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Experimental Investigation on The Effect of Control Parameters on MRR and Surface Finish of Titanium Alloy Grade 5 Using Abrasive Water Jet Machining

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ABSTRACT - Abrasive water jet (AWJM) machining process is non-conventional machining process, which has been used in industrial applications. AWJM machining process operates at relatively high pressure (10-1000MPa) and focused stream of abrasive particles carried by high pressure water is made to impinge on the work material is removed by erosion by high velocity Abrasive particles. Titanium grade5 (Ti-6Al-4V) alloy gained a significant importance because of its corrosive resistant, light weight and high strength properties even at low to moderate temperatures. Basically, this titanium alloy is employed in fabricating medical device applications, aircraft industry, aerospace fasteners, high- performance automotive parts, marine applications, and sports equipment. It is difficult to machining Titanium alloy using conventional machining process. Abrasive water Jet Machining (AJM) process under un-conventional machining process is one such solution which provides the solution for machining Titanium alloy grade 5 (Ti-6Al-4V composite material). In this project, an effort has been made to optimize machining parameters employed during cutting on Ti-6Al-4V composite material by using Abrasive Jet Machining. The process parameters abrasive flow rate, Transverse speed and Stand-off distance are optimized to investigate their influence on metal removal rate (MRR) and Surface Roughness (R_a) of Titanium (Ti-6Al-4V) alloy grade 5. The machining process is carried out by L9 orthogonal array. Taguchi design analysis is employed to determine optimal combination of control parameters. The grey relational analysis is also applied to identify the optimal process parameters have been determined by the grey relational grade for multi performance characteristics that is MRR and surface roughness.

Key words: Abrasive water jet machine, Titanium alloy grade 5, Material removal rate (MRR), Surface roughness, Taguchi, Grey relational analysis

I. INTRODUCTION

In abrasive water jet machining a small stream of fine grained abrasive particles is mixed in suitable proportion of water, which is forced on a work piece surface through a nozzle. Material removal occurs due to erosion caused by the impact of abrasive particles on the work surface. AWJM is especially suitable for machining of brittle material like glass, ceramics and stones as well as for composite materials and ferrous and nonferrous material. The characteristics of surface produced by this technique depend on many factors like water pressure, Stand-off distance of nozzle from the target, Abrasive flow rate, Traverse rate, works materials. Non-contact of the tool with work piece, no heat affected zone, low machining force on the work surface and ability to machine wide range of materials has increase the use of abrasive water jet machining over other machining processes.

Many researchers have been carried out on different parameters of AWJM, Arun S, Balaji N, Kannan S [1] through their experimental studies revealed that Investigation of Metal Removal Rate and Surface Finish on Inconel 718 by abrasive Water Jet Machining and analysis of various parameters and on the basis of experimental results, analysis of variance (ANOVA) and SN Ratio the following conclusions can be drawn for effective machining of Inconel 718 by AWJM process as follows: The recommended parameter combination for optimum material removal rate is abrasive flow rate 100 g/min, transverse speed 50 mm/min and standoff distance 0.5mm; for surface roughness abrasive flow rate 200 g/min, transverse speed 40 mm/min and standoff distance 0.5mm.

K.Nagendra Prasad et.al.,[2] conducted L27 (3 levels.3 parameters) experiments to optimize machining parameters i.e., pressure, nozzle diameter and stand-off distance with abrasive jet machining of Ti 6AL-4V to increase metal removal rate and good quality of Kerf accuracy and recommend parameters to increase MRR are

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air pressure 8bar, stand-off distance 6mm, nozzle diameter 4mm and to get good quality Kerf accuracy air pressure 10 bar, stand-off distance 3mm, nozzle diameter 3mm.

Yuraj Natarajan et.al [3]., conducted experiments on D2 steel by different jet impingement angles and abrasive meshes with abrasive water jet machine and experimental data was analyzed using the simos- grey relational method and ANOVA test. The AWJ cutting performance achieved by optimal process parameters settings namely jet pressure 225 MPa, abrasive mesh size #100 and jet impingement angle 70^o by the simos-grey relational analysis.

D.V. Srikanth et.al.[4] in his research, proposed a method of optimization for machining of ceramics with abrasive jet machining with different parameters like pressure, standoff distance, abrasive flow rate, on the metal removal rate and Kerf width on ceramic tiles. It was concluded that maximum aching is achieved at optimal values of pressure 8 kg/cm^2, abrasive flow ratio (AFR) 5.5 gm/min, SOD at 20 mm.

Vishal Guptha et.al [5] revealed through his experiments conducted on marble by using abrasive water jet machining that, the ideal settings of process parameters influenced the top and bottom width of the Kerf with water pressure and nozzle transfer speed as 340 MPa and 100 mm/min respectively.

M.Santhanakumar et.al [6] in his paper focuses on studying the surface roughness, Striation zone (length to angle) and striation angle in abrasive water jet cutting of AL/SIC/AL_2O_3 composites and the process parameters are water pressure, transverse speed, abrasive flow rate and stand-off distance. The optimal parameter setting predicted by the grey theory based response surface methodology. The atomic force microscopy (AFM) images and P-profile plots were also studied to observe the texture of the cut surface.

A large number of studies were carried out on Abrasive water jet machining. Many researchers has done this abrasive water jet machining on brittle material and some material like inconel 718, 800H, D2 steel, glass/graphite/epoxy, cooper, composite materials and non ferrous metals. Some Rare researchers has done experimentation on Ti 6AL-4V alloy. K.Nagendra Prasad[2] done drilling process on Ti 6Al-4V alloy by abrasive water jet drilling and proposed optimum process parameters to improve the metal removal rate. So, now this present study is used to find out the optimum process parameters to enhance the cutting performance of abrasive water jet machining on Titanium alloy grade 5.

II. EXPERIMENTAL WORK

2.1 Materials

In this experimental investigation, the work material Titanium alloy grade 5(Ti-6Al-4V) was used. Titanium alloy grade 5 is a Alpha and beta alloys, which are meta stable and generally include some combination of both alpha and beta stabilizers, and which can be heat treated. Titanium alloys are metals that contain a mixture of titanium and other chemical elements. Such alloys have very high tensile strength and toughness (even at extreme temperatures). They are light in weight, have extraordinary corrosion resistance and the ability to withstand extreme temperatures. However, the high cost of both raw materials and processing limit their use to military applications, aircraft, spacecraft, bicycles, medical devices, jewelry, highly stressed components such as connecting rods on expensive sports cars and some premium sports equipment and consumer electronics. However, these alloys are very difficult to machine by conventional methods because of the heterogeneous property of Titanium alloy structure and may cause discontinuity in the fibre, delamination, Kerf taper angle and heat affected zone in the cutting area which directly affects the properties of the composite material. The dimension of the material is (216mm X 150mm X 4mm).The abrasive material used was garnet 80 mesh. The chemical composition of Titanium alloy grade 5 (Ti-6Al-4V) are described in table 1.

Table 1: Composition of Ti-6Al-4V

Elements	Ti	Al	V	C	Fe	O	N
Weight%	89.57	6	4	0.08	0.21	0.1	0.04

2.2 Experimental Design:

The experimental layout for the machining parameters using the L9 orthogonal array was used in this study. This array consists of three control parameters and three level, as shown in table 2. In the taguchi method, most all of the observed values are calculated based on 'the larger the better' and 'the smaller the better'. Pressure is kept constant at 3800 bar. The optimization of the observed values was determined by SN ratio which was based on the Taguchi method and Grey relational analysis. Further the optimal equations for better results are obtained and experiments are conducted to verify the optimal output. The surface finish of the material are verified with the experimental setups and the metal removal rate is calculated by using the following formulae.

$$MRR = \frac{(W_b - W_a)}{Machining\ Time \times Density\ of\ work\ piece}$$

W_b- Weight of work piece before machining

W_a- Weight of work piece after machining

Density of titanium alloy grade5-4.42 gr/cm^3

2.3 Process parameters setting

The process parameters are Abrasive flow rate, Transverse speed and Stand-off distance are varying to enhance the MRR and the surface finish during machining on Ti-6Al-

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4V with AWJM process. To observe the affect of input process parameters during the machining, three sets of experiments are conducted by considering the data listed in Table 2. In this experiment process parameter abrasive flow rate and Transverse speed are adjusted manually by control switches on control panel and stand-off distance is mentioned in NC program which consist of all cutting dimensions according to orthogonal array L9 table. NC program loaded to control panel which control all the parameters like pressure, nozzle angle, feed rate etc.

Table.2 Design structure of experiment of parameters and levels

Control parameter	Min	Inter	Max	Observed Values
Abrasive flow rate (gr/min)	300	400	500	1.Material removal rate 2. surface roughness
Transverse speed (mm/min)	450	500	550	
Stand-off distance (mm)	3	4	5	

2.4 Optimization based on Taguchi

Taguchi developed a special design of orthogonal arrays to study the entire parameter space with a small number of experiments only. The experimental results are then transformed into a signal-to-noise (S/N) ratio. It uses the S/N ratio as a measure of quality characteristics deviating from or nearing to the desired values. There are three categories of quality characteristics in the analysis of the S/N ratio, i.e. the lower the better, the higher the better, and the nominal the better. The formula used for calculating S/N ratio is given below.

Smaller the better: It is used where the smaller value is desired.

$$S/N\ Ratio\ (\eta) = -log_{10}\ \frac{1}{n}\sum_{i=1}^{n} y_i^2$$

Where y_i = observed response value and n = number of replications.

Nominal the best: It is used where the nominal or target value and variation about that value is minimum.

Where μ = mean and σ = variance.

$$S/N\ Ratio\ (\eta) = -log_{10}\ \frac{\mu^2}{\sigma^2}$$

Higher the better: It is used where the larger value is desired.

$$S/N\ Ratio\ (\eta) = -log_{10}\ \frac{1}{n}\sum_{i=1}^{n} \frac{1}{y_i^2}$$

where y_i = observed response value and n = number of replications.

Here the desirable objectives for MRR S/N ratio are considered as a higher value. and for Surface roughness S/N ratio considered as a lower value.

2.5 Experimental Procedure

A 216x150x4mm Ti-6Al-4V material is considered for machining on AWJM machine. Initially, Ti-6Al-4V material weight has been measured before placing on the table of the machine with the help of a digital weighing machine. After measuring the weight of the specimen it is clamped below the nozzle of the discharging chamber of AWJM. Before the start of the experimentation, all connections are ensured in order to avoid the leakage of the high pressure water. Once the machining is start, the required pressure of the water is maintained constantly, abrasive grains particles are then mixed thoroughly incoming water jet and subjected on to the specimen through the nozzle. Once the cutting operation commences, the metal removal rate is calculated with respect to the initial and final weight of Ti-6Al-4V material in given time interval. Surface roughness is calculated with surf test machine. Repeated number of experiments is conducted at different levels based on orthogonal array L9 by varying different process parameters (Abrasive flow rate, Transverse speed, Stand-off distance). After machining process titanium alloy work pieces shown in fig.2 are used to measure surface roughness by using SURF TEST machine shown fig.4 and tabulated the measured values.

Fig.1 Abrasive water jet machine

Fig 2. Titanium alloy cutting pieces

Fig 3.Titanium alloy work piece after machining

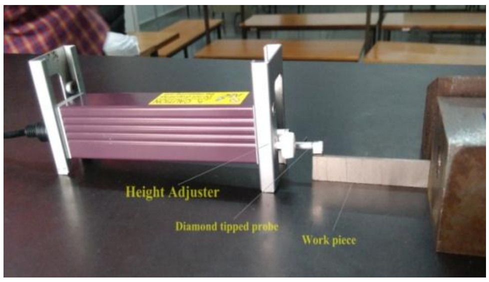

Fig 4. SURF Test Machine

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III. RESULTS AND DISCUSSIONS

The following discussion focuses on the different process parameters varying to observed values Metal Removal Rate, Surface Finish based on the Taguchi methodology. Once the series of experiments are completed, considering process parameters such as Abrasive flow rate, Transverse speed and Stand-off distance as input variables, the output characteristics such as metal removal rate, Surface roughness are recorded. The analysis of the each result obtained by Taguchi and Grey analysis. The results obtained from the experiments are discussed in table 2. The S/N ratio for the metal removal rate is considered with “Larger the Best” criteria and for surface finish “Smaller the Best” criteria is considered for optimization.

Observed process parameter characteristics during machining are extracted and noted with respect to MRR and Surface roughness are represented in table 2.

Table.2 EXPERIMENTAL RESULTS

Trails	Abrasive flow rate (g/min)	Transverse speed (mm/min)	Stand-off distance (mm)	Weight before machining (g)	Weight after machining (g)	Time taken for machine (sec)	Metal removal rate (cm^3/sec)	Surface Finish (µm)
1.	300	450	3	370	346.963	37.42	0.1392	3.9545
2.	300	500	4	346.963	324.342	30.72	0.1665	4.2815
3.	300	550	5	324.342	301.342	28.64	0.1816	4.6745
4.	400	450	4	301.342	279.564	36.40	0.1306	4.0010
5.	400	500	5	279.564	257.676	32.87	0.1506	3.4875
6.	400	550	3	257.564	236.505	25.11	0.1897	3.9390
7.	500	450	5	236.676	213.903	36.88	0.1386	4.1465
8.	500	500	3	213.903	193.361	32.99	0.1408	4.3255
9.	500	550	4	193.361	170.002	29.36	0.1801	3.9055

3.1 Taguchi analysis of metal removal rate

The analysis of response data is done by software “MINITAB 18” is used for the design of experiment applications.

Table 3. Response table for metal removal rate

Level	Abrasive flow rate	**Transverse speed**	Stand-off distance
1	-15.84	-17.32	-16.20
2	-16.19	-16.35	-16.05
3	-16.36	-14.72	-16.14
Delta	0.52	**2.61**	0.15
Rank	2	**1**	3

The following Table 3 shows the effect of each process parameter on metal removal rate by using Taguchi method and the predicted values of Signal-to-Noise Ratio(S/N). It resulted by the Taguchi method that, the highest Signal-to-Noise Ratio(S/N) value of the **Transverse speed 2.61** yield maximum MRR value. The highest value of S/N resembles as a most significant parameter among the remaining values.

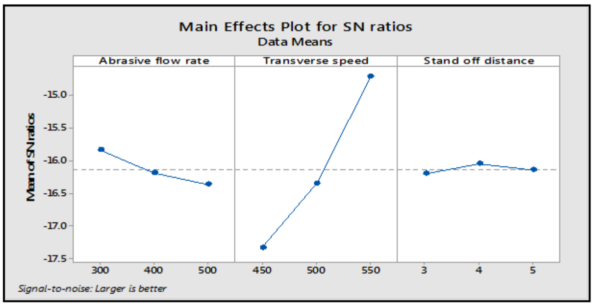

Fig 5. Effect of process parameters on MRR for S/N ratio

Figure 5 predicts the effect of process parameters on metal removal rate we determined the optimum parameters Abrasive flow rate- 300 gr/min,Transverse speed-550 mm/min,Stand-off distance- 4 mm and its effect is reflected on the maximization of MRR.

3.2 Taguchi analysis of surface roughness

Table 4. Response table for surface roughness

Level	**Abrasive flow rate**	Transverse speed	Stand-off distance
1	-12.66	-12.11	-12.19
2	-11.60	-12.07	-12.17
3	-12.30	-12.38	-12.20
Delta	**1.06**	0.31	0.03
Rank	**1**	2	3

The following Table 4 shows the effect of each process parameter on Surface roughness by using Taguchi method and the predicted values of Signal-to-Noise Ratio(S/N). It resulted by the Taguchi method that, the highest Signal-to-Noise Ratio(S/N) value of the **Abrasive flow rate 1.06** yield good Surface roughness. The highest value of S/N resembles as a most significant parameter among the remaining values.

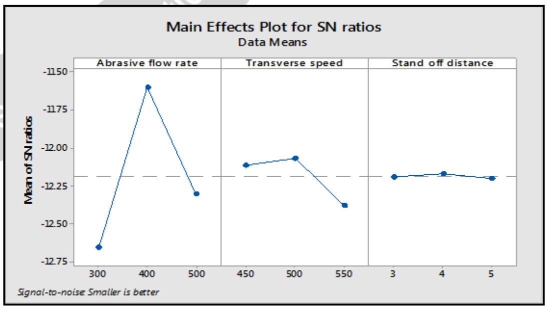

Fig 6. Effect of process parameters on Surface Roughness for S/N ratio

Figure 6 predicts the effect of process parameters on surface roughness we determined the optimum parameters Abrasive flow rate- 400 gr/min,Transverse speed-500 mm/min,Stand-off distance- 4 mm and its effect is reflected on the minimization of Surface roughness.

3.3 Grey relational analysis

In GRA, data pre-processing is required since the range and unit in one data sequence may differ from the

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others. Data pre-processing is also necessary when the sequence scatter range is too large, or when the directions of the target in the sequence are different. Data pre-processing is a process of transferring the original sequence to a comparable sequence. For this purpose, the experimental results are normalized in the range between zero and one.

The procedure is given below.

Identify the performance characteristics and process parameters to be evaluated. Determine the number of levels for the process parameters. Select the appropriate OA and assign the process parameters to the OA .Conduct the experiments based on the arrangement of the OA. Normalize the experimental results of MRR and surface roughness. Perform the grey relational generating and calculate the grey relational coefficient. Calculate the grey relational grade by averaging the grey relational coefficients. Analyze the experimental results using the grey relational grade. Select the optimal levels of process parameters.

For the "Smaller-the-better" characteristic like surface roughness, the original sequence can be normalized as follows:

$$x_i(k) = \frac{y_i(k) - \min y_i(k)}{\max y_i(k) - \min y_i(k)} \quad (3.1)$$

Where $y_i(k)$ is the original sequence,$x_i(k)$ is the sequence after data preprocessing, min $y_i(k)$ is the smallest valueof $y_i(k)$ and for the kth response, and max $y_i(k)$is the largest value of $y_i(k)$for the kth response.

For the "larger-the-better" characteristic like MRR, the original sequence can be normalized as follows:

$$x_i(k) = \frac{\max y_i(k) - y_i(k)}{\max y_i(k) - \min y_i(k)} \quad (3.2)$$

Where $y_i(k)$ is the original sequence,$x_i(k)$ is the sequence after data preprocessing, min $y_i(k)$ is the smallest valueof $y_i(k)$ and for the kth response, and max $y_i(k)$is the largest value of $y_i(k)$for the kth response.

To obtain optimal process parameters, the “smaller-the-better” quality characteristic has been used for minimizing the surface roughness and “larger-the-better” quality characteristic has been used for maximizing the MRR.

Now, Δ_{0i} (k) is the deviation sequence of the reference sequencex_0(k)and the comparability sequence x_i (k),

$$\Delta_{0i}(k) = | x_0(k) - x_i(k) | \quad (3.3)$$

After data pre-processing is carried out, a grey relational coefficient can be calculated with the pre-processed sequence. It expresses the relationship between the ideal and actual normalized experimental results. The definition of the Grey relational grade in the course of the Grey relational analysis is to reveal the degree of relation between the 9 sequences. The grey relational coefficient (ξ_i(k)) is defined as follows:

$$\xi_i(k) = \frac{\Delta_{min} + \xi\Delta_{max}}{\Delta_{0i}(k) + \xi\Delta_{max}} \quad (3.4)$$

Where $\Delta_{0i}(k)$is the deviation sequence of the reference sequencex_0(k)and the comparability sequence is x_i (k), distinguishing or identification coefficient. Considering all the parameters are given equal preference, ξ is taken as 0.5.After obtaining the grey relational coefficient, the grey relational grade is computed by averaging the grey relational coefficient corresponding to each performance characteristic. The overall evaluation of the multiple performance characteristics is based on the grey relational grade, that is:

$$\gamma_i = \frac{1}{n}\sum_{k=1}^{n} \xi_i(k) \quad (3.5)$$

Where γ_i the grey relational grade for the ith experiment and n is the number of performance characteristics. The higher grey relational grade represents that the corresponding experimental result is closer to the ideally normalized value.

Using above equation 3.1, 3.2, 3.3, 3.4 and 3.5 calculated values are tabulated below in table 3. As all the parameters are given equal preference, ξ is taken as 0.5. The grey relational coefficient for each experiment of the L9 OA can be calculated using Equation 3.4 and the grey relational grade for each experiment is calculated using Equation 3.5 and the calculated grey relational grade and its order in the optimization process is presented in Table 3.

The higher grey relational grade represents that the corresponding experimental result is closer to the ideally normalized value. Experiment 6 has the best multiple performance characteristics among nine experiments because it has the highest grey relational grade. It can be seen that in the present study, the optimization of the complicated multiple performance characteristics of AWJM of Titanium alloy grade 5 has been converted into optimization of a grey relational grade.

Table 3.Grey Relation Grade

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S.No	Grey Relatonal Grade		Grey relational grade (γ_i)	Rank
	MRR (cm³/sec)	R_a(μm)		
1	0.3691	0.5595	0.4643	6
2	0.5601	0.4277	0.4939	5
3	0.7848	0.3333	0.5590	4
4	0.3333	0.5360	0.4346	7
5	0.4304	1	0.7152	2
6	1	0.5679	0.7839	1
7	0.3663	0.4738	0.4200	8
8	0.3766	0.4145	0.3955	9
9	0.7547	0.5867	0.6707	3

Table 4.Response table for means of grey relational grade

Symbol	Process Parameters	Grey Relatonal Grade			Main Effect (max – min)	Rank
		LEVEL 1	LEVEL 2	LEVEL 3		
A	Abrasive flow rate	0.5057	0.6445*	0.4954	0.1491	2
B	Transverse speed	0.4396	0.5348	0.6712*	0.2316	1
C	Stand-off distance	0.5479	0.5330	0.5647*	0.0317	3
Total mean value of the grey relational grade γ_m =0.5485 * Levels for optimum grey relational grade						

Since the experimental design is orthogonal, it is then possible to separate out the effect of each machining parameter on the grey relational grade at different levels. For example, the mean of the grey relational grade for the Abrasive flow rate at levels 1, 2 and 3 can be calculated by averaging the grey relational grade for the experiments 1 to 3, 4 to 6 and 7 to 9 respectively as shown in table 4.

The mean of the grey relational grade for each level of the process parameters, namely, Abrasive flow rate, Transverse speed, Stand-off distance can be computed in the same manner. The mean of the grey relational grade for each level of the machining parameters is summarized and shown in Table 4. In addition, the total mean of the grey relational grade for the nine experiments is also calculated and shown in Table 4.

Therefore, the optimal parameters setting for less surface roughness and high MRR are **(A2B3C3)** as presented in Table 4. Optimal level of the process parameters is the level with the highest grey relational grade.

IV.CONCLUSIONS

This paper presents the optimization of process parameters namely, abrasive flow rate, Transverse speed and Stand-off distance in cutting of Titanium alloy grade 5 on abrasive water jet machining. The machining process is carried out using L9 orthogonal array and the optimization of process parameters is done by using Taguchi Technique and Grey Analysis. Optimization is done to determine better parameters to obtain maximum material removal rates and lesser surface roughness values. By Taguchi analysis the optimum parameter combination to achieve high metal removal rate(MRR) are Abrasive flow rate 300gr/min, Transverse speed 550mm/min, Stand-distance 4mm and after confirmation test is done by using above combination parameters the optimum response value of MRR is 0.2152 Cm^3/sec and optimum parameter combination to achieve better surfacefinish(R_a)are abrasive flow rate 400gr/min, Transverse speed 500mm/min and Stand-off distance 4mm and after confirmation test is done by using optimum parametric combination the optimum response value of surface finish is 2.985μm. Transverse speed is the most influence parameter on MRR and Abrasive flow rate is the most influence parameter on surface finish. Multi response optimization of process parameters are obtained by Grey relational analysis. According to response table for the means of grey relational grade the optimum parameter combination to achieve both high MRR and better surface finish are abrasive flow rate 400gr/min, Transverse speed 550mm/min and Stand-off distance 5mm and after the confirmation test the optimum response value of MRR is 0.2050 Cm^3/sec and optimum response value of surface finish is 3.065μm. From grey relational analysis, it is revealed that the Transverse speed is the most significant process parameter followed by Abrasive flow rate and Stand-off distance which affects the Abrasive water jet machine process when performed on Titanium alloy grade 5.

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