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Investigation on Influence of Coolant Strategy on the Surface Roughness During Milling of Ti-6Al-4V Alloy Plate

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Abstract.Ti-6Al-4V (Ti grade 5) alloy finds salient applications in aerospace and automotive industries. But milling of thin Ti-6Al-4V plates is a challenging process due to its high strength and low thermal conductivity. In the present work, Ti-6Al-4V plates have been end milled using two distinct coolants—soluble oil based and Servo Cut and the corresponding surface roughness values have been compared.Titanium plates were milled using a coated carbide tool. The milling parameters such as cutting speed, feed rate, and depth of cut were kept same for both coolant types to ensure a fair comparison. After the milling process, the surface roughness values of the specimens were measured and the results were analysed and compared using two-way Latin Square Design. Also, the specimen flatness was evaluated before and after milling process using an appropriate method. The influence of the coolant on the flatness of the titanium thin plates was studied. The flatness analysis gives idea about the modifications or deformations brought on by the milling process, while the surface roughness data will aid in assessing the quality of the milled surfaces.
Keywords: Milling, Thin plate titanium alloy (Ti-6Al-4V), Surface roughness test, soluble oil, servo cut.

Introduction

Titanium is a transition metal with a very high melting point, making it ideal for high-temperature applications. In the natural world, titanium is a mineral that is frequently found in rocks and soils. Due to its combination of strength, lightweight, and corrosion resistance, it finds wide range of applications in aeronautical, medical, and automotive sectors. Titanium is considered a unique material, due to its superior mechanical and thermal properties, high value of strength-to weight ratio and the possibility to be utilized in harsh environments, e.g., environments with pollutants, corrosive environments, or when high temperatures are involved, with a substantially extended lifespan than that of other common materials. Titanium machining is still considered as one of the formidable challenges in manufacturing field.

A Pramanik [1] in his work has highlighted the problems of machining titanium. Challenges like variation of chip thickness, high pressure loads, springback and residual stress were reflected upon. The resulting higher tool wear, reduced machined surface integrity and decreased machinability were also discussed. To address these problems adoption of various coolant material and its delivery, thermal enhanced machining, cutting tool material and its fixture were possibly suggested. C Veiga et al. [2] has attributed the challenges in Titanium cutting to low thermal conductivity and elastic modulus, high hot hardness and high chemical reactivity. Cutting forces, chip formation and cutting temperature evolved when turning Ti-6Al-4V alloy have been explained. Using statistical and soft computing methods, N.E. Karkalos and N.I. Galanis [3] explored the surface roughness behaviour while milling Ti-6Al-4V alloy and observed that the feed rate is the predominant factor in influencing the surface roughness. D.Ulutan and T Ozel [4] have provided an overview of machining induced surface integrity in titanium and nickel alloys. Residual stresses, white etch layer and work hardening layers and microstructural alterations were studied and the various influencing parameters like cutting speed, feed rate, depth of cut, tool material were used to investigate the surface integrity of machined workpiece. Both finite element based approach and experimental approach were used to study machining induced surface integrity. In the paper [5]chip morphologies and material properties of the Ti-6Al-4V thin plate were investigated under different cutting parameters. Characteristics of multi-surface chips were observed under scanning electron microscope. Variations in the chip micro hardness and mill cutter wear were investigated under various machining parameters. Micro hardness increases with increase in cutting speed. Also, key challenges in high speed milling of thin Ti-6Al-4V plates were identified. J.Sun, Y.B.Guo [6] in their paper stated that surface integrity of milled titanium parts easily deteriorate due to poor machinability and cyclic chip loading. It is understood that machined surface roughness depends on cutting speed, tool wear, feed, tool materials and geometry. In the study conducted, a series of end milling trials were carried out to characterise the surface integrity at various milling conditions. Results obtained show roughness values from 0.6 to 1.0μm. Surface roughness values increase with feed and radial depth-of-cut (DOC), but shows less variation in the cutting speed range. C.Bandapalli et.al [7] carried out tool wear investigation of uncoated and PVD coated Al-Ti-N, Ti-Al-N tungsten carbide end mills in high speed micro end milling of Titanium grade 12 alloy(Ti-0.3Mo-0.8Ni) under dry cutting conditions. Upon EDX analysis, diffusion, oxidation, adhesive and abrasive wear mechanisms were major phenomena taking place on the cutting edge of micro end mills. Also, uncoated tools performed better than AlTiN and TiAlN tungsten carbide tools. MZA Yazid and M Razak [8] have highlighted the effect of tool path strategies and pocket geometry on surface roughness in pocket milling process. Work piece taken was mould steel DF2 and cutting tool used was carbide insert end mill. Tool material, tool path strategies and pocket geometries were varied at three levels each while the cutting parameters were kept constant. Effectiveness of different tool path strategies and different pocket geometries were evaluated in terms of measured surface roughness(Ra) of the work piece. Lowest surface roughness measurement was recorded with parallel spiral cutting tool path strategy. Xian Wu et.al [9] in their work have established a theoretical surface roughness model when micro milling was carried out. Milled roughness mainly depends on the feed per tooth, tool nose radius and bottom edge inclination angle. PCD micro end mills were used. The difference in surface roughness results is induced by unstable cutting behaviour of Titanium alloy.

The effects of coolant flow rate on tool life and wear development during cryogenic and wet milling of Ti-6Al-4V were examined by M. Ibrahim Sadik and Simon Isakson [10] and conclusions drawnwere that higher tool life was achieved with increased flow rates of coolant. Muhammad Jamil et.al [11] in their article have suggested the usage of hybrid lubri-coolants as an alternative to high cost and poor lubricity cryogenics in order to reduce the temperature efficiently. Cutting temperatures were observed at various cutting speeds under hybrid lubri-coolants and compared with cutting temperatures obtained from FEM simulation software. An error of 6.5% was estimated. Nouari and Ginting [12] investigated the performance of alloyed carbide tools during dry machining of Ti-6242S which is used in aero engines. Uncoated carbide tool and multi-layered CVD coated tool were used. Tool failure modes and wear mechanisms were examined at various cutting conditions. Localised flank wear (major face) was dominant for both tool materials. Adhesion and diffusion wear mechanism were clearly evident.

The main objective of this work is to investigate the influence of different coolants such as soluble oil and servo cut during milling of Ti-6Al-4V alloy plate the study the influence of surface roughness and flatness over the machined surfaces.

Materials and methodology

Materials:

The chemical composition of the specimen satisfies the ISO code 5832-3:2021 &thickness of the specimen taken is in reference to the ISO 7209:2023. The chemical composition of the specimen is as shown in Table 1. As per the recommendation, CVD coated carbide with coating of TiAlN is selected as the tool due to better workpiece surface finish, increased lubricity, resistance to thermal shock etc.

Table 1: The chemical composition of the specimen

Ti	Si	Sn	Fe	Cr	Mo	V	Al
88.800	0.010	0.160	0.290	0.008	0.028	4.000	6.660

The work piece material is a thin plate of Ti-6Al-4V alloy of 200mm×150mm with a height of 5 mm. The tool specification is as shown in the Table 2.

Table 2: Cutting tool specification.

Material of tool	Tungsten carbide
Coated materials	Ti-Al-N
Flute number	4
Tool length	72 mm
Flute length	22 mm
Tool diameter	10 mm

The major benefits of TiAlN coating are improved hardness and resistance, higher cutting speeds, better surface finish, increased lubricity and resistance to thermal shock. Two Coolants employed are soluble oil (soluble oil + distilled water) & servo cut C-945. Coolants are selected based on the market cost, availability and suggestions sought from industrial experts. For the fixture, a mild steel block (215×185×75mm) has been selected and tapped for the thread to fix the thin plate with bolt (M12×20) at the top of the block to avoid the vibration & noise during the end mill. Figure 1 shows the fixture for mounting the Titanium alloy work piece.

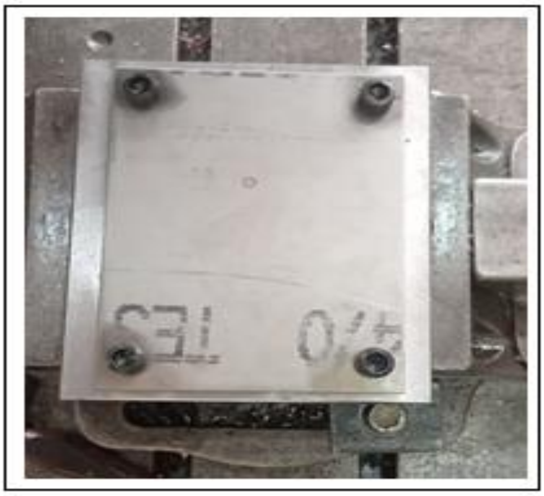


Figure 1: Fixture designed for mounting the work piece]

Methodology

The methodology is shown in the flow chart (Figure 2). The entire work piece was divided into 6 regions (floors) and the milling operation was performed on the specimen to measure surface roughness with two different coolants namely soluble oil and servo cut C 945. The deviation at each 6 floors at 9 different points were checked using the Microlite height gauge. The main aim of the experiment is evaluating the surface roughness and deviations using two different coolants. Surface roughness parameters (R_a)were measured on the milled regions. Along with surface roughness the surface flatness was also measured for both before and after milling using CMM (Coordinate Measuring Machine).

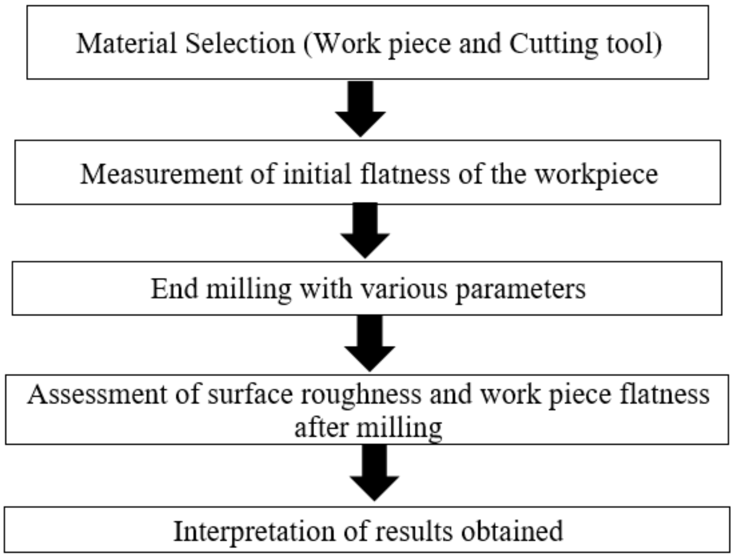


Figure 2: Methodology

Fluctuations in depth (after milling) is measured using the Microlite height gauge 900.The experimental procedure involves checking depth at 9 points on the particular milled floor using two different coolants such as soluble oil and servo cut C945 & compared the deviation valuesfound while adopting soluble oil and servo cut C945. Cutting parameters such as speed of 40 mm/min, feed of 0.05 mm/ tooth and depth of cut of 1 mm were employed. Table 3 shows the cutting parameters used for the experimentation.

Table 3: Cutting parameters used for machining

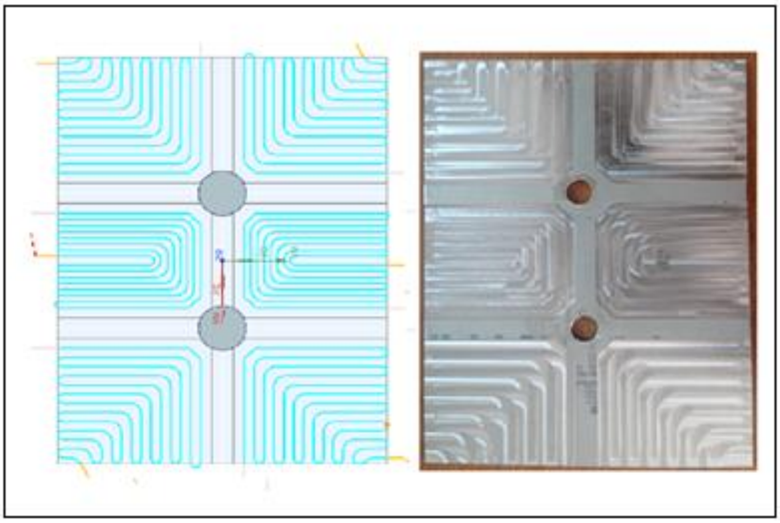
Parameters/Level	1	2	3
Cutting Speed (m/min)	30	40	50
Feed (mm/tooth)	0.025	0.050	0.075

Result and discussion

Surface roughness tests:

In experiments conducted, the influence of the cutting conditionson the surface quality of the workpiece was observed. Surface roughness is measured using Mitutoyo Surface Roughness Tester Surf test SJ-310. Figure 2 (a) shows the planned tool path and Figure 2 (b) shows the machined specimen used to measure surface roughness. The measured surface roughness value which are milled using the coolant soluble oil is given in the Table 4.It shows that increasing cutting speed and reducing the feed lead to the reducing the value of the surface roughness or vice-versa(i.e., It shows that at feed 0.025 mm/tooth surface roughness value is less as compared to the other feed such as 0.05 mm/tooth and 0.075 mm/tooth). Initially 1^{st} plate is milled using the soluble oil whereas the 2^{nd} plate is milled using the servo cut C-945. Table 5 (ANOVA table) shows that when soluble oil is used the feed is the main factor which impacts the surface roughness value.

In the case of the servo cut C945, speed and feed both have significant impact on the surface roughness. Table 6 and Table 7 show the surface roughness value and ANOVA values for the Servo cut C945 respectively. Figure 3 (a) shows the Boxplot graph for the Ra vs feed vs speed using soluble oil whereas, Figure 3 (b) shows the Boxplot graph for the Ra vs feed vs speed using servo cut C945.



(a) (b)

Figure 2: (a) Tool path; and (b) Machined specimen used to measure surface roughness

Table 4: Surface roughness value using the soluble oil

Sl no	Cutting speed Vc (mm/min)	Feed (mm/tooth)	Ra (µm) Trail 1	Ra (µm) Trail 2	Ra (µm) Trail 3
1	30	0.025	0.227	0.217	0.258
2	30	0.05	0.281	0.303	0.313
3	30	0.075	0.705	0.601	0.513
4	40	0.025	0.260	0.249	0.204
5	40	0.05	0.321	0.303	0.390
6	40	0.075	0.736	0.709	0.830
7	50	0.025	0.214	0.262	0.264
8	50	0.05	0.494	0.703	0.810
9	50	0.075	0.414	0.501	0.485

Table 5: ANOVA table for surface roughness value using the soluble oil

Source of variables	Df	Sum of Square	Mean Square	F-value	P-value
Speed	2	0.03309	0.016547	0.7791	0.4722586
Feed	2	0.62003	0.310016	14.5968	0.0001234
Replicate	2	0.00958	0.004789	0.2255	0.8001324
Error	20	0.42477	0.021239		
Total	26	1.08747			

Table 6: Surface roughness values using Servo cut C945

Sl No	Cutting speed Vc (mm/min)	Feed (mm/tooth)	Ra (µm) Trail 1	Ra (µm) Trail 2	Ra (µm) Trail 3
1	30	0.025	0.213	0.340	0.213

2	30	0.05	0.543	0.521	0.681
3	30	0.075	0.408	0.380	0.529
4	40	0.025	0.190	0.194	0.151
5	40	0.05	0.188	0.275	0.154
6	40	0.075	0.433	0.353	0.214
7	50	0.025	0.164	0.112	0.190
8	50	0.05	0.431	0.443	0.468
9	50	0.075	0.466	0.538	0.468

Table 7: ANOVA table for surface roughness value using the servo cut C945

Source of variables	Df	Sum of Square	Mean Square	F-value	P-value
Speed	2	0.162284	0.081142	8.5967	0.002021
Feed	2	0.290655	0.145327	15.3969	8.957e-05
Replicate	2	0.000858	0.000429	0.0455	0.955661
Error	20	0.188774	0.009439		
Total	26	0.642571			

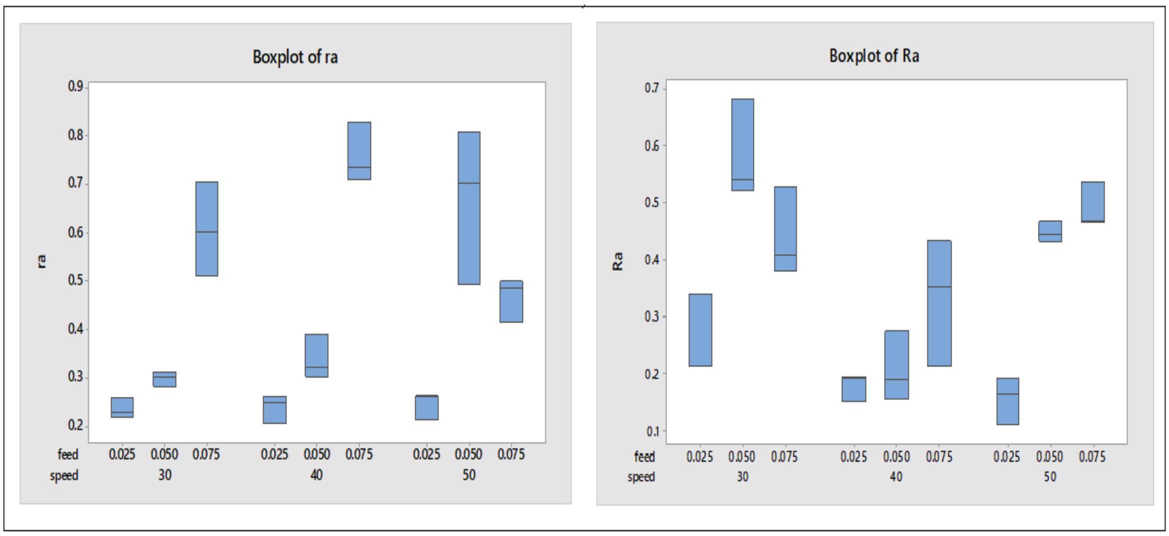


Figure 3: (a) Boxplot between R_a vs feed vs speed using soluble oil; (b) R_a vs feed vs speed using servo cut C945

Flatness assessment

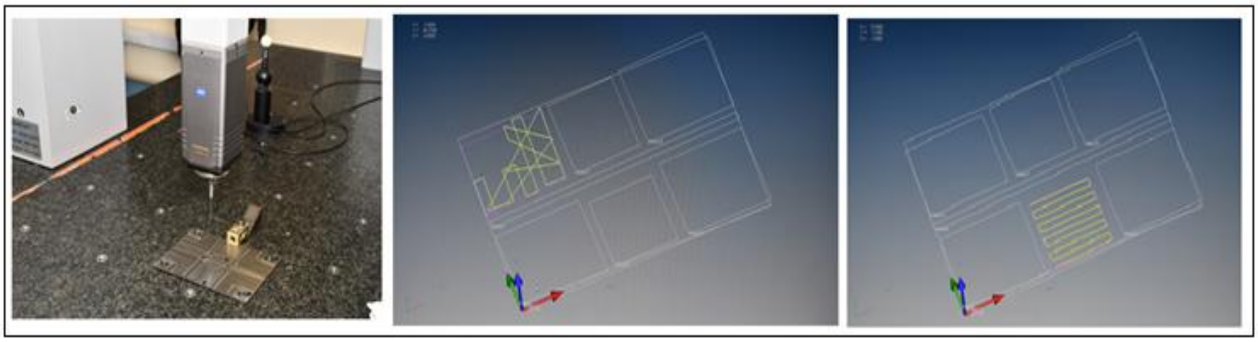
Surface flatness is a geometric feature that describes how far a surface deviates from a perfect plane. Flatness is commonly defined as the largest permitted departure from the reference plane, which is sometimes given as a precise tolerance value or a range of values.In this experiment flatness of each 6 floor are measured using CMM

(Zeiss Contura C32 bit). Before machining initial flatness value of the Ti-6Al-4V alloy plate was 38.50 microns on the overall specimen withthe dimension of specimen 200×150×5mm. Six floors are milled with different cutting parameters using servo cut C945 and soluble oil. Flatness measurement was carried out using polyline strategy.

Figure 4 (a) shows that experimental setup and (b) & (c) show that polyline strategy for the corner floor and for the middle floor. Table 8 shows the flatness of specimen after milling floor with 6 different cutting parameters, where V_c is cutting parameter in m/min.

Table 8:Flatness of specimen after milling floor with 6 different cutting parameters

Sl. No	Cutting parameters	Flatness (micron)
1	Vc=30 Feed =0.025	85.4 using servo cut
2	Vc=40 Feed=0.075	66.67 using soluble oil
3	Vc=30 Feed=0.05	57.3 using servo cut
4	Vc=40 Feed= 0.025	51.3 using servo cut
5	Vc=50 Feed=0.075	64.6 using soluble oil
6	Vc=50 Feed=0.05	39.8 using servo cut



(a) (b) (c)

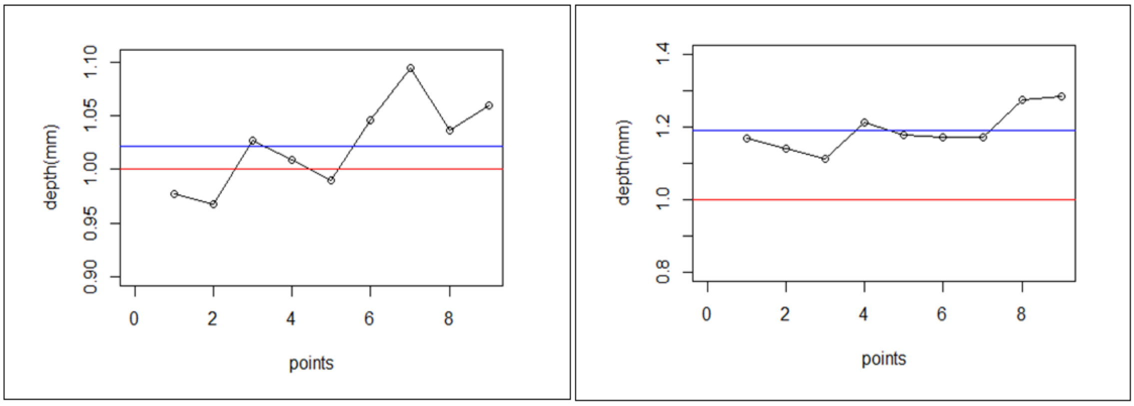
Figure 4: (a) Experimental setup to find out flatness; (b) Polyline strategy for floor at the corner; and (c) Polyline strategy for floor at the at the middle

It is clearly seen thatthecoolant used during machining processes can have an impact on the flatness of a thin plate and also the impact of coolant on flatness may vary depending on the specific machining process, material properties, plate thickness, and other factors. When machining a thin plate, such as through milling or grinding, heat is generated due to the friction between the cutting tool and the workpiece. Coolant is often applied to dissipate this heat and prevent damage to the tool or workpiece. The choice of coolant and its application can affect the thermal characteristics of the machining process, which in turn can impact the flatness of the thin plate. When compared to servo cut C945, soluble oil gives more cooling effect due to this the flatness value is consistent.

Geometrical deviation

Geometrical deviations, also known as geometric variations or dimensional variations, refer to the differences or discrepancies that can occur in the shape, size, or orientation of manufactured parts or components compared to their intended design specifications. These variations can occur due to a variety of factors, including manufacturing processes, material properties, toolinglimitations, and environmental conditions.

The properties of the coolant can affect the overall machining performance and the quality of the milled region.By selecting the appropriate coolant and ensuring its proper application, including flow rate, concentration, and cooling strategy, the deviations in the milled region can be minimized, leading to improved machining accuracy and surface quality.In Figure 5, the graph with red line indicates the actual depth to be achieved and blue line indicates the average of the overall points. Figure 5 (a) shows a deviation of 30 microns during machining with soluble oil as coolant whereas with servo cut C945 oil it is observed a deviation of 200 microns as shown in Figure 5 (b). From the graph it is clearly observed that deviation of depths on floor is more in the servo cut C945 when compared to the soluble oil due to the increased cooling effect of soluble oil.



(a) (b)

Figure 5: Deviation of depth on 9 points on which floor milled using (a) soluble oil as a coolant & (b) servo cut C945 oil as a coolant.

Conclusion

Titanium alloy exhibits the low thermal conductivity when compared to other materials. This property has made the titanium one of the tough material to machine. The thermal conductivity aspects can be controlled by using appropriate coolant strategy during machining. The present study revealed the influence of different coolants such as servo cut and soluble oil on the milling of Titanium alloy. The deviation of the work piece was controlled by the usage of soluble oil and not much deviation was observed for different cutting speed. When using servo cut oil the deviation was comparatively high. Adopting a proper coolant strategy, the surface level deviations can be minimized. The deviations observed on the surface after milling has been induced due to the elastic recovery tendencies of Titanium grade-5 (Ti-6Al-4V) alloy plates or thin-sections.

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