MODELING OF RESIDUAL STRESS DURING EDM OF AISI 4340 FOR MARINE PROPULSION APPLICATION

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SUMMARY

This investigation is conducted to estimate the extent of residual stress induced in the workpiece when machined on EDM. The Residual stresses induced post machining a product can led to lower life and inadequate failures during service. AISI 4340 finds its applicability in propulsion parts of marine engine and thus chosen as the material for study. Tungsten-Copper is selected as material for tool. Response Surface Methodology (RSM) with Central Composite Design (CCD) is utilized preparing the trails using current, on-time of pulse, voltage, and duty factor as machine variables. X-Ray Diffraction (XRD) was performed to estimate the d-space lattice of machined as well as un-machined specimens. Furthermore, Scanning Electron Microscopy (SEM) was executed to analyze effect of residual stress on surface post machining. The model suggested that voltage and on duration were crucial factors for residual stress while duty factor and current were less influential. Residual stress in the machined surface results from gradual heating and cooling during machining. The developed model was predicted to be accurate through the validation test. The micro-cracks resulted from the thermal stresses developed during machining of the workpiece.

KEYWORDS

EDM, Residual Stress, XRD, SEM

1. INTRODUCTION

AISI 4340 is among those materials which are used in marine propulsion parts. It possesses high tensile strength and abrasion resistance when heat treated. Along with these properties, it is easily weldable, castable, and machinable. EDM process in undertaken to machine the materials precisely with minimal residual stress. Residual stress is the stress induced in a job when no external load is applied. The major reason for the formation of residual stress is inhomogeneous distortion of grains. The techniques entailing excessive temperature frequently led to the formation of residual stress due to inhomogeneous distortion of grains caused by varying cooling rates [1]. The extent of stress development counts on the EDM variables and the heat treatment that the surface of the composite is prone to.

While machining on EDM, when molten metal solidifies, it starts to shrink but as it is in junction with base metal which is at lower temperature, the contraction is hindered to some degree. Due to this hindering of surrounding region, residual stress development initiates in the machined surface.

Internal strains created on the machined surface as a result of the workpiece's abrupt cooling and phase shift are known as residual stresses [2]. Research has been done to examine how residual stress, whether tensile or compressive, develops. The majority of studies have demonstrated that the development of residual stress is exclusively related to the temperature factor.

The quick cooling and phase shift that take place throughout the machining process are what cause the tensile residual stress [4,5,7,9,10,13]. On the machined surface, residual stresses lead to the creation of fractures [1,4,5,6,7,9,10,11,12].

A mixed picture of the depth to which these stressors evolved is presented in the review. Some conclusions state that residual stress is formed close to the surface and then

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rapidly decreases with depth [2], while others state that it grows fast with respect to depth and reaches its maximum value within the heat-affected zone [3].

Research demonstrating the impact of electrical factors on the formation of residual stress has been conducted less often. Relative stress was shown to be influenced by peak current and to rise in value with Ip [8,10]. Likewise, the pulse on time has a direct impact on how residual stress develops on the machined surface [8].

The literature on the generation of residual stress in machined workpieces was quite limited. Nevertheless, research on the impact of EDM's electrical characteristics has not been done. There isn't any literature on the connection between machined surface degradation and residual stress.

Based on the literature review, this study is planned to assess the impact of machine parameters to analyze the degree of residual stress developed while machining on EDM and simultaneously outlining the optimum condition for minimal residual stress. Furthermore, the impact of residual stress on surface damage will also be studied as AISI 4340 is used in marine propulsion parts.

2. MATERIALS AND METHOD

Electronica manufactured EDM machine was used to cut AISI 4340 using tungsten-copper electrode. Figure 1 illustrates the machining of workpiece on EDM.

Kerosene being the most viable dielectric due to its properties is used as dielectric medium. AISI 4340 is selected as work material as it found its application in marine industries. For better machining results, tungsten-copper electrodes are selected as tool material. Table 1 depicts the range of EDM variables. This range is chosen as per the preliminary trials conducted on EDM. Below the lower range, the sparking was not so effective. While above the selected range, arcing was observed making an undesirable condition of machining.

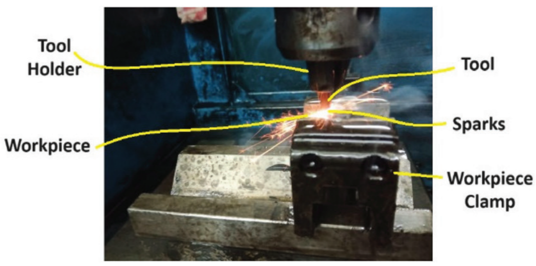

Figure 1. Machining of workpiece on EDM

Table 1. Parameters and their levels

Parameter/Level	Range
Peak Current (A)	1, 4, 7, 10, 13
Pulse on Time (μsec)	10, 15, 20, 25, 30
Voltage (V)	75, 90, 105, 120, 135
Pulse duty factor	0.5, 0.6, 0.7, 0.8, 0.9

To investigate the influence of EDM process parameters on various aspects of residual stresses developed during machining and optimizing, RSM method with CCD is used.

Residual stress is measured by diffraction method that includes measuring of angles of ultimate diffracted intensities occurring while the crystalline solid is put through the X-rays. Using Bragg's law shown in Eq. 1, the inter-planar spacing is found by using the estimated angles.

$$2 \times d \times sin\theta = \lambda \tag{1}$$

Wrhere λ is radiation wavelength, d is lattice plane spacing and θ is the angular position of diffraction peak. By comparing stressed and unstressed condition, strain is estimated as shown in Eq. 2.

$$Strain(\in) = \frac{d_s - d_u}{d_u} \tag{2}$$

Where d_s are the stressed lattice spacing and d_u is unstressed lattice spacing.

The residual stress is estimated by the relation depicted by Eq. 3.

$$Residual\ Stress = \frac{E \times \in}{\mu} \tag{3}$$

Where E is the elastic modulus (E = 196 GPa for AISI 4340) and μ is the poisons ratio (μ = 0.3 for AISI 4340).

3. RESULTS AND DISCUSSION

3.1 RESIDUAL STRESS

Residual stresses developed due to thermal gradients experienced during spark erosion is assessed by the diffraction of each machined specimen. The diffraction of the machined specimen is compared with the un-machined specimen to estimate the strain. Figure 2 depicts the XRD graphs of machined sample 4, and machined sample 9. The d-spacing value of un-machined surface is 2.03035. From the graphs, the d-spacing values are used to calculate the strain developed during machining. The table 2 illustrates the estimated residual stress for each trial.

After estimating the developed stress, Sequential Model Sum of Squares (SMSS) and Lack of fit tests were conducted as depicted in table 3 and table 4. The tests suggested that the relation between the EDM parameters and residual stress can be modeled using 2FI equations.

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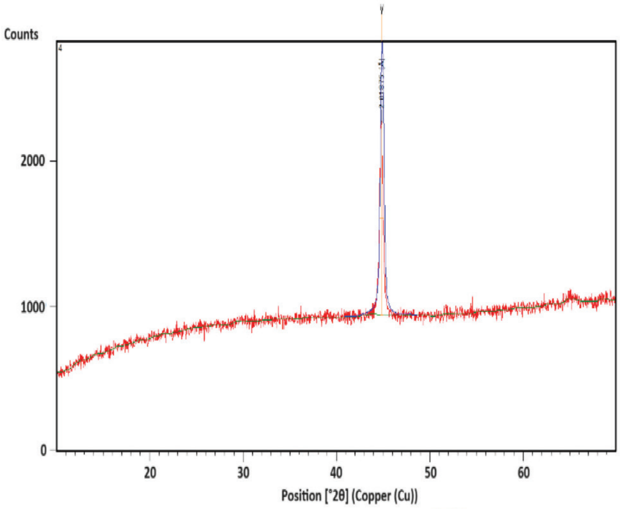
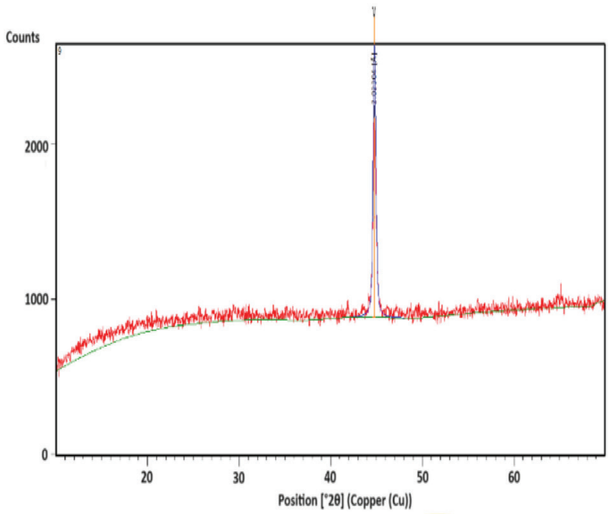


Pos. [°2θ]	Height [cts]	FWHM Left [°2θ]	d-spacing [Å]	Rel. Int. [%]
44.8622	1337.98	0.4056	2.01875	100.00

(a)



Pos. [°2θ]	Height [cts]	FWHM Left [°2θ]	d-spacing [Å]	Rel. Int. [%]
44.7619	1294.63	0.3120	2.02304	100.00

(b)

Figure 2. XRD graphs (a) for machined sample 4; (b) for machined sample 9

The ANOVA analysis for 2FI model of Residual Stress shown in Table 5, where the F-value of 8.05 implicit the significancy of the model. From the test, on duration, voltage, interaction of on duration-voltage, on duration-duty factor voltage-duty factor were influential terms. Among them, Voltage with p-value less than 0.0001 has major dominance on residual stress followed by on duration. Previous studies have only looked at the machining process's thermal characteristics. On duration also had an impact on residual stress, which is consistent with previous studies. Out of all the variables that were chosen, the duty factor had the least impact on residual stress.

F-value of 422.44 for lack of fit suggests that it is significant. It has only 0.01% chance for a lack of fit of this order can happen because of noise.

A polynomial equation is generated from the model to find relation between EDM variables and residual stress.

$$\text{Residual Stress (GPa)} = -46.85776+0.393306\times Ip+0.986717\times Ton+0.314094\times V+41.90583\times\tau-0.007967\times Ip\times Ton-0.001047\times Ip\times V-0.283750\times Ip\times\tau-0.004490\times Ton\times V-0.792000\times Ton\times\tau-0.226583\times V\times\tau \quad (4)$$

The above equation Eq. 4 depicts the relation of response with parameters to predict the residual stress at different level of each variable.

The surface plot of 2FI response model of residual stress is shown in Figure 3. The parameters under consideration are pulse on duration with voltage as they are significant factors for residual stress identified by ANOVA. It was found that RSM was an effective tool for predicting output values for the corresponding input, which was justified from the residual graphs[14,15].

The figure 4 shows the main effect plot of various EDM parameters under consideration with the induced residual stress. It has been noted that the residual stress value for pulse duty factor and peak current is quite close to its mean value. As a result, these two factors have the least impact on residual stress. When the pulse is punctual, residual stress first drops for up to 25µs before gradually increasing. The residual stress tends to rise with voltage. As indicated by ANOVA, residual stress is found to be mostly dominated by voltage and pulse on time. In contrast to earlier studies, peak current for the current model indicates a declining trend and has no influence on residual stress.

3.2 MODEL VALIDATION FOR RESIDUAL STRESS

The validation is carried out to analyze the feasibility of the evolved response surface model. This is done through point prediction ability of Design Expert and process variables were selected for validation run. Table 6 shows the result of validation with the set of EDM variables. From Table 6, the 4.19% residual error specifies the model adequacy to predict the resulting residual stress under 95% CI while the residual error corresponding to predicted value is within 5%.

3.3 MICRO CRACKS DEVELOPMENT

Using scanning electron microscopy (SEM), the micro-cracks that formed on the EDMed surface were evaluated. The development of internal tensions generated during machining is the primary factor contributing to the

Table 2. Estimation of residual stress during various trials

Exp. No.	Peak Current Ip (A)	Pulse on Time Ton (µsec)	Voltage (V)	Pulse Duty Factor (τ)	d_s	Strain	Residual Stress
1	4	15	90	0.6	2.01592	-0.00710715	-4.643
2	10	15	90	0.6	2.01847	-0.00585121	-3.823
3	4	25	90	0.6	2.01967	-0.00526018	-3.437
4	10	25	90	0.6	2.01875	-0.0057133	-3.733
5	4	15	120	0.6	2.02818	-0.00106878	-0.698
6	10	15	120	0.6	2.02799	-0.00116236	-0.759
7	4	25	120	0.6	2.02562	-0.00232965	-1.522
8	10	25	120	0.6	2.02522	-0.00252666	-1.651
9	4	15	90	0.8	2.02304	-0.00360036	-2.352
10	10	15	90	0.8	2.02241	-0.00391066	-2.555
11	4	25	90	0.8	2.01978	-0.005206	-3.401
12	10	25	90	0.8	2.01887	-0.0056542	-3.694
13	4	15	120	0.8	2.02882	-0.00075356	-0.492
14	10	15	120	0.8	2.02898	-0.00067476	-0.441
15	4	25	120	0.8	2.02271	-0.0037629	-2.458
16	10	25	120	0.8	2.02089	-0.0046593	-3.044
17	1	20	105	0.7	2.02531	-0.00248233	-1.622
18	13	20	105	0.7	2.01805	-0.00605807	-3.958
19	7	10	105	0.7	2.02901	-0.00065998	-0.431
20	7	30	105	0.7	2.02247	-0.0038811	-2.536
21	7	20	75	0.7	2.0195	-0.00534391	-3.491
22	7	20	135	0.7	2.02639	-0.0019504	-1.274
23	7	20	105	0.5	2.02434	-0.00296008	-1.934
24	7	20	105	0.9	2.02258	-0.00382693	-2.500
25	7	20	105	0.7	2.02099	-0.00461004	-3.012
26	7	20	105	0.7	2.02087	-0.00466915	-3.051
27	7	20	105	0.7	2.02099	-0.00461004	-3.012
28	7	20	105	0.7	2.02102	-0.00459527	-3.002
29	7	20	105	0.7	2.02089	-0.0046593	-3.044
30	7	20	105	0.7	2.02117	-0.00452139	-2.954
31	7	20	105	0.7	2.02084	-0.00468392	-3.060

Table 3. SMSS analysis for residual stress

Source	Sum of Square	DOF	Mean Square	F-Value	p-value	
Mean vs Total	194.14	1	194.14			
Linear vs Mean	25.02	4	6.25	11.30	<0.0001	
2FI vs Linear	6.54	6	1.09	2.79	0.0388	Suggested
Quadratic vs 2FI	4.21	4	1.0525	4.62	0.0114	Suggested
Cubic vs Quadratic	3.24	8	0.405	8.56	0.0031	Aliased
Residual	0.3801	8	0.0475			
Total	233.54	31	7.533			

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Table 4. Lack of fit test for residual stress

Source	Sum of Square	DOF	Mean Square	F-value	p-value	
Linear	14.39	20	0.7195	543.21	<0.0001	
2FI	7.84	14	0.56	422.44	<0.0001	Suggested
Quadratic	3.62	10	0.362	273.96	<0.0001	Suggested
Cubic	0.3724	2	0.1862	140.63	<0.0001	Aliased
Pure Error	0.0078	6	0.0013			

Table 5. ANOVA for residual stress

Source	Sum of Square	DOF	Mean Square	F-value	p-value	
Model	31.56	10	3.156	8.05	<0.0001	Significant
A-Peak Current	1.2	1	1.2	3.07	0.0951	
B-Pulse on Time	5.4	1	5.4	13.79	0.0014	
C-Voltage	18.38	1	18.38	46.93	<0.0001	
D-Pulse duty Factor	0.022	1	0.022	0.0510	0.8237	
AB	0.2284	1	0.2284	0.5830	0.454	
AC	0.0356	1	0.0356	0.0905	0.7664	
AD	0.1158	1	0.1158	0.2957	0.5925	
BC	1.80	1	1.80	4.61	0.0438	
BD	2.50	1	2.50	6.4	0.0199	
CD	1.84	1	1.84	4.71	0.0421	
Residual	7.84	20	0.3918			
Lack of fit	7.83	14	0.5591	422.44	<0.0001	Significant
Pure Error	0.0078	6	0.0013			
Cor Total	39.4	30				

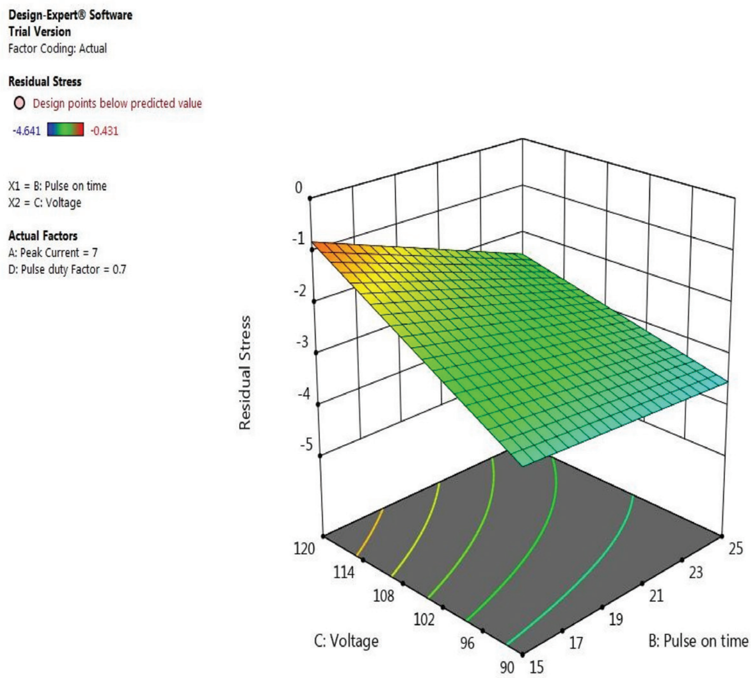

Figure 3. Response surface plot for residual stress while holding peak current at 7A and pulse duty factor at 0.7

Fig. 4 Main effect plot for residual stress

Table 6. Validation for residual stress

S.No.	Input Parameters				Prediction	Validation	Residual Error %
	Ip	Ton	V	τ	Residual Stress (GPa)	Residual Stress (GPa)	
1	7	20	105	0.7	-2.50258	-2.612	4.19

formation of cracks. Crack appearance is dependent on the EDM setting and machining condition. Furthermore, a significant emphasis on crack initiation is also placed on the spark's discharge energy.

The thermal tensions that formed during the workpiece's machining were the cause of the microcracks. The machined surface opens as a result of the residual stress evolving due to the uneven temperature distribution. Because of the strong temperature gradients, larger fractures are seen at greater pulse on duration levels. When the internal residual stress created by machining surpasses the material's maximal tensile strength, crack development begins.

Figure 5 (a) depicts the microscopy image, a tensile stress of 4.541 GPa yields cracks on the machined surface. Due to the created temperature gradient, the fractures are distributed across the machined surface. Image also depicts the voids all over the machined surface.

Considering lower stress of 0.441 GPa induced in sample 14, the Figure 5 (b) yields a crack free surface. Insufficient strain is developed to cause surface cracking. Furthermore, sample 31 microscopy images in Figure 5 (c) shows wider and concentrated cracks on the machined surface. Voids are observed on almost all the machined surfaces.

3.4 EFFECT OF RESIDUAL STRESS ON SURFACE DAMAGE

From the preceding section it is perceived that while machining on EDM, the residual stress is generated on account of gradual heating and cooling of machined surface. The developed internal residual stress causes surface damage. It is found from ANOVA table 5 that voltage and pulse on duration are major process variables for the present model while peak current and pulse duty factor almost yield insignificant impact over residual stress. Stresses are created on the machined surface during cooling. Cracks will appear on the surface when the amount of internal stress is greater than the material's tensile strength.

The development of internal stresses generated during machining is the primary factor contributing to the formation of cracks. Crack appearance is dependent on the EDM setting and machining condition. Furthermore, a significant emphasis on crack initiation is also placed on the spark's discharge energy. The thermal stresses that are formed during the workpiece's machining were the cause of the microcracks. The machined surface opens as a result of the residual stress evolving due to the uneven temperature distribution.

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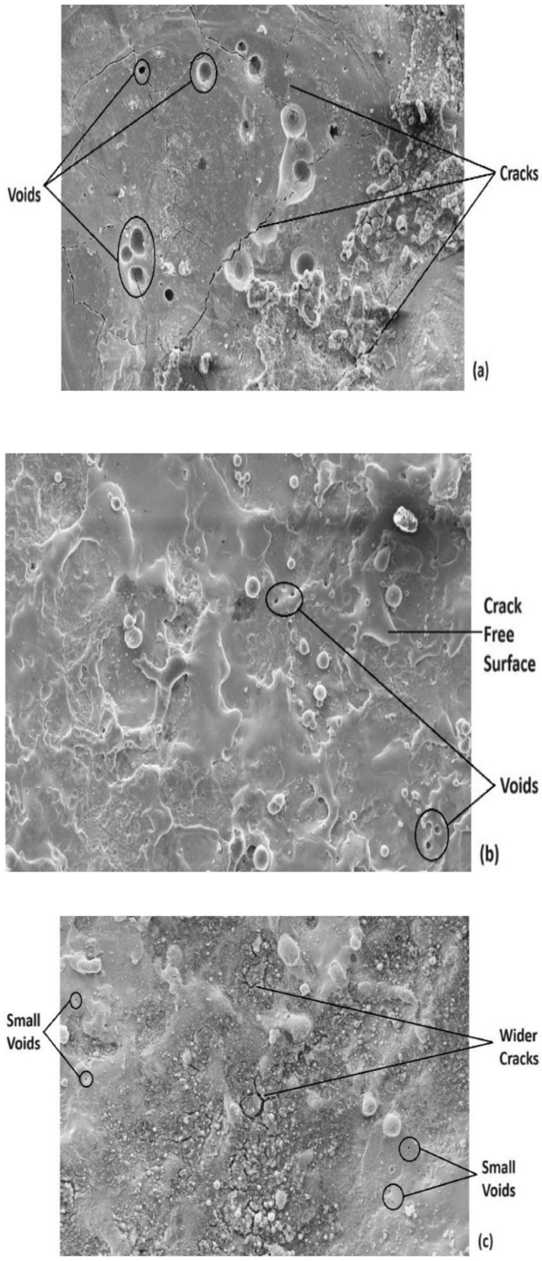

Figure 5. SEM images of machined surface (a) Sample 1, (b) Sample 14, (c) Sample 31

Because of the strong temperature gradients, larger fractures are seen at greater on duration levels. When the internal residual stress created by machining surpasses the material's maximal tensile strength, crack development begins.

4. CONCLUSION

The modeling carried out for analyzing the development of residual stress in AISI 4340 for marine propulsion part application post machining on EDM using Tungsten-Copper tool made following conclusions:

1. XRD process employed to assess the residual stress yields that its extent can be up to 4.641GPa under the selected machining conditions. Among the chosen parameters, voltage and on duration were crucial. Current has lesser impact but was a significant model term. Only duty factor was found to be an insignificant variable for induced stress.
2. An upper level of current, on duration and duty factor with low potential must be selected to achieve a low-stressed product. The analysis yields the range of parameters as $7A \leq Ip \leq 13A$, $20\mu sec \leq Ton \leq 30\mu sec$, $75V \leq V \leq 105V$, $0.6 \leq \tau \leq 0.9$ for the present model.
3. The 4.19% residual error specifies the model's adequacy to predict the resulting residual stress under 95% CI.
4. Gradual heating and cooling during machining yields residual stress in the machined surface. The sparks cause the machined surface to get heated. Stresses are created on the machined surface upon cooling. Cracks will appear on the surface when the amount of internal stress is greater than the material's tensile strength.
5. The development of internal stresses generated during machining is the primary factor contributing to the formation of cracks. Crack appearance is dependent on the EDM setting and machining condition. Furthermore, a significant emphasis on crack initiation is also placed on the spark's discharge energy.
6. The thermal stresses that are formed during the workpiece's machining were the cause of the microcracks. The machined surface opens as a result of the residual stress evolving due to the uneven temperature distribution.
7. Because of the strong temperature gradients, larger fractures are seen at greater on duration levels. When the internal residual stress created by machining surpasses the material's maximal tensile strength, crack development begins.

The above conclusions state that by using optimum range of parameters while machining AISI 4340, minimal residual stress will be induced thus making it suitable for its applicability in propulsion parts of marine industry.

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