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Predicting the Tensile Strength of Metal Matrix Composites Joined by Friction Stir Welding and Optimization of Parameters using Firefly Algorithm

C.Devanathan*, A.Suresh Babu**, R.Giri*** and A.Azad**

Keywords： Friction Stir Welding, AlCrN Coated tools, Fire fly Algorithm, parameter optimization, Metal Matrix Composites.

ABSTRACT

Friction stir welding is a novel green welding technique developed primarily to weld lightweight materials like aluminum alloys, now extended to variety of materials including steels and metal matrix composites. In the present work, an attempt was made to join Metal Matrix Composites of Al 5083 reinforced with B4C particles using AlCrN Coated tool with square pin profile in order to observe the tensile strength of the welded joint. Joints were prepared by changing the spindle speed, tool traverse feed and axial force in three different levels based on Box Behnken method. A mathematical model for tensile strength of the joints was developed in terms of process parameters. To ensure the adequacy of the developed mathematical model ANOVA technique was used and results showed that, model was adequate to 95% confidence level. The effect of process parameters on Tensile strength of welded composites has been analyzed in detail. In order to find the optimized process parameters the newly developed metaheuristic algorithm firefly was applied and obtained the best results of 152.72MPa for the parameters of spindle speed 1500 rpm, tool traverse feed 20 mm/min, and axial force 6 kN. To understand the behavior of the welded specimen Macrostructure and microstructural analysis was carried out. Condition of the tool after welding was discussed briefly with SEM analysis.

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* *Assistant Professor, Department of Mechanical Engineering, Rajalakshmi Engineering College, Chennai, Tamil Nadu, India.*

** *Associate Professor, Department of Manufacturing Engineering, Anna University, Chennai, Tamil Nadu, India.*

***. *Associate Professor, Department of Mechatronics Engineering, Rajalakshmi Engineering College, Chennai, Tamil Nadu, India.*

INTRODUCTION

Metal Matrix composites have recently received a great attention in aerospace, automobile and other industrial fields because of its high strength to weight ratio and high specific stiffness. Dinaharan.I et al. (2012) stated in his work the use of Metal Matrix Composites for the industrial application is limited due to the problems encountered when they are joined by gas shield metal arc welding, laser welding, gas tungsten arc welding, and electron beam welding. During welding matrix material reacts with added reinforcement which leads to the formation of objectionable phase which outcome with strength depleted zone along the weld line.

Tracie prater (2014), a novel autogenous process has captured the attention of the fabrication industries and research organizations. The process was invented and patented by W. Thomas of The Welding Institute (TWI) in 1991, named as friction stir welding. The process can be successfully pioneered by NASA as a replacement technique for Variable Polarity Plasma Arc (VPPA) welding technique on its super lightweight external tank. Later the technique was adopted by Boeing, united launch, lockhead in their respective lunch vehicle.

The process uses the rotating tool which is designed with shoulder of larger diameter and specially shaped probe. The tool is plunged between the adjoining faces of the joint, till the bottom of the shoulder contacts the top surface of the workpiece and provides frictional heat to soften the workpiece material. Though the workpiece does heat up during friction stir welding, the temperature does not reach the melting point of the workpiece. The basic Principle of the FSW process is shown in the Fig .1. Elongovan et al. (2009) analyzed the effect of Friction Stir Welding process parameters on tensile strength in joining of Al 6061 aluminium alloy and submitted the results that ultimate tensile strength improved with increasing the spindle speed, axial force, and welding speed and reaches the highest.

Any more increase in these parameters decreased the tensile strength of the welded joint. These results almost agree with the results of Palanivel.et.al (2011).

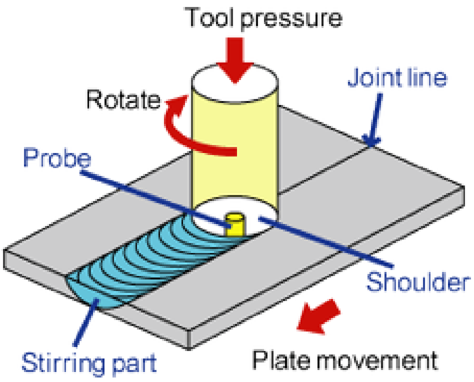

Fig.1. Basic Principle of FSW Process

Eun-Yeong Ahn et al. (2017) investigated the joining of two dissimilar automotive structural aluminium alloys based on their position about tool travel direction and concluded that tensile test results and electron backscatter diffraction results were affected by orientation of the plates. Palanivel et.al (2016) used Artificial Neural Network (ANN) practice to forecast the durability of the dissimilar joints of aluminum, concluded that the developed model were capable of predicting values with less than 5% error and the results were sensitive to pin profile, rotational speed, welding speed, and axial force. Sanjay Kumar et.al (2015) had made an effort to optimize the process parameters using gray relational analysis, and concluded that tool rotational speed was the most substantial parameter with contribution of 96.24%. Shashi Prakash dwivedi (2014) carried an examination on Friction stir welding of A356 / C 355 aluminium alloys and studied the process parameters effect on tensile strength and results publicized that tool rotational speed and welding speed had directly proportionate relation with tensile strength, axial force had inverse relation. Mohamed Ackier Mohamed et al. (2015) taken 6mm thick 6061 T651 aluminium alloy and applied multi objective Taguchi method to determine the ideal welding parameters. His results confirmed that the tool traverse speed plays a key role in deciding the good mechanical properties, and the developed model has been found to be well fitted.

Many researchers (A.Govind reddy et al 2013; M.Balasubramanian et al 2008) used Response Surface Methodology to develop a mathematical model for tensile strength of the joints in terms of welding parameters.

In the present investigation an attempt was made to develop a mathematical model for tensile strength in terms of process parameters considered. The competence of the model was tested using ANOVA and the effect of each process parameter on output response was also analyzed. At the end of the investigation tool condition after welding was discussed with SEM analysis.

EXPERIMENTAL PROCEDURE

Fabrication of Metal Matrix composites

The Aluminium alloy Al 5083 was melted in an electrical furnace using a crucible. The chemical Composition of Al 5083 is presented in the Table 1. The weighted quantities of B4C particles were added in to the molten metal aluminium to produce the metal matrix composite. The melt was stirred by stirrer coupled with electric motor to assist the uniform distribution of particles in the molten metal which is shown in the Fig.2. The temperature of the melt was maintained at 8500℃ and molten metal was poured into a preheated die to produce the MMC Castings which is given in Fig.3.

Visual inspection is carried out to find out the presence of surface defects. Plates of size 100mm x 50mm x 6mm are prepared from cast Aluminium matrix composite blocks using Wire EDM Process to carry out the weld trail. The composites blocks prepared and Wire EDM cut Composites are shown in the Fig 4 and Fig. 5 respectively.

Table 1. Chemical Composition of Al 5083

Chemical composition	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al
Al 5083	0.4	0.4	0.1	0.44	4.1	0.22	0.1	0.1	Bal

Fig .2. Stirring of Molten motel

Fig.3. Pouring of melt into die

Fig. 4. Composites Blocks

Fig.5. Wire EDM Cut Composites

Fabrication of FSW tool

Friction Stir Welding Tool is most decisive one for the successes of the process. D3 tool steel was chosen as the material to prepare the tool. From the literature, it was clear that square pin profile have been giving better performance. Keeping that in consideration the tool was designed with square pin profile of side 4mm and length of 5.7mm, shoulder of 19.5mm diameter which is shown in the Fig.6. Tool wear is the most important issue when it is used for welding Metal Matrix Composites. During welding tool material worn out as a consequence of contact with hard reinforcing particles. In the present investigation to combat the wear, the tool was coated with AlCrN of 4 microns thickness.

Fig.6. FSW tool with Square pin profile

Selection of Process Parameters

There are a number of welding parameters taking control over the final weld quality. From the literature, it was found that the FSW process parameters, to be precise spindle speed, traverse feed, Profile of the tool pin and plunge force (axial force) extensively plays a major role in deciding the quality of the weld. In the present investigation joints were prepared by changing spindle speed, traverse feed, and axial force in three different levels. Parameters and their levels are shown in the table 2.

Table 2. Welding Parameters and their levels

S. No	Welding Parameter	Symbol	Unit	Level 1	Level 2	Level 3
1	Spindle speed	A	Rpm	1200	1500	1800
2	Traverse feed	B	mm/min	20	40	60
3	Axial force	C	kN	6	7	8

Development of Design Matrix

The selection of appropriate design matrix will depends on number of factors and their levels. Box Behnken design is having the maximum efficiency for an experiment involving three factors and three levels and also the number of experiments required to conduct based on this design is much lesser compared to a central composites design. The design matrix considered along with the tested results is shown in the Table 3.

Table 3. Design Matrix with Output Response

Trail No	FSW Process Parameters			Output Response
	Spindle Speed "N" (rpm)	Welding Speed "S" (mm/min)	Axial Force "F" (kN)	Ultimate Tensile Strength (MPa)
1	1200	20	7	148.65
2	1800	20	7	151.27
3	1200	60	7	150.67
4	1800	60	7	149.29
5	1200	40	6	148.54
6	1800	40	6	151.81
7	1200	40	8	149.72
8	1800	40	8	148.64
9	1500	20	6	150.26
10	1500	60	6	152.65
11	1500	20	8	151.54
12	1500	60	8	149.75
13	1500	40	7	151.77
14	1500	40	7	150.46
15	1500	40	7	150.86

Conducting the Experiments as per the design Matrix

The plates were butt friction stir welded using a CNC Friction Stir Welding Machine as per the experimental plan based on Box Behnken method.

The sample welded specimens are shown in the Fig.7.

Fig. 7. Sample Welded Specimens

RESULTS AND DISCUSSION

Tensile test specimens were prepared as per the ASTM E-8 standard in order to assess the tensile strength of the welded specimen which is shown in the Fig 8. Three specimens were prepared and tested from each sample welded.

Fig.8. Tensile specimens

Developing the Mathematical Model

Ultimate Tensile Strength (UTS) is the function of Tool rotational speed, welding speed, and axial force and it can be expressed as,

$$Y = fn\,(A, B, C) \qquad (1)$$

Where

Y = The Output Response
A = Tool Rotational Speed, rpm
B =Welding Speed, mm/min
C =Axial Force, KN.

The details regarding Response Surface Methodology, experimental design and method of acquiring the regression model are not discussed at this point, but can be found in Raymond.H.Myers [11]. In the present investigation, the values of the coefficients were determined using the commercial statistical package DESIGN EXPERT 11.0 software package.

After determining the coefficients, the mathematical model developed for determining the tensile strength of the welded specimens is presented in the Eq. 2.

$$UTS = 151.03 + (0.4287A) + (0.080\ B) - (0.4513C) - (1.000AB) - (1.09AC) - (1.05BC) - (1.22A^2) + (0.1563\ B^2) - (\ 0.1363C^2) \qquad (2)$$

Inspecting the correctness of the Developed Model

The competence of the developed model is reviewed by means of Analysis of Variance (ANOVA). The consolidated results of ANOVA are presented in the Table 4. The Fisher's test, F value of 11.39 implies that the developed model is significant. From the ANOVA results it was observed that spindle speed and axial force were important model terms.

Table 4. ANOVA Test results

UTS	Output Response	
21.96	Regression	Sum of Squares
1.07	Residual	
2.44	Regression	Mean Squares
0.2141	Residual	
9	Regression	Degrees of Freedom
5	Residual	
11.39	F – Ratio	
0.9535	R2 Value	
0.8698	Adjusted R2	
Significant	Remarks	

The coefficient of determination (R2) and adjusted value of R2 for the above model are 95% and 86% respectively. These values indicate that the regression model is quite adequate. Another measure that is commonly used to demonstrate the adequacy of the regression model is adequate precision which is a measure of Signal to Noise ratio. Normally for any model a ratio greater than 4 is desirable. The Model developed is having adequate precision value of 11.02 which indicates that the model developed was more adequate.

The scatter diagram of the ultimate tensile strength for the model is presented in the Fig.9, in which the observed values and predicted values of the response are scattered close to the 450 line, indicating an almost perfect fit of the developed empirical model.

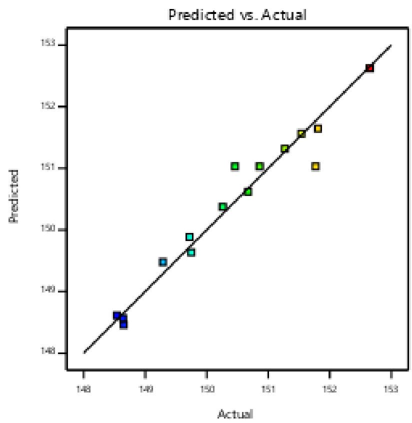

Fig. 9. Scatter diagram of Ultimate tensile strength

EFFECT OF PROCESS PARAMETERS

Effect of Spindle Speed

The Fig.10 shows the effect of tool rotational speed on ultimate tensile strength of the welded joint. From the figure it is apparent that maximum tensile strength was attained at the tool rotational speed of 1800 rpm. At lower rotational speed the tensile strength of the joint was poor

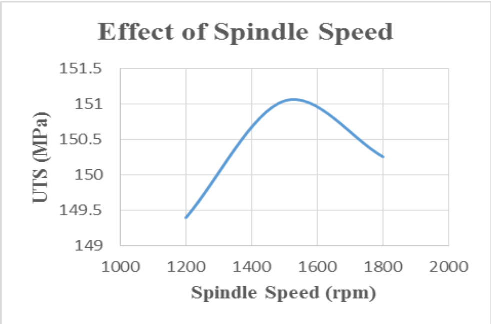

Fig. 10. Effect of Spindle Speed

From the literature study it was observed that, there is threshold limits beyond which any further increase in spindle speed may produce an unnecessary release of stirred material on the top surface, which resulted in diminish of tensile strength.

Effect of Welding Speed

The effect of Welding speed on ultimate tensile strength is presented in Fig. 11. At lower welding speed of 20mm/min, the UTS of the FSW joint were low. Increasing the welding speed to 40 mm/min, increases the UTS of the welded joint. Further increase in welding speed, reduces the strength of the joint.

At higher welding speed, the frictional heat input to the work piece material was low which creates the poor plastic flow of the metal which causes few defects in the weld zone.

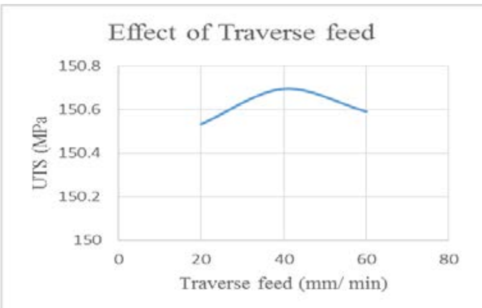

Fig. 11. Effect of Traverse feed

Therefore poor tensile strength was obtained. When the welding speed is lower than specific value it can produce the joints with improved tensile strength.

Effect of Axial Force

Axial load is more responsible for the plunge depth of the tool pin into the workpiece. At the load of 6KN the tensile strength attained was maximum. The strength of the composite joint was decreased with increasing the axial load due to the expel of materials from the weld region and insufficient coalescence of the transferred material. The effect of axial force on output response is shown in the Fig. 12.

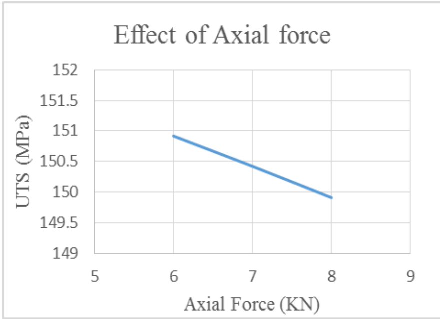

Fig. 12. Effect of Axial Force

Firefly Optimization

Xin –She Yang (2013) proposed algorithm of metaheuristic type inspired by flashing behavior of fireflies proposed in late 2007 at Cambridge university. Based on the available literature it was found that, Firefly algorithm was mostly applied by researchers to resolve the optimization related problems in almost all areas and especially in engineering domain and in most of the cases FA technique has outperformed when compared to other metaheuristic algorithm.

Azlan Mohd Zain et al. (2013) stated that fireflies are feathered beetles that produce light and flashing at night. This algorithm follows the three basic assumptions.

The Assumptions are as follows,

1. Fireflies will be attracted each other and they are unisex.
2. Brightness plays a major role because attractiveness is directly proportional to brightness.
3. When their brightness is same they move randomly.

Firefly Algorithm

Objective function $f(\boldsymbol{x})$, $\boldsymbol{x} = (x_1, ..., x_d)^T$
Generate initial population of fireflies $\boldsymbol{x}_i$ $(i = 1, 2, ..., n)$
Light intensity I_i *at* $\boldsymbol{x}_i$ *is determined by* $f(\boldsymbol{x}_i)$
Define light absorption coefficient γ
while $(t <$ *MaxGeneration*$)$
for $i = 1 : n$ *all n fireflies*
  for $j = 1 : n$ *all n fireflies (inner loop)*
  if $(I_i < I_j)$, *Move firefly i towards j;* **end if**
    Vary attractiveness with distance r via $\exp[-\gamma r]$
    Evaluate new solutions and update light intensity
  end for j
end for i
Rank the fireflies and find the current global best $\boldsymbol{g}_*$
end while
Postprocess results and visualization

Fig.13 Pseudo code for Firefly Algorithm (Yang, 2010)

Nur Farahlinga Johari et al (2017) was used this firefly algorithm technique for optimizing the parameters for surface roughness while doing turning operation and found firefly algorithm has given better solution when compared to Response Surface Methodology. In the present research work, an effort has been taken to introduce and provide the description of Firefly algorithm in optimizing the process parameters in Friction Stir Welding in order to obtain the better tensile strength. MATLAB 2018a version software was used to optimize and maximum tensile strength obtained was 152.70MPa for the spindle speed, traverse feed, and axial force of 1500 rpm, 60mm/min, and 6KN respectively. To obtain the best results, population strength of the firefly and number of iterations was taken as 50. The Fig. 14 shows the convergence graph from which it was clear that the maximum tensile strength can be obtained in minimum number of iterations say 16 for average of five runs. In order to check the feasibility of the firefly optimization, the confirmation test was carried out for the optimized parameters.

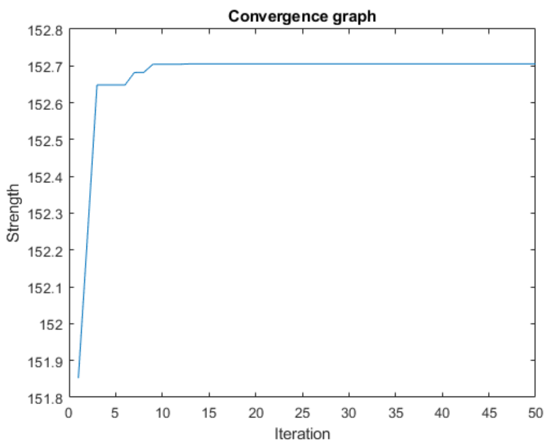

Fig.14. Convergence graph

Confirmation Test

A confirmation test was carried out with the specific combination of input parameters using the obtained levels of the parameters. The welded workpiece was cut as per the ASTM standards and tested. The result obtained was given in the table 5. The result obtained in the confirmation test was 152.12 MPa with the Error percentage of 0.372% when compared to the predicted value. Thus the optimization using the Fire fly algorithm was precise.

Table 5: Results of confirmation Test

Optimized Parameters	Predicted Value	Experimental Value	Error %
1500rpm, 60mm/min, 6kN	152.70MPa	152.12MPa	0.372

Macro structural Investigation

In order to understand the process further, two welded samples were selected, whose macro structure was analyzed and given in Fig 15 and 16 respectively. The sample which produced maximum strength had clear stir zone and surfaces were clear except small crack just below the surface. Whereas it shows the macro structure of the weld specimen pertaining to trail 10 (ref. table 3) which had maximum tensile strength. It shows stir zone clearly with a small crack just beneath the surface.

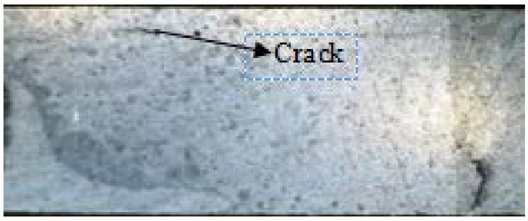

Fig. 15. Macrostructure of trail 6

The Fig 16 illustrates the macro structure of the trail 7. It was observed that lots of voids are there in weld region due to higher value of axial force. At higher axial force, the certain amount of material got squeezed of from weld region. This loss of material leads to creation of voids in the weld zone.

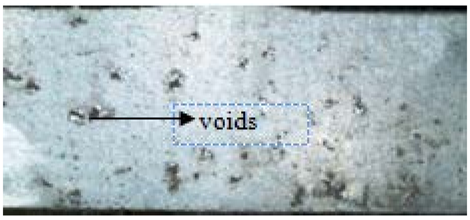

Fig. 16. Macrostructure of trail 7

Micro structural Investigation:

Fig. 17. Microstructure of trail 6

The microstructural study of the trail 6 and 7 were given in the Fig 17 and 18. It is very clear from the Fig 17, that the grains are very fine due to higher spindle speed and low axial force. When the speed brought lower and increased axial force from 6KN to 8 KN the grains was comparatively larger in size and defects were present in the weldment which in turn reduce the strength of the welded joint.

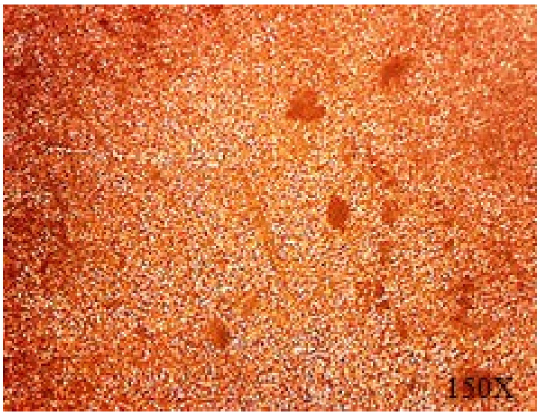

Fig. 18. Microstructure of trail 7

Condition of the Tool

Fig.19. Condition of the tool

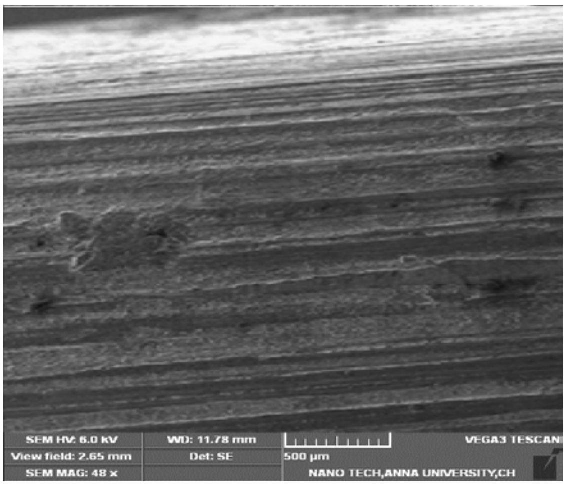

Fig.20. SEM image of the Worn tool

The condition of the FSW tool before and after welding is shown in the Fig 19. SEM image of worn FSW tool probe is presented in the Fig. 20 and has the white layer formation in the top surface of the tool which lead to tool wear. The surface of the tool probe exhibits the circumferential and parallel groove characteristic of abrasive wear processes.

CONCLUSION

Aluminium Matrix Composites were friction stir welded by varying the spindle speed, welding speed, axial force, and the ultimate tensile strength of the joints were measured. Response Surface Methodology was used to develop the mathematical model for output response. The following conclusions are arrived from the above investigation. Friction stir welding can be effectively used to join the metal matrix composites with anticipated mechanical properties. The spindle speed and axial force was significant model terms in the model developed. The results of the ANOVA showed that the model developed was having the F value of 11.09 which confirmed the adequacy of the model. Increasing the spindle speed up to 1500 rpm increases the tensile strength of the joint and reaches the maximum. Any further increase in speed reduces the tensile strength. The trend was common for welding speed also. Increasing the axial force resulted in a decrease in the tensile strength of the composites materials welded. The Fire fly algorithm was applied successfully for optimizing the process parameters in Friction stir welding for getting better tensile strength. For the given condition we got the maximum tensile strength of 152.70 MPa. Confirmation test was conducted for optimized process parameters and results revealed that the predicted value is very nearer to the experimental value with the error percentage of 0.37%. The macro structural and microstructural analysis revealed that increasing axial force resulted in squeezing of material from the weld zone which in turn resulted voids in the weld area. The surface of the tool probe experienced the abrasive tool wear which was clear from the presence of parallel and circumferential grooves.

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