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Paper:

Experimental Investigation of Abrasive Waterjet Machining of Titanium Graphite Laminates

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High temperature Fiber Metal Laminate – Titanium/Graphite (Ti/Gr) is an advanced material system, developed to meet the high temperature requirements in aerospace applications. High specific strength and stiffness of composite core along with its protection from aggressive environment by tough titanium alloy sheets qualify FMLs for a promising alternative material where metallic and composites overcome each other's limitations. However, industrial employability of this three phase system is often limited by the machining challenges posed by the difference in material removal mechanisms of Titanium alloy, PIXA thermoplastic polyimide resin and graphite fibers. An experimental investigation was conducted to evaluate the machinability of 1 mm thick Ti/Gr laminate sheets through Abrasive Waterjet (AWJ) machining process in terms of kerf characteristics and material removal rate. The parametric influence of AWJ operating variables on machining performance was studied by systematically measuring operating variables (traverse speed and Abrasive flow rate) using fully crossed Design of experiment (DOE) scheme, and statistically analyzing using ANOVA (Analysis of variance) technique. Empirical models were developed to quantify these effects and predict the influence of process parameters on material removal rate, kerf taper, entry damage width and overcut in straight cutting of Ti/Gr sheets.

Keywords: abrasive waterjet technology, fiber metal laminate, titanium graphite

1. Introduction

Hybrid composite laminates, also known as Fiber Metal Laminates (FML) is a group of engineered materials consisting of polymer matrix composites (PMC) plies interspersed with metal foils. The capability to withstand aggressive environment, high temperature; to resist oxidation and moisture ingress while maintaining structural integrity are few reasons why these are known as new age engineered materials. This hybrid material system was first developed by Delft Research Group as ARALL® (Aramid Fiber Aluminum Laminate) followed by GLARE® (Glass fiber Aluminum Reinforced Epoxy). However development of Titanium Graphite laminate (TiGr) by The Boeing Research Group has outperformed both the previously developed material systems in terms of fatigue strength, tensile strength and Inter-Laminar Shear Strength (ILSS). Bourlegat et al. [1] reported 95% improvement of tensile strength and 37% improvement in ILSS of TiGr when compared to GLARE®. TiGr is composed of alternate layers of graphite reinforced thermoplastic composite (PIXA-M) and titanium sheets. It is widely characterized as a futuristic material and finding employability in aerospace applications to address the future needs where aircrafts could high skin temperatures (177°C) at supersonic speeds greater than Mach 3. The directional properties of carbon composite (better fatigue characteristics, high stiffness-to-weight, and strength-to-weight ratio) with added benefits of Titanium alloy sheets (high tensile and flexural strength, high stiffness) coupled with properties rendered by hybrid nature of the system such as protection of composite core from heat and moisture, better distribution of point load and enhanced compression after impact (CAI) strength [2–5] by titanium sheets.

Although, TiGr laminates are generally molded/autoclaved to a near net shape, secondary machining is often required. Machining of composites alone poses a great challenge, which becomes even worse in a three phase material system – hybrid composites, where the non-homogeneity and anisotropy of composites together with the difference in the removal mechanism for all the three different phases aggravate machining problem. Conventional processes have several limitations when composite machining is concerned viz. excessive tool wear and thermal distortion, fiber pull out, matrix cratering, delamination, fraying, dust and burr formation from metal foils [6–8]. Several investigations have reported that up to 60% of the rejected composite parts come from secondary machining defects [9], foregrounding the need and importance of more precise and non-traditional methods in composite machining.

Several non-traditional methods have been studied for the machining of composites. Ultrasonic machining is widely employed for brittle matrix composites (ceramic composites). Electrical discharge machining (EDM) has been employed to machine electrically conductive composite materials. However, objectionable surface integrity, high delamination due to arching and low material removal rates (MRR) accounts for its inaptness for machining fiber metal laminates. Laser cutting is well suited for contour trimming of carbon fiber reinforced plastics because of point-sized geometry and multidirectional cutting ability. However, uneven kerf width and decrease in static strength of components due to thermal cracking and large heat affected zone (HAZ) restricts its use. Abrasive Waterjet (AWJ) machining is a widely used unconventional alternative because of properties such as no thermal damage to the workpiece, high cutting speed, wide working range and environmental friendly [10–18]. Several FEM, analytical and experimental models have been developed to predict the effect of process parameters on the performance of machining ceramics and composites. However, the AWJ machining of fiber metal laminates is seldom studied due to the complexity of the cutting process. Paul et al. [19] studied the material removal process and quantified the effect of different parameters on GLARE®. Among hybrid materials involving titanium and composites, only AWJ machining of CFRP/Ti6Al4V stacks has been studied [20]. No investigation for AWJ machining and parametric optimization of TiGr has been reported so far.

In this study, the machinability of TiGr is investigated and determined in terms of Material Removal Rate (MRR), kerf characteristics – overcut, damage width and taper as performance parameters of straight profile thin TiGr sheets. AWJ process variables are evaluated and optimized for high machinability. ANOVA (Analysis of Variance) is applied to statistically quantify the response of these variables and develop regression models to establish a nexus between these variables and machining response.

2. Experiment

2.1. Workpiece

Rectangular sheets of $228 \times 28 \times 1$ mm, aerospace grade Titanium Graphite (TiGr) were obtained from The Boeing Company. The workpiece composed of 8 plies with layers of graphite reinforced thermoplastic (PIXA-M) matrix composite interspersed between 117 μm thick titanium alloy foils (Ti-15V-3Cr-3Sn-3Al). The laminate layers were stacked together using autoclave consolidation process with the stacking sequence [Ti/90°/Ti/0°/0°/Ti/90°/Ti].

The mechanical properties of carbon fibers (IM-7 intermediate modulus), matrix (LARC-IAX polymer), and titanium alloy are mentioned in **Table 1**.

2.2. Experimental Design and Methodology

All the experiments were performed using Flow Water Jet Pro WJP 1313 equipped with 276 MPa intensifier was used along with the vacuum assist. The experimental conditions (variable and constant process parameters) are mentioned in **Table 2**.

The experiments were divided into three sets based on cutting profile: straight cutting, piercing and trepanning operations, and were studied with fully crossed three factorial scheme of experimental design, as shown in **Table 3**. The primary aim of this study is to comparatively analyze the AWJ machining quality for trepanning and straight cutting. Piercing is studied as an auxiliary initiation step for trepanning operation.

Three levels of traverse speed (60, 390, 720 mm/min) and three levels of Abrasive Flow rate (AFR) (3.53, 6.23, 9.78 g/s) were selected on the basis of previous investigations [12–18] for both trepanning and cutting experiments. The cutting time, jet entry and exit kerf width,

Table 1. Mechanical properties of TiGr constituents.

Properties	Material		
	Ti-15-3	*LARC-IAX*	*IM7*
Longitudinal modulus (GPa)	100.61	3.33	272.2
Transverse modulus (GPa)	–	–	13.58
Shear modulus (GPa)	33.75	1.25	200
Poisson's ratio	0.36	0.33	0.25
Yield strength (MPa)	1307	67.92	–
Ultimate strength (MPa)	1459	105	36612
Percent elongation (%)	4.1	6	1.8

Table 2. Mechanical properties of TiGr constituents.

Parameter (constant)	Description
Orifice	Sapphire, Ø 0.381 mm
Nozzle	Length 76.2 mm, Dia. Ø 1.016 mm
Grit type	Garnet
Grit size	Mesh 80
Impact angle	90°
Variable	**Range**
Traverse speed (mm/min)	60, 390, 720
Abrasive flow rate, AFR, (g/s)	3.53, 6.23, 9.78

Table 3. Experimental design for AWJ straight cutting.

S.No	Parameters		Measurement data		
	Abrasive flow rate (g/s)	*Traverse speed (mm/min)*	*MRR (mm^3/ min)*	*Entry damage (mm)*	*Kerf Taper*
1	3.53	60	0.8000	0.136	0.0744
2	3.53	390	2.8015	0.077	0.0930
3	3.53	720	3.5904	0.059	0.1155
4	6.23	60	0.8156	0.193	0.0695
5	6.23	390	2.8234	0.106	0.0890
6	6.23	720	3.6182	0.097	0.0959
7	9.78	60	0.8210	0.286	0.0656
8	9.78	390	2.8897	0.165	0.0832
9	9.78	720	3.7216	0.155	0.0930

and discolored region was measured using MicroVu Sol® Precision measuring machine. The machining quality was assessed using ANOVA with material removal rate, overcut, kerf taper and damage width. Material removal rate (MRR) was calculated based on the volume of material removed over the total cutting time which included dwell, traverse and rapid traverse. Overcut was calculated as the difference between cutting width and tool width, tool width being the nozzle diameter. Since the standoff distance was kept constant in this experimental study, overcut variation measures the jet expansion due to difference in jet power density at different machining conditions.

$$\text{Overcut} = \frac{d - d_{tool}}{2} \quad \ldots\ldots\ldots\ldots \quad (1)$$

Kerf taper was calculated as the difference between entry and exit cutting width normalized with the workpiece thickness.

$$\text{Kerf taper} = \frac{d_{entry} - d_{exit}}{2t} \quad \ldots\ldots\ldots \quad (2)$$

Damage width is the width of discolored region on titanium alloy face sheet around the cut, observed under optical microscope.

$$\text{Damage width} = \frac{D - d}{2} \quad \ldots\ldots\ldots\ldots \quad (3)$$

where D is the spread of discolored region around the machined profile and d is the width of cut. Only entry damage width is reported due to poor visibility of negligibly small exit damage.

2.2.1. Straight Cutting

Cutting operation was carried out by machining nine straight cuts of approximately 22 mm long at constant jet pressure setting (275.8 MPa) with 8 mm spacing between each cut. **Fig. 1(a)** shows the kerf top surface in straight cutting.

2.2.2. Piercing

For piercing operation, two levels of standoff distance (3 and 6 mm) and three levels of pressure (82.7, 137.9 and 206.8 MPa) were used in the study. The purpose of studying this operation is to identify parameters causing least delamination, required to proceed with subsequent trepanning operation. The workpiece used in this operation was different from the rest of the experimental study, and was 1.3 mm thick with stacking sequence (Ti/0°/90°/0°/0°)$_s$. The common site of delamination is expected near the top and bottom plies [13–15, 21–23], justifying the use of a different layup specimen and projecting the same effect on standard specimen. The specimens were inspected through optical microscopy and Ultrasonic C-scan technique and then the highly damaged specimen was dissected to inspect the damage characteristics.

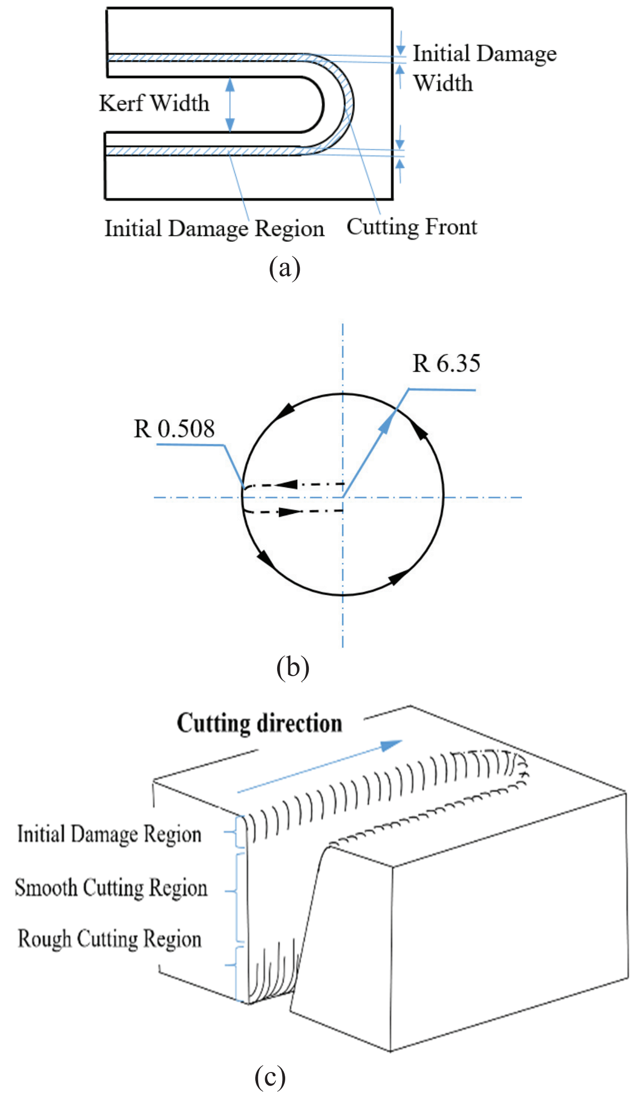


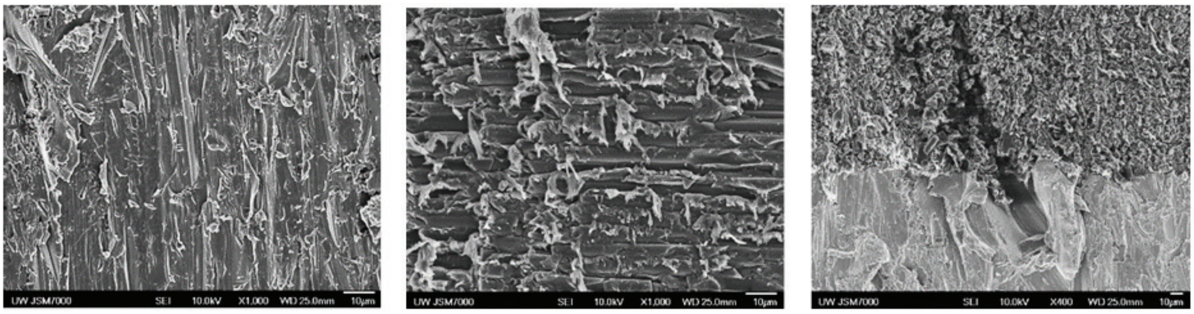
Fig. 1. Schematic diagram of (a) AWJ straight cutting, (b) Trepan hole with circular lead in/out drawing, (c) Cutting zones and typical kerf geometry observed in AWJ machining.

2.2.3. Trepanning

Trepanning experiments were performed in two steps. Firstly, a hole was pierced with the minimum delamination parameter setting as determined in the piercing study. This followed the rapid traverse of cutting head up until the beginning of circular edge. The cutting pattern is shown in **Fig. 1(b)** and machining variables and conditions are mentioned in **Table 2**.

3. Results and Discussion

Several contrasts as well as similarities are apparent between AWJ machined TiGr laminates, and conventional materials. These characteristics are revealed by SEM inspection, optical microscopy and surface profilometry. Similar to AWJ machined conventional and composite materials, initial damage region, smooth cutting and



(a) (b) (c)

Fig. 2. SEM images of (a) Titanium ply (b) 90 degree PIXA-M composite ply (c) Grit embedment in titanium ply at 720 mm/min traverse speed and 3.35 g/s AFR.

rough cutting regions were identified as demonstrated by Ramulu et al. [15, 18] and shown in **Fig. 1(c)**. Kerf characteristics such as visible damage and distortion in the middle composite plies reveal the possible effects of jet interaction behavior due to discrepant material properties of constituent layers.

The material removal mechanism was studied by SEM inspection of titanium, graphite fiber and thermoplastic matrix as different phases. As shown in **Fig. 2(a)** abrasive wear tracks and signs of shear deformation on titanium ply were observed in the specimen machined with low energy setting -60 mm/min traverse speed and 9.78 g/s abrasive flow rate.

This affirms the removal of titanium by ductile shearing, abrasive plowing, and scratching action, as observed by Seo et al. [24]. The matrix shearing and plastic deformation was observed in matrix material of the composite layers, while carbon fibers underwent micro chipping, brittle fracture, and bending failure. **Fig. 2(b)** shows the bending and chipping in composite ply machined at 720 mm/min traverse speed and 3.35 g/s AFR. Most of the experimental conditions resulted in large smooth cutting zone, except a few where grit embedment was observed near the jet exit side. One such case is depicted in **Fig. 2(c)** where an abrasive particle plowed through the material, fractured, and embedded at the bottom of the wear track.

The surface characteristics for machined surfaces were investigated. It was observed that using fast traverse speed and low AFR resulted in more irregular surface. However, entry damage on the top titanium ply was smaller. Cleaner and smoother cut surface were achieved at slow traverse speed and high AFR. At this condition, shallower grooves and smaller titanium burrs were obtained. All plies remained intact and no delamination was observed. Average roughness for the best and worst surface condition is 0.636 μm and 0.899 μm respectively for cutting, and 0.662 μm and 0.671 μm respectively for trepanning operation.

3.1. Straight Cut

Owing to the criticality of material removal rate (MRR) as a response function in machining difficult-to-cut materials, the effect of traverse and abrasive flow rate was investigated using ANOVA. **Fig. 3(a)** shows the parametric effects on material removal rate. The analysis showed a positive effect of jet traverse speed and positive effect of abrasive flow rate on the material removal rate. MRR was found to change significantly with traverse speed which is supported by its high Fisher's test value in the analysis.

Positive kerf taper was observed throughout the experimental range with value varying between 0.065 and 0.115 mm/mm. Kerf taper showed a positive trend with traverse speed and negative trend with abrasive flow rate, as depicted in **Fig. 3(c)**. Overcut was observed 12% to 25% more at jet entry side in comparison to exit side. This can be accounted by initial high energy abrasive jet at the entry side of the cut in the cutting wear zone which reduces with the penetration depth.

As shown in **Figs. 4(a)**, **(c)** both the entry and exit overcut showed negative trend with traverse speed and positive trend with the abrasive flow rate. The kerf width was observed within the range of 1.15–1.3 times nozzle diameter (447–647 μm) at entry side and 0.92–1.16 times nozzle diameter (458–580 μm) at exit side. In addition, a low p-value of traverse speed indicated higher sensitivity to traverse rate in comparison to abrasive flow rate. The visible entry damage width exhibited a trend similar to overcut and lies within the range of 59–286 μm.

A low traverse speed increases jet exposure time and resulted in lesser amount of high energy abrasive particles impacting the work piece. This induced smoother kerf wall, smaller kerf taper, larger kerf width, and larger initial damage width.

3.2. Piercing

In AWJ piercing, the effect of standoff distance and standoff pressure on damage was studied. Visible pop-up delamination at the exit side of the specimen was observed.

The total visible delamination area was compared with the ultrasonic C-Scan and was greater than the visual observations as shown in **Fig. 5**.

This means the subsurface, interlaminar damage was greater than the visible damage at the titanium facesheets. At 137.9 MPa jet pressure, the variation of C-Scan and

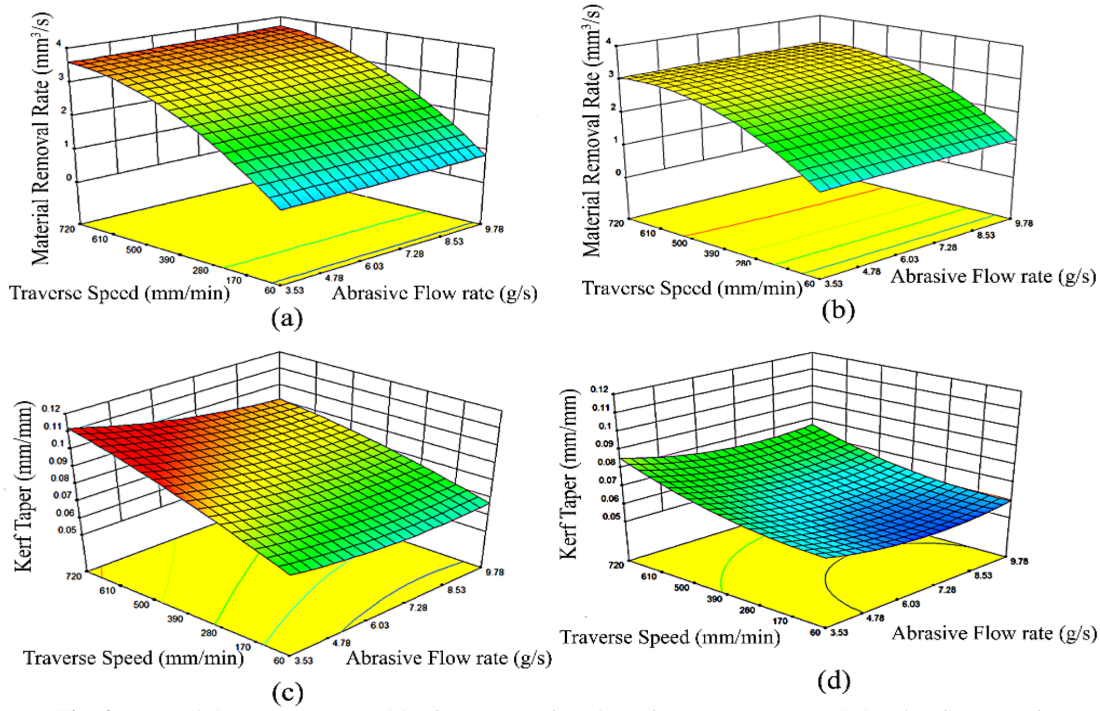


Fig. 3. Material removal rate and kerf taper as a function of traverse speed and abrasive flow rate for (a), (c) Straight cutting, and (b), (d) Trepanning.

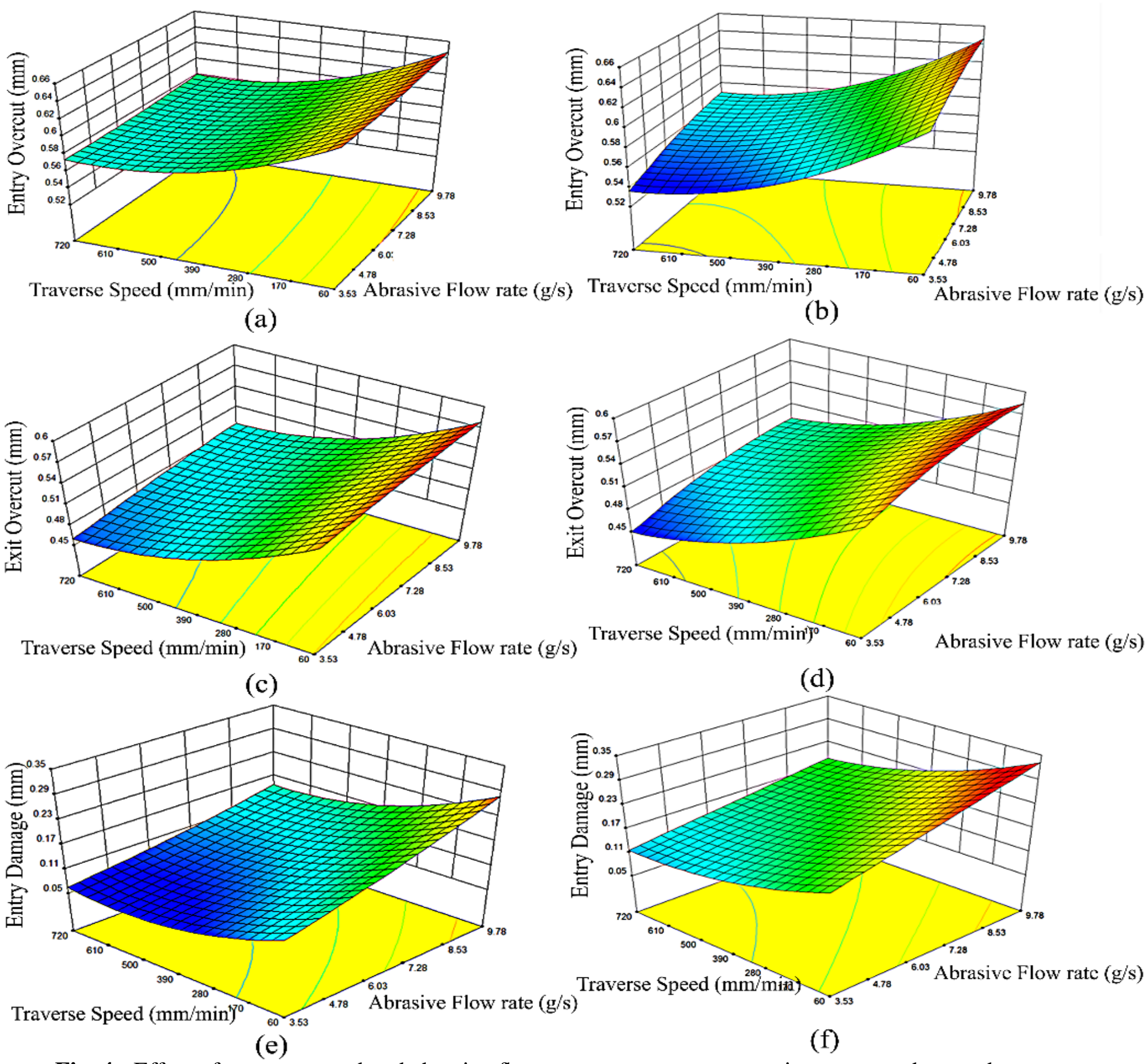


Fig. 4. Effect of traverse speed and abrasive flow rate on entry overcut, exit overcut and entry damage respectively for (a), (c), (e) Straight cutting, and (b), (d), (f) Trepanning.

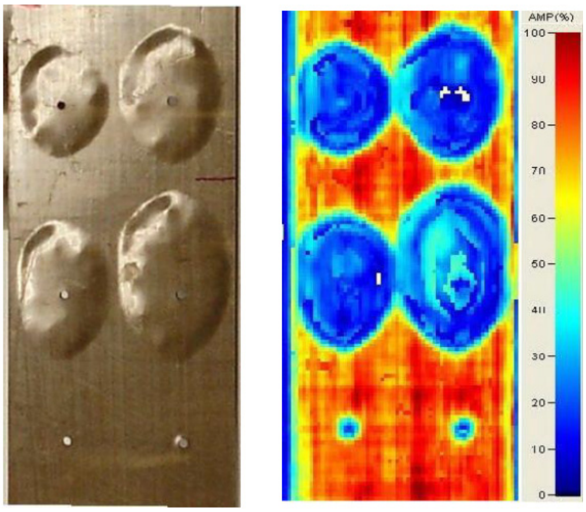


Fig. 5. Visible and C-Scan delamination around pierced holes.

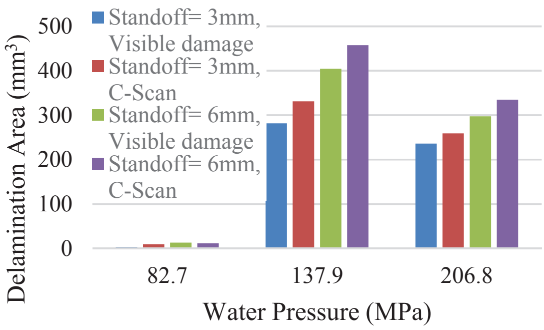


Fig. 6. Visible and C-Scan delamination area around pierced hole at three pressure levels.

visible damage area was found to be in the range of 14–18%. The delamination area was found to be minimum at a low pressure (82.7 MPa) as shown in **Fig. 6**, which agrees with observations made by Scott [25] that jet pressure lower than 103 MPa was ideal for piercing. Also, delamination area was found maximum at an intermediate pressure (137.9 MPa) instead of high or low jet pressure setting.

The delamination area was increased from 30–40% when standoff distance was doubled. The conditions leading to minimum delamination were found to be 3 mm standoff distance and 82.7 MPa pressure resulting in a delamination area of 2.2 mm^2 (excluding hole area) or an equivalent delamination diameter of 2.25 mm. The hole machined with conditions leading to maximum delamination was sectioned with a low speed diamond grit cutter and the cross-section was examined. The separation between the bottom two plies of titanium face sheet and adjacent zero degree composite ply was found to be the main delamination failure.

Figure 7 shows the embedded abrasive particles between layers of last two plies. Least delamination was obtained at optimized pressure (82.7 MPa) and standoff distance 3 mm was further verified on six different plies and an average entry, exit hole diameter, and entry dam-

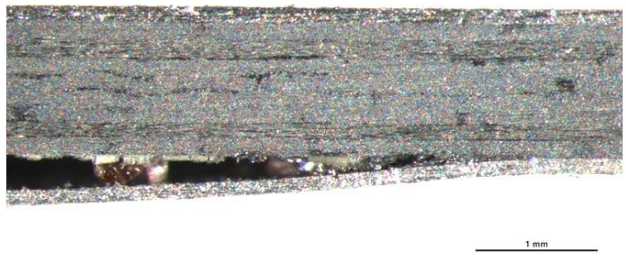


Fig. 7. Embedded abrasive particle near the delamination boundary.

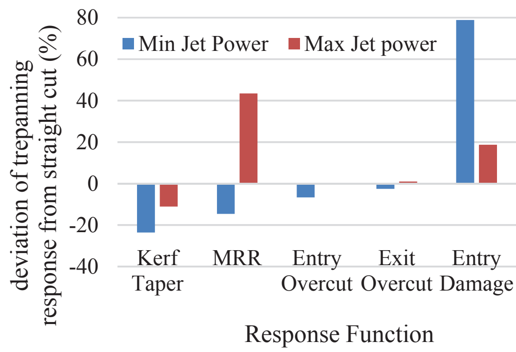


Fig. 8. Deviation of trepanned response functions for from straight cut AWJ response for minimum and maximum jet power conditions.

age diameter for the pierced hole were 1.51, 1.35, and 2.85 mm, respectively.

3.3. Trepanning

Similar to straight cutting, higher traverse speed and low abrasive flow rate resulted in low jet power and low cutting ability of the jet. This, in turn resulted in large kerf taper with small kerf width, small entry damage and small overcut. The parametric effects are shown in **Figs. 3(b)**, **(d)** and **Figs. 4(b)**, **(d)**, **(f)**.

It was observed that the machining response for trepanned and kerf surface was significantly dependent on the type of cutting geometry. **Fig. 8** shows the deviation of trepanning response from straight cut response for minimum and maximum jet power conditions. Here, minimum jet power corresponds to traverse speed and abrasive flow rate as 720 mm/min and 3.53 g/s respectively; whereas maximum jet power condition corresponds to 60 mm/min and 9.78 g/s as traverse speed and abrasive flow rate respectively. The kerf taper was reduced up to 24% when cutting geometry was changed from straight cut to trepanning. This can be attributed to unavoidable jet deceleration which effectively increases the overall exposure time. Material removal rate was reduced up to 14% for low power conditions, whereas a significant 43.5% increment was observed for trepanned surface. The result clearly indicates that the low power conditions lead to less material removal even with significantly low cutting time. However, at high jet power, the volume of material removed due to high cutting ability offsets the effect of deceleration in trepanned geometry. This is suggestive of an optimum range of cutting conditions to cater the reduction of response variation due to cutting geometry. The effect of cutting profile on entry and exit over cut was negligible, however, entry damage was found significantly high for trepanned surface when compared to straight cut. This can attributed to high jet exposure and abrasive frosting while entering the workpiece.

4. Conclusion

Difficult-to-cut multi-layered titanium/graphite fiber metal laminate was successfully machined with Abrasive Waterjet Technology in this experimental study. The cutting mechanism was studied for individual constituents of this material system and several kerf observations, both contrastive and similar to the AWJ machined conventional materials, were made. The machinability of TiGr was evaluated by studying the effect of traverse speed and abrasive flow rate on straight cutting and trepanning. The machining quality was statistically assessed in terms of kerf taper, material removal rate, entry and exit overcut, and entry damage.

Piercing was studied as an auxiliary step for trepanning and the invariant parameters for trepanning viz. standoff distance and water pressure were optimized to obtain delamination free cut.

Following key conclusions can be drawn from this study.

1. The material removal mechanism was different for different constituents in the three phase material. Titanium is removed by ductile shearing, abrasive plowing, and scratching action. The matrix material is removed by shearing and plastic deformation while fibers experience micro chipping, brittle fracture, and bending failure.

2. The effect of increasing AFR was similar to slowing down the traverse speed as increasing AFR would mean large amount of abrasive particles exposed to the work piece per unit time performing the cutting operation. However, a balance between these two process variables is critical.

3. A delamination free starting hole can be produced by using the lowest pressure (82.7 MPa) and small standoff distance (3 mm). Higher delamination is likely to occur at an intermediate pressure due to increased stagnation pressure buildup with insufficient abrasive cutting action.

4. The machining response is not independent of the cutting geometry with up to 43.5% variation in material removal rate. Use of optimized cutting conditions is necessary to avoid this geometry dependent variation.

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Main Works:
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