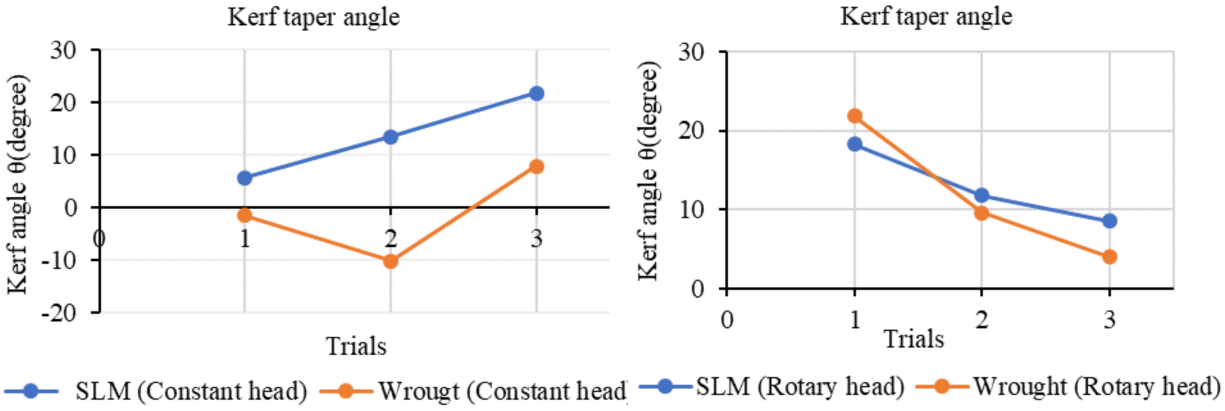


Figure 5. Kerf taper angle variations

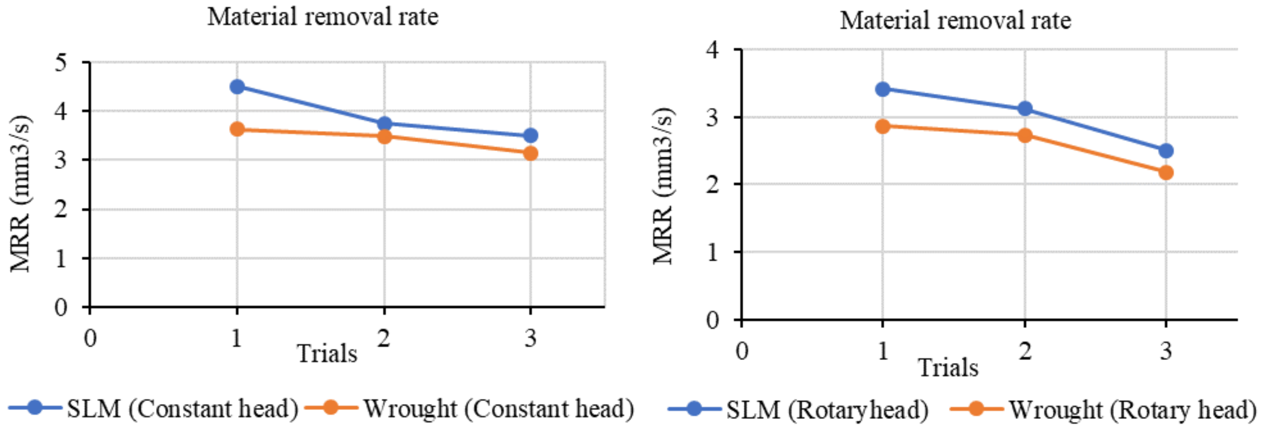


Figure 6. Material removal rate variations

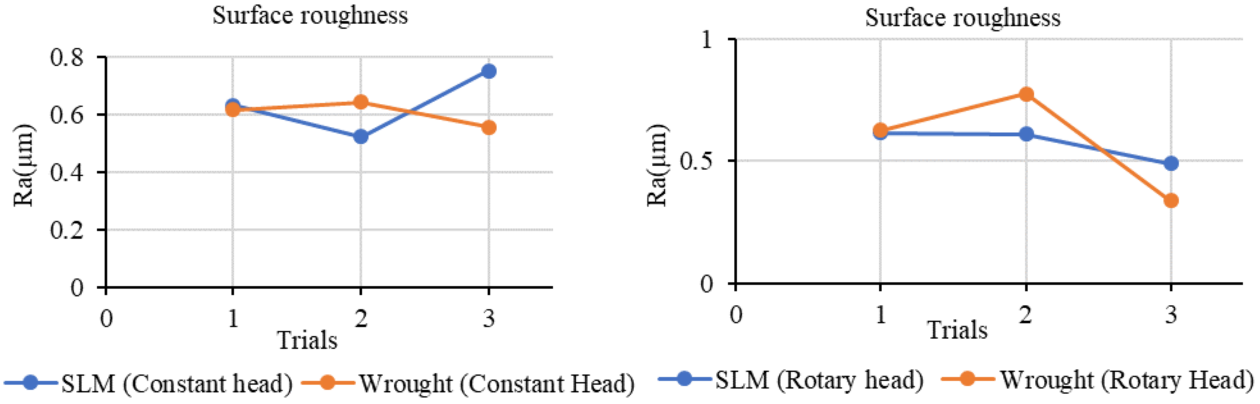


Figure 7. Surface roughness variations

The variation for kerf taper angle for different trials using the combination of head setting and material – wrought and SLM is shown in fig. 5. For a successful AWJM process, the kerf taper angle should be near to the reference point (0o) or minimal deviation. Some exceptions such as negative taper was noticed during trial 1and 2 under constant head setting.

The variation in MRR under the constant and rotary head setting for wrought and SLM Ti-6Al-4V is shown in fig.6. Rotary head delivered a better performance than a constant head in relation to kerf taper angle. This may be attributed to the assistive torque provided due to the rotary action.

In sync with the previous research works, the results infer that the hardness of the material and abrasive particles play an important role in the controlling the dimensional accuracy (kerf taper angle). It is known that MRR is inversely proportional to time taken to complete the process. It can be witness for wrought and SLM Ti-6Al-4V under a fine finish setting (trial 3) where it takes long time to complete the process, the MRR was comparatively lower. For a similar material type and trial, constant head setting produced a higher MRR compared to the rotary head. The reason may be due to the cut direction being parallel to the abrasive flow. Surface roughness/finish is an important factor in deciding the hole quality especially in a design application where precision/tolerance is utmost for an assembly/fit. The surface roughness variations of the generated holes for SLM and wrought titanium under constant and rotary head is shown in fig. 7. The signature of a successful hole making operation (good machinability) lies in having a lower surface roughness. It is evident from the graphs that for SLM and wrought titanium Ti-6Al-4V, constant head setting produces a higher surface roughness compared to the rotary head setting. This can be attributed to higher MRR (trial 1 and trial 2) especially the abrasive flow rate. As defined, trial 3 having a fine cut, reflects a good finish in a rotary head setting which is lower surface roughness (Ra) value. An exception can be observed for similar cut (fine) in a constant head setting where there is a significant increase in surface roughness (Ra).

IV. CONCLUSION

The research concludes by evaluating and analysing factors responsible for the hole quality in wrought and SLM Ti-6Al-4V using AWJM. An attempt has been made to answer the research question of evaluating the influence of machining parameters on the AWJM process and finding ways to improve the quality of the hole generated. In this research, the machinability has been evaluated using three factors: dimensional accuracy-kerf taper angle, MRR and surface roughness (Ra). Analysing the results, it can be inferred that machinability is poor in SLM compared to the wrought titanium. This can be attributed to the lower tensile strength and brittle nature of the SLM due to the short grain microstructure. Kerf taper angle was higher in SLM compared to the wrought titanium. Rotary head setting produced inferior results compared to constant head setting. The MRR was higher in constant head than the rotary head setting. Although few exceptions were observed in kerf taper angle and surface roughness especially under constant head setting. There arises a scope for additional research to determine the relationship between the machinability factors, variable head setting and study the vortex effect of abrasive flow especially in rotary head setting.

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