SYNTHESIS AND EFFECT OPTIMIZATION OF M R FLUID COMPOSITION FOR REDUCTION IN INDUCED RESIDUAL STRESS

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Abstract

Stresses are produced during manufacturing of Mechanical parts. Sometimes these stresses are useful and sometimes detrimental for the parts depending upon the application of these parts. The stress generated during the manufacturing processes of parts affects the life of these parts and are responsible most of the time for premature failure of parts. Therefore, the detailed analysis of induced stresses in machined parts is essential to the performance of a machined component. There are many methods available for stress analysis of mechanically manufactured parts. The first type of method which is Non-Destructive techniques i.e., x-ray diffraction, Neutron diffraction, etc. The second type of method is the destructive technique i.e., Contour method and sectioning method. The third type of method which is Semi Destructive techniques i.e., hole drilling, deep hole drilling, etc. The Induced residual stress in a component machined with traditional manufacturing processes i.e., Grinding, Milling, Turning, etc. can be reduced by using the Novel finishing process of BEMRF (Ball End Magnetorheological finishing). This finishing process can produce a very good surface finish with comparatively low induced residual stress in finished components. In this paper, we will explain the residual stress analysis of machined hard metal work-piece before and after Ball End Magneto-rheological finishing. Experimental method employing a Bi-dispersible composition of M R Fluid will be investigated. Further optimization of Bi-dispersible M R Fluid results will be done by use of optimization techniques to find out the best operating parameters to achieve a maximum % reduction in residual stress. M R fluid composition with Bi-dispersible CIP used in this experiment has not been investigated so far by using BEMRF.

Keywords: Residual Stress, Non-destructive method, X-ray diffraction, Neutron diffraction, Bi-dispersible MRF, BEMRF, Magnetic tool, Tool rotational speed, Working gap, etc.

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1. Introduction

Residual stress is the stress which residue in a part that is not exposed to external forces. Residual Stress is being caused by manufacturing operations or processing operations or the service environment. Generation of residual stresses happens during most manufacturing processes which involve deformation of the material, generation of heat, and change in physical shape or size or variation in material's mechanical properties. They can be originated from many sources during manufacturing and can exist in the mechanical components even due to in-service loading. Term surface integrity is used to indicate the properties of machined surface post manufacturing operations. Surface integrity aspects include metallurgy characteristics, topography, and residual stress. The topography is a mix of surface roughness, flaws, and waviness. The metallurgy characteristics include grain size, micro-hardness, plastic deformation, re-crystallization, phase transformation, etc. The analysis of residual stress is crucial in predicting working lifespan, investigating distortion and the reasons for failure. All the stress measurement techniques can be classified into two classes: One which measures actual strain, and the second which measures changes in strain (Mishra & Prasad, 1985). The method of measurement choice should be based on the type of information required, economic factors, and limitations of each technique. The relieving of residual stress present in a component after conventional machining method of cylindrical grinding can be done by using advance finishing techniques i.e., Magnetorheological finishing. The effect of this finishing process on residual stress present in machined components will be studied by experimental technique.

1.1. Residual Stress

Residual stresses are in equilibrium as tensile residual stresses (disadvantageous) and compressive residual stresses (advantageous). For example, if a component's surface is created in tensile stresses, it will be containing compressive residual stresses, and if the component's surface is created in compressive stresses, it will be containing tensile residual stresses (Mishra & Prasad, 1985).

1.1.1. Tensile Residual Stresses: - The generations of tensile residual stresses (TRS) generally happen due to production processes i.e., aggressive grinding which produces the growth of cracks. They can also be created with other mechanical methods i.e., Fitting, shrinking, bending, or torsion. For example, Cracks on the component surface are produced due to remaining tensions as residual stresses in components produced using the casting method. Moreover, due to the presence of tensile residual stresses, the defect of stress corrosion cracking also happens in these components (Mishra & Prasad, 1985).

1.1.2. Compressive Residual Stresses: - The fatigue strength, as well as resistance to stress corrosion cracking, is enhanced by compressive residual stresses (CRS). Compressive residual stress is intentionally generated during manufacturing processes i.e., laser peening, shot peening, auto-fretting, low plasticity burnishing, etc. During these processes strain hardening of material takes place due to cold working. The detrimental effect of residual tensile stress is counter balanced with the introduction of compressive residual stresses. Residual tensile stresses can also be reduced by using suitable heat treatment processes (Perry, Sue, & Martin, 1996).

The Sum of all the residual stresses and all the applied service stresses on a component is called the total stress of that component. The known residual stresses are of three types: -

(A) Type-1 Residual Stress: - When the stresses are developed in several grains of material, it is called Macro-residual stress. Macroscopic dimensions will change if there is any change in the Type-1 residual stress equilibrium. Residual stresses of Type-1 are produced because of methods that cause inhomogeneous strain distribution.

(B) Type-2 Residual Stress: - When development of stresses in one grain of the material happens, it is called Micro-residual stress. Type-2 residual stresses are produced during martensitic transformation where the incomplete transformation of austenite is observed during the transformation process. Due to the difference in the volume of austenite and martensite, residual stresses are produced.

(C) Type-3 Residual Stress: - When within several atomic distances of the grains, stresses are developed; it is called sub-micro residual stress. It is produced due to crystalline defects such as dislocations, vacancies, etc.

In actual conditions, all the residual stress types are present in all the components. All manufacturing Operations produce some quantity of residual stresses. Cracks can occur because of these stresses. Due to these residual stresses welded and cast components even at room temperature and without any external loading may fail disastrously. The service lifetime of the components is directly affected due to residual stresses present in these components. Due to this, the investigation of residual stress is very essential in many industries.

1.2. Residual Stress Analysis Methods

There are many residual stress analysis (RSA) techniques. In these techniques, the residual stress effect is measured and not stresses itself. There are three types in which these techniques can be classified: Non-destructive techniques, semi-destructive techniques, and destructive techniques (Perry, Sue, & Martin, 1996)

1.2.1. Destructive Technique

The destructive residual stress measurement technique is also called MSR (Mechanical Strain Release) technique. The methods used under this technique are detailed below: -

1) Sectioning method.
2) Contour method.

1.2.2. Semi-Destructive Technique

The semi-destructive techniques use the "strain release" principle for residual stress measurement. They do not change the overall integrity of the structure of component material; by removing a small amount of material under this category following methods are included:

1) Deep hole drilling (DHD) Method.
2) Incremental hole drilling (IHD) Method.

1.2.3. Nondestructive Technique

This technique is based on a relationship between the component's physical properties and stress. The diffraction method (NDT) measures variations in properties due to lattice space variation in component material due to stress. In this technique, ultrasound waves passed through the stressed material and variations in the speed of ultrasound waves are measured to determine the residual stress in the ferromagnetic material components.

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1) Neutron diffraction.
2) X-Ray diffraction.
3) Ultrasound method.

2. Materials and Methods

2.1. Synthesis of Magnetorheological Fluid (MRF)

Magnetorheology is a branch of material science where the impact of employed magnetic field at material deformation and movement pattern of material are studied. Jacob Rabinow invented MR fluid in 1949. The rheological properties of M R fluid help to control its actions in the application of an exterior magnetic field (Jian & Peng, 2012) (Jha & Jain, 2004). The Composition of M R fluid generally consists of three components or faces i.e., Magnetic face (20 %), Cutting Face (25 %), and Carrier face (55 %) (Singh, Jha, & Pandey, 2015). The magnetic face contains materials such as Carbonyl Iron Powder, Nickel Alloys, Cobalt Alloys, etc. The desirable property of these materials is that their physical flow and shape can be changed using a changeable magnetic effect. Cutting Face contains abrasive materials such as SiC, which is used for cutting off material from the surface of work-piece. The Carrier Face contains the materials which help for movement of the two other faces such as AP-3 Grease, heavy-duty Paraffin oil, etc. Conventionally MRFs (magnetorheological fluids) are a combination of micron-sized ferromagnetic grains mixed with micron-sized SiC grains and hydraulic oil (mono-disperse). If the particle size of materials is within the range of equal to or less than 100 nm, then these materials are called nano-materials. The surface chemistry of the micro-scale particles differs from nano-scale particles. Hence by varying the % of nano-scale particles the behavior of the mixture can be controlled. If M R fluid contains micron size and nano-sized particles it called bi-disperse fluid. The advantage of nano-sized particles is that it reduces the M R fluid settling rate as Nano-sized particles fill the pores between micron-size particles (Kumar, Kumar, & Niranjan, 2020).

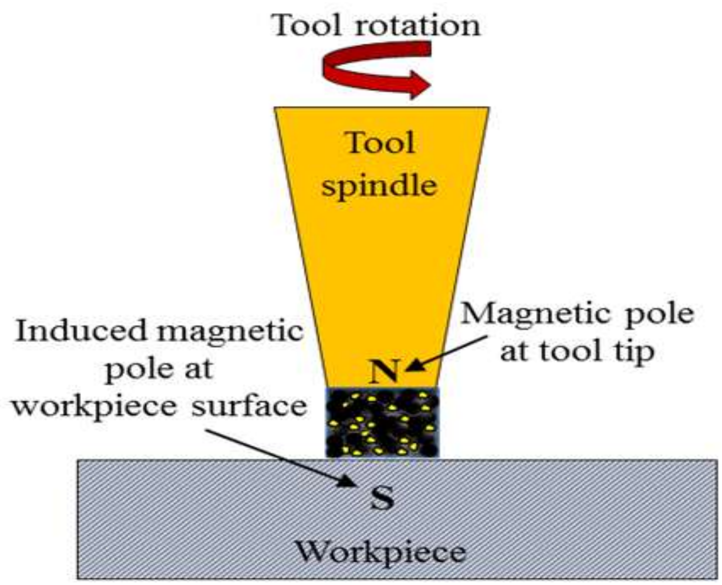

Fig.1 Mechanism of Ball End Magnetorheological finishing Tool

In preliminary experiments, different compositions of Bi-dispersible M R fluid were tested to find the best composition of M.R fluid on % reduction in Residual stress. The composition of bi-dispersible fluid which is used in this experimentation work has not been investigated earlier for its performance on finishing a hard metal work-piece. The composition which produced the highest % reduction in residual stress in components machined by conventional cylindrical grinding was 20 % Magnetic face (having 4% Nano CIP and 16% Micro CIP CS grade), 25% Cutting face (SiC of 800 mesh size) with 55% Carrier fluid (20 % AP-3 Grease and 80% Heavy duty Paraffin oil) on volume % basis (optimum M R fluid composition). Now during this experimentation work, confirmatory experiments to confirm the findings of earlier experiments and further optimize the effectiveness of M R Fluid composition by varying the process parameters of the BEMRF (Ball end magneto-rheological finishing) process to achieve better results. The schematic layout of the BEMRF process mechanism is displayed in the fig. No.1 (Peter, Andreas, Helmut , & Svea , 2017).

2.2. Experimental Set Up To Study Effect of M R Fluid Composition on Induced Residual Stress in Machined Hard Metal Work-Piece

The constituents of Magnetorheological fluid such as Carbonyl Iron Powder and SiC has been procured from BASF Corporation for using in this experimental study. BEMRF [Ball End Magneto-rheological Finishing] process is considered a new innovative finishing process and precisely used to finish simple as well as very complex three-dimensional surfaces (Singh & Singh, 2018). The residual stress and surface finish produced during the manufacturing processes of parts affect the life of these parts and are responsible most of the time for the premature failure of these parts. Therefore, the detailed analysis of induced stresses in machined parts is very important for the desired performance of a machined component (Singh, Jha, & Pandey, 2015). The goal of this experimental paper is to confirm and optimize the % reduction in residual stress of hard metal specimens by using BEMRF process. EN-31 work-pieces were used in this experimental work as specimens (Shunmugam & Kanthababu, 2020). These work-pieces were first finished using a cylindrical grinding process. Their residual stress measurements were done at four points across each specimen length of 70 mm. All the measurements were done using portable x-ray residual stress analyzer micro-µ-x360s.

[A] MR Fluid Sample

[B] MR Finishing Process Set Up

Fig 2. Actual set up of the BEMRF Equipment

The EN-31 work-pieces were then finished using BEMRF set up as shown in fig.1.The BEMRF process setup (Niranjan & Jha, 2015) and its components are shown in figure no 2. During this experiment, the same optimum composition was used to carry out confirmatory experiments to confirm the findings of earlier experiments and further optimize the effect of process parameters to achieve better results. The optimum Magneto-rheological fluid has a composition of 20 % Magnetic face (having 4% Nano CIP and 16% Micro CIP CS grade), 25% Cutting face (SiC of 800 mesh size) with 55% Carrier fluid (20 % AP-3 Grease, and 80% Heavy duty Paraffin oil) on volume % basis was used during the finishing process (Kumar, Kumar, & Niranjan, 2020). DC Power supply was used to provide current supply to the magnetic tool for producing magnetization effect on the tooltip of the magnetic tool that helps in the development of the bi-dispersible MRF hard ball at the tooltip. This MRF ball acts as a cutting tool and its stiffness can be manipulated by altering the current supply in the magnetic coil of the magnetic tool. The supply current is controlled with the help of a DC power supply.

The MR fluid ball rotates at the speed of the magnetic tooltip. The current was kept at 2.5 amperes (MC) during the experiments. The tool rotational speed (TRS) was kept at 500 R.P.M. during the experiments. The working gap in the middle of the magnetic tooltip and the work-piece (WG) was kept at 1.5 mm. The total operation time for finishing each work-piece was maintained as 30 minutes. The feed rate was maintained as 50 mm/min. (Manjesh, Hari, Abhinav , & Manas, 2021). After finishing the EN-31 work-pieces with the BEMRF process, residual stress measurements were again repeated at the same points as it was done before finishing. It was noticed that induced residual stress level that was at 130 MPa before finishing the work-pieces with BEMRF was reduced to 62 MPa level after the finishing process. It proves the fact that BEMRF is one finishing process that can help to relieve the stress present in machined components. Further analysis and optimization were done by doing more experiments as per the Design of Experiments (DOE) and to study the impact of different process factors that have substantial influence on the output of the BEMRF process i.e., Magnetizing Current(MC), Tool Rotational Speed (TRS) and working Gap (WG) (Iqbal Faiz & Sunil Jha, 2019).

2.3. Experimental Setup for Residual Stress Analysis of a Hard Metal Work-piece

X-ray diffraction (Perry, Sue, & Martin, 1996) types of equipment are based on non-destructive type technique. The micro-μ-X360s residual stress analyzer is used to evaluate residual stress [RS] in components without having direct contact between the component and sensor unit. It is very secure and popular due to its various unique features (N., M. , K., & A., 2012). Important features of this device are given below: -

i. It's lightweight and portable having only 2.4kg sensor unit weight.
ii. It can measure the inner surface residual stress of the pipe down to the diameter of 170mm.
iii. Easy it is set up, having a sample position tolerance of +/-5mm.
iv. It has a CCD camera to assist with sample positioning and a built-in marker as well to highlight important points.

v. It has a fast measurement speed of 60 seconds per measurement point.
vi. It has high reliability & repeatability as measurement by the cos α method ensures reliable and repeatable data.
vii. Its 2D detector captures the complete Debye ring.
viii. It is secure and has low power X-ray emission due to the high sensitivity of the detector.

2.3.1. Construction and Working of Portable x-ray residual stress analyzer micro-µ-X360s: -
It is a non-contact type Instrument and consists of the following parts: -
(a) Sensor Unit (b) Power Supply Unit (c) Flexible Arm (d) Hand Carry Case (e) Safety Cabinet

2.3.2. Measurement of Residual Stress using Portable X-ray Residual Stress Analyser Micro-µ-X360s: -
The experimental setup is illustrated in figure no.3. This setup measures the residual stress of all the samples of EN-31 having the size of 10 * 10* 60 mm were finished using grinding operation. After that four points (A, B, C, and D) were marked on each work-piece to measure the residual stress at these four points in each sample. Now by using the procedure prescribed by the manufacturer, the residual stress value was recorded one by one on all four points in each work-piece by directing the sensor unit on these points as shown in fig. 2. The recorded values obtained during this experiment are tabulated in table no. 2 (Perry, Sue, & Martin, 1996).

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Fig.3 Components of Portable X-Ray Residual Stress Analyser Micro-µ-360s

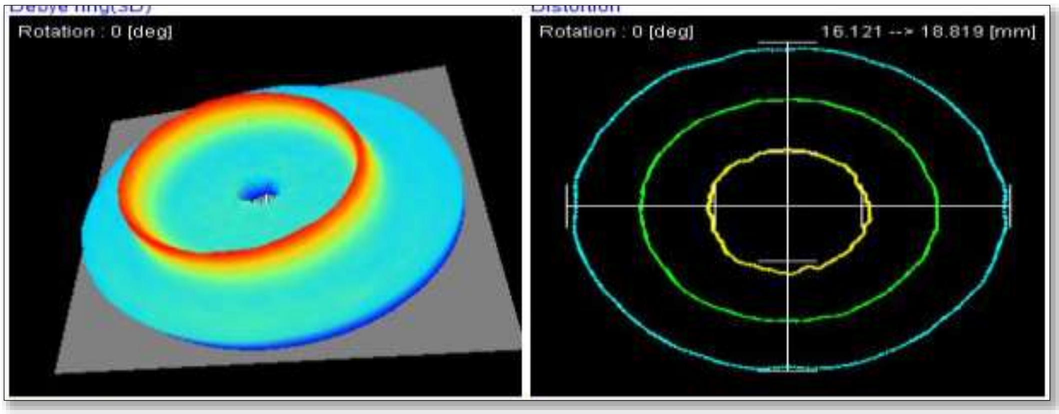
3. Results Interpretation and Evaluations

The output value of residual stress in specimens before finishing and after finishing with BEMRF using Pulse (with a duty cycle 0.16) is listed in the table 2. The % reduction in induced residual stress (%ΔRS) can be calculated using the equation given below: -

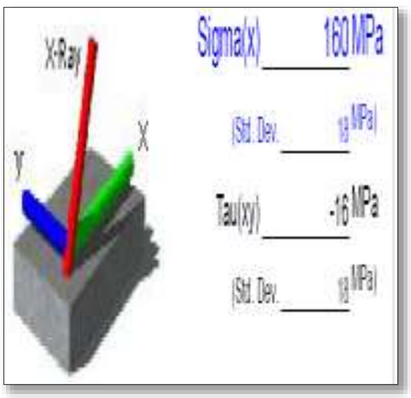
%ΔRS = (Initial Residual Stress - Final Residual Stress) X 100/ Initial Residual Stress

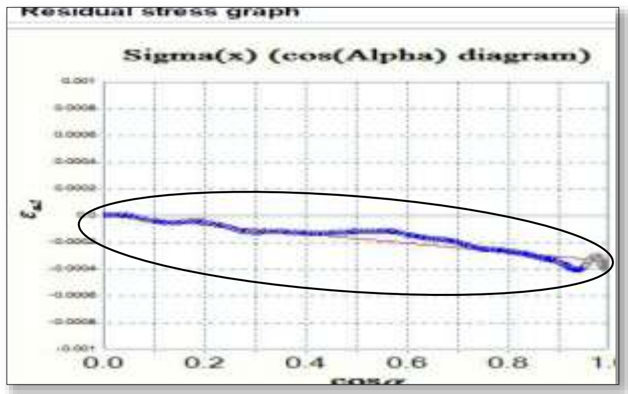
From the Debye ring given in fig. No. 4 (A), the grinding process finished work-piece has more irregularities and not having a very clear ring; its Distortion diagram also is also less uniform. Whereas as displayed in Fig No. 4 (B) the Debye ring for work-piece finished with BEMRF process using MR fluid has fewer irregularities and a clear ring, as seen in its distortion diagram the ring is also more uniform (Kumari, Chak, & Vani, 2020). The Residual stress Cos α Graph also shows more deviation of the center line for the grinding process finished work-piece, whereas the deviation from the center line is decreased after finishing the work-piece with the BEMRF process. During the preliminary experimentation on EN-31 steel work-pieces, it was found that after finishing these work-pieces with the BEMRF process the induced residual stress during the grinding process which was 160 MPa was reduced to 66 MPa, which is very important for the working life of a component. Surface roughness was also reduced after this process. The component with little Induced residual stress can complete their expected working life without premature sudden failure. There are main three factors which have significant impact on the output response in residual stress reduction. One factor is Magnetizing

Current, Second is the Working Gap between the work-piece and Tool tip and the third factor is Tool rotational speed. The impact of these three parameters can be observed in % reduction in residual stress by varying these parameters over the range of their significance (Niranjan & Jha, 2015).



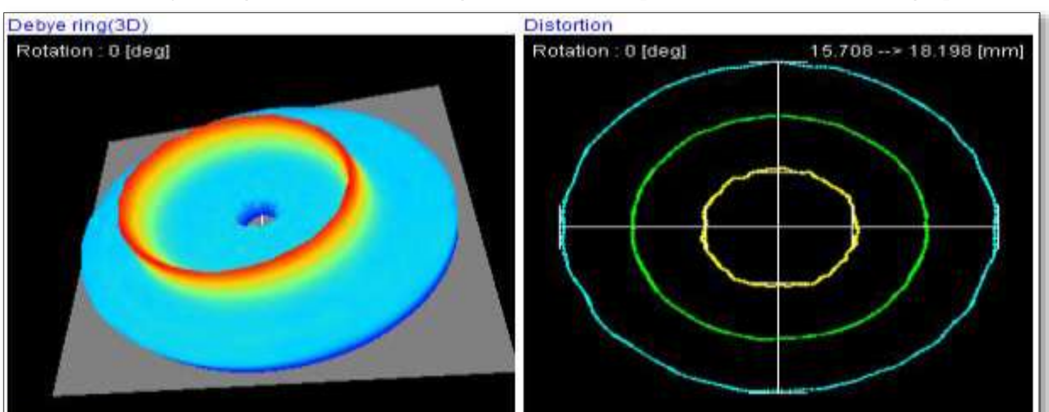
[A] [B]



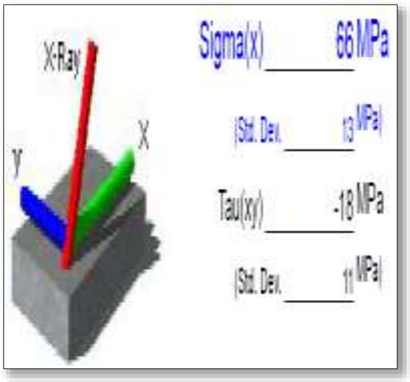


.. [C] [D]

Fig.4 (a) Residual Stress Graphs [160 MPa] of point "A" of sample-1(S-1) after Grinding Process generated by Micro- μ-x360s
[A] Debye Ring [B] Distortion Ring [C] Stress Components [D] Cos α stress graph



[A] [B]



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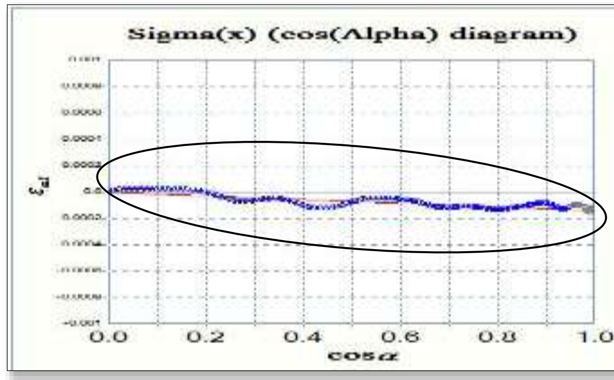

[D]

Fig.4 (b) Residual Stress Graphs [66 MPa] of point "A" of Sample1(S-1) after finishing with BEMRF Process generated by Micro-μ-x360s
[A] Debye Ring [B] Distortion Ring [C] Stress Components [D] Cos α stress graph

To analyze the influence of process factors over the range of its significance, analyze and optimize output response, further experiments were done at different parameter combinations. Design Expert software was used. The RSM Method with Central Composite Design (CCD) was utilized to find order of RUNs and parameter's values for the experiments. The Output responses % reduction in Residual stress is tabulated below Given Table No1 and 2 respectively:

Table 1**:** Factors, Levels, and Range of Process Parameters for Design of Experiments using (CCD)

S No	**Process Parameter**	**Unit**	**Levels**				
			-2	**-1**	**0**	**1**	**2**
1	Magnetizing Current (MC)	A	1.5	2	2.5	3	3.5
2	Tool Rotational Speed (TRS)	RPM	300	400	500	600	700
3	Working Gap (WG)	MM	0.5	1	1.5	2	2.5

Based on these limits of parameter further experiments were designed and performed.

Table 2: Design of Experiments with % Residual Stress Reduction (% RSR)

Std Order	**Run Order**	**Magnetizing Current (A)**	**Tool Rotation Speed (Central Core) (RPM)**	**Working Gap (MM)**	**% Residual Stress Reduction (RSR)**
10	1	2.5	700	1.5	52.63
6	2	3	400	1	53.83
18	3	2.5	300	1.5	38.21
5	4	3.5	500	1.5	55.36
20	5	2	400	1	25.65

19	6	3	600	2	40.84
3	7	3	400	2	39.65
2	8	2.5	500	1.5	45.26
13	9	2	400	2	23.38
17	10	2.5	500	2.5	22.53
15	11	1.5	500	1.5	16.96
1	12	2	600	2	29.13
11	13	2.5	500	1.5	44.53
9	14	2	600	1	37.93
16	15	2.5	500	0.5	52.21
14	16	2.5	500	1.5	49.69
4	17	3	600	1	56.93
8	18	2.5	500	1.5	48.13
7	19	2.5	500	1.5	45.96
12	20	2.5	500	1.5	45.76

As per CCD Design total of 20 Experiments were done with parameter combination as indicated in table No 3, after finishing with the same composition of MRF the residual stress of all the 20 work-pieces was measured using Micro-µ-x360s, and recorded are shown in table No 2. The information generated by the analysis is tabulated in the table No.3 and 4.

Table 3: Fit Summary for Response: Residual Stress Reduction (RSR)

Source	**Sequential p-value**	**Lack of Fit p-value**	**Adjusted R^2**	**Predicted R^2**	**Remarks**
Linear	< 0.0001	0.0083	0.7929	0.7277	
2FI	0.4848	0.0067	0.7875	0.6365	
Quadratic	**0.001**	**0.105**	**0.9418**	**0.801**	**Suggested**
Cubic	0.6332	0.025	0.9332	-1.9012	**Aliased**

Quadratic Model was selected for analysis of the results given in table No.2.

Table 4: ANOVA table for % Residual Stress Reduction

Source	**Sum of Squares**	**Df**	**Mean Square**	**F-value**	**p-value**	**Remarks**
Model	602.56	9	66.95	60.27	< 0.0001	**Significant**
A-MC	354.47	1	354.47	319.09	< 0.0001	
B-TRS	25.98	1	25.98	23.39	0.0007	
C-WG	156.94	1	156.94	141.27	< 0.0001	
AB	0.183	1	0.183	0.1647	0.6934	
AC	35.07	1	35.07	31.57	0.0002	
BC	0.8515	1	0.8515	0.7665	0.4018	
A^2	14.25	1	14.25	12.83	0.005	
B^2	8.11	1	8.11	7.3	0.0223	
C^2	18.29	1	18.29	16.46	0.0023	
Residual	11.11	10	1.11			
Lack of Fit	9.16	5	1.83	4.69	0.0575	**Not Significant**
Pure Error	1.95	5	0.3901			
Cor Total	613.66	19				

The F-value 60.27 of Model in table no. 4, suggests that the model being used for further analysis is meaningful. As the Lack of Fit is therefore not substantial so that model is suitable for further analysis. The equation for an actual reduction in Residual stress on a % basis can be written as: -

%∆Residual Stress =

$$+46.29+18.17*MC+6.05*TRS-11.30*WG-4.87*MC*TRS-8.60*MC*WG-4.22*TRS*WG-12.09*MC^2-2.36*TRS^2-12.80*WG^2$$

Based on a statistical analysis of data given in table No 4 by using analysis of Variance (ANOVA) the outcome of many process constraints such as Magnetizing Current (MC), Tool Rotational Speed (TRS), and Working Gap (WG) is clarified with the help of Graph plots and 3D diagrams generated for all three factors used during the experiments.

3.1. Impact of Magnetizing Current (MC) on % Residual Stress Reduction (RSR):

From figure No 5[A] given below it can be seen that due to the increase in magnetization current the Residual Stress reduction (RSR) increases. The effect of Increasing magnetization current has been found as the best useful factor for residual stress reduction as compared to other two factors as per details available in table 5 where value of F for all the three factors is given (Niranjan & Jha, 2015). The contribution of this factor (MC) is 58.24% reduction in residual stress.

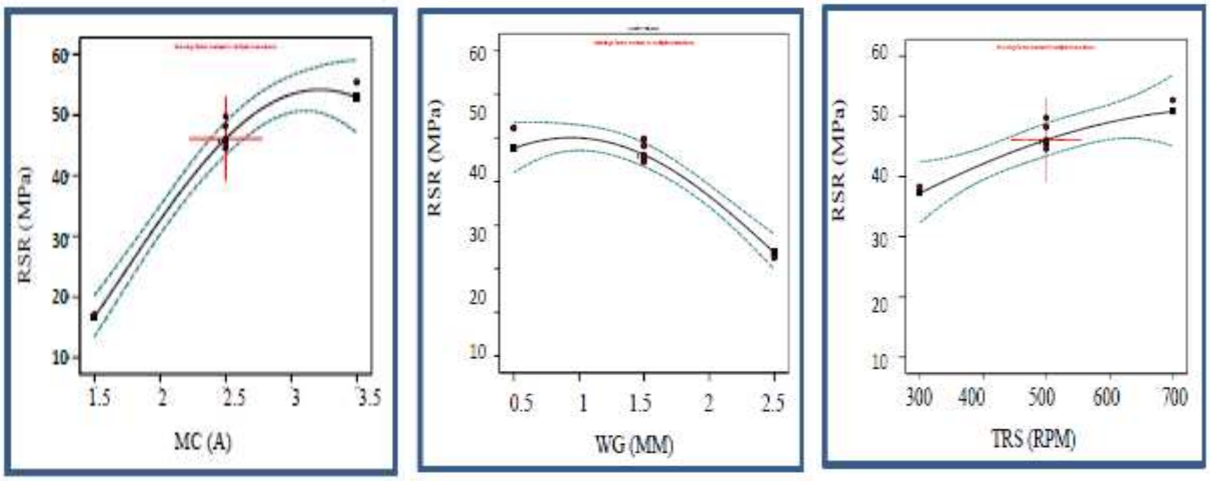

Fig 5. [A]. RSR (MPa) Vs MC (A), [B].RSR (MPa) Vs WG (MM) AND [C] RSR (MPa) Vs TRS (RPM)

3.2. Impact of Working Gap (WG) on % Residual Stress Reduction (RSR):

From figure No 5[B] given above due to the increase in working Gap the Residual Stress reduction (RSR) decreases. The effect of increasing the working gap is less effective than the effect of increasing Magnetizing current but it is more effective than the effect of increasing Tool rotational speed (TRS) as per details available in ANOVA table 5, this factor has 141.27 as F value (Niranjan & Jha Sunil, 2016).

3.3. Impact of Tool Rotational Speed (TRS) on % Residual Stress Reduction (RSR) (Niranjan & Jha Sunil, 2016)**:**

From the figure, No 5[C] given above it noticed that on increasing the tool rotational speed (TRS) the Residual Stress reduction (RSR) rate increases. The effect of increasing tool rotational speed is found least effective factor as compared to other two factors. This factor has least 23.39 as F-value.

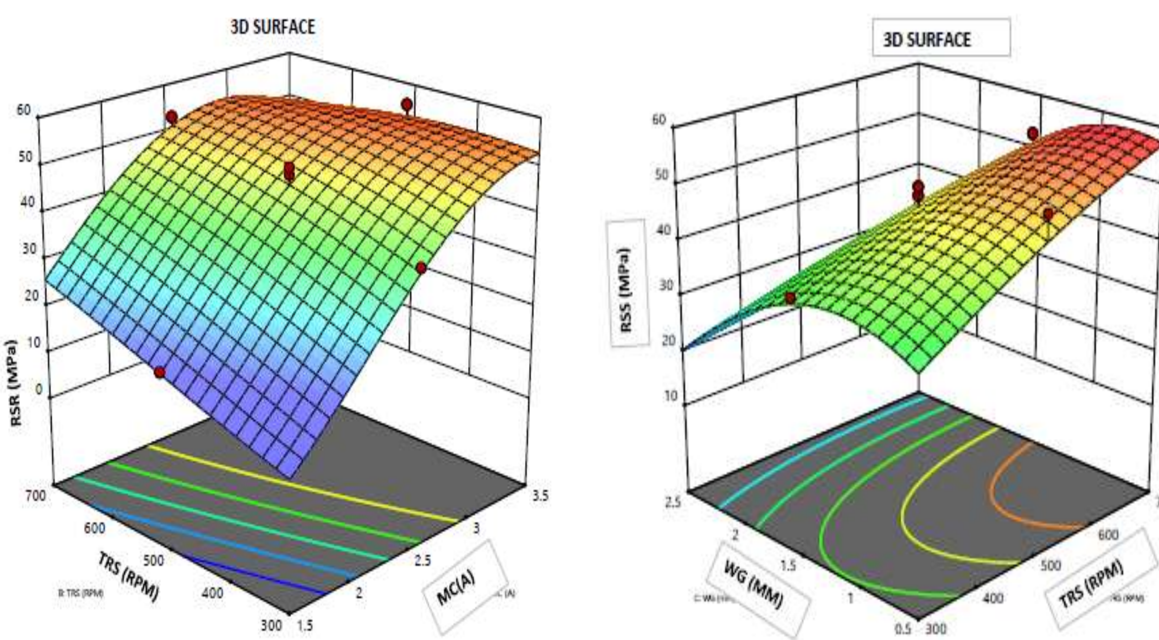

FIG. 6[A]. FIG. 6[B].

Fig. 6 [A] [B] &[C]. Percentage Reduction in Residual Stress with 3D Surface Diagrams

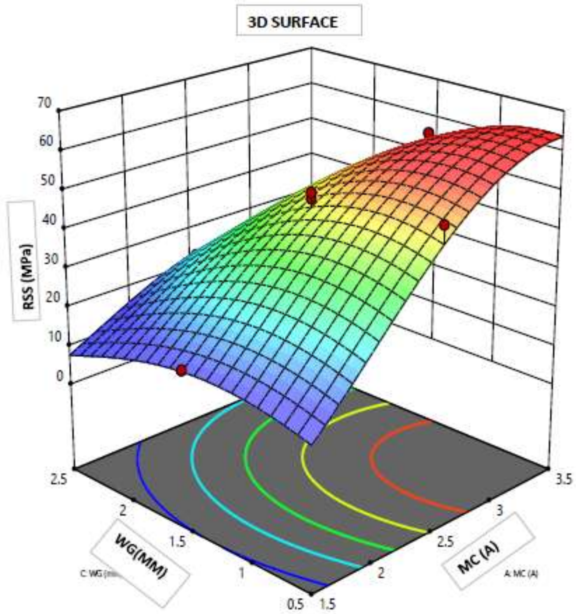

FIG.6[C].

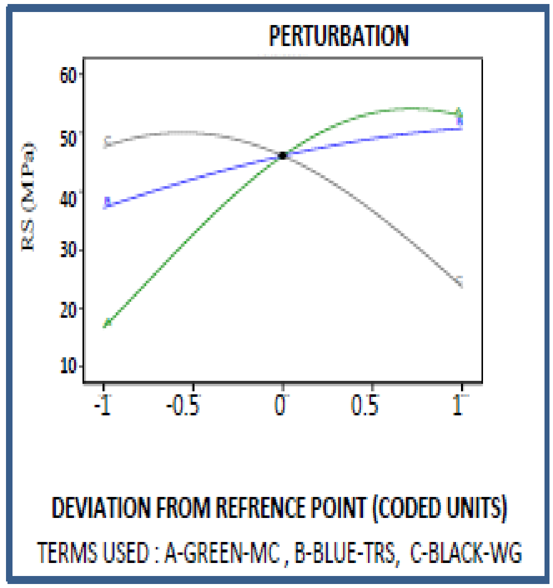

Fig.7. Perturbation Diagram for % Δ RSR

3.4. Interactive impact of different process factors at the Residual Stress Reduction (RSR)

The interactive effect of magnetization current (MC), Working Gap (WG) and Tool Rotational Speed (TRS) are shown in figure No 6.The Perturbation Graph of all three factors is also drawn as shown in fig. (7) (Kumari, Chak, & Vani, 2020).

4. Optimization of Output Responses

To optimize the output responses to obtain the best results in respect of Residual Stress reduction (RSR) Desirability Technique was used.

Table No. 5: Top Ten Predicted Solutions using the Desirability Technique

S. No.	MC (A)	TRS (RPM)	WG (MM)	%RSR	Desirability	Remarks
1	**3.20**	**660**	**0.60**	**61.23**	**1**	**Selected**
2	**3.10**	**670**	**0.90**	**60.54**	**1**	**Selected**
3	3.00	654	0.85	60.81	1	
4	3.26	531	0.77	60.07	1	
15	3.02	583	0.927	59.30	1	
6	3.06	537	0.69	58.47	1	
7	3.28	562	1.19	58.35	1	
8	3.27	459	0.86	58.23	1	
9	3.46	430	0.76	58.18	1	
10	3.43	433	0.70	58.09	1	

The top ten best solutions for residual stress reduction are shown in table no.5. The responses having a highest % Residual Stress reduction rate &having desirability value of '1' on the top of the table are selected for further confirmatory experiments. The results of confirmatory experiments are listed in table No. 6. The confirmatory experiments have confirmed that these results can be reproduced, and the solution obtained after optimization is correct.

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Table No.6**:** Confirmatory Experiments Results

S. No.	**MC (A)**	**TRS (RPM)**	**WG (MM)**	**% RSR**		**% Error**	**Remarks**
				Predicted	**Actual**	**% RSR**	
1	**3.20**	**660**	**0.60**	**61.23**	**61.96**	**-1.19**	**Selected**
2	3.10	670	0.90	60.54	60.92	-0.62	

5. Conclusions

Residual stresses in machined parts play a very important role and it will affect the performance & expected life cycle of these parts.

I. Three main factors are affecting the performance of the BEMRF process i.e., Magnetizing Current, Tool Rotational Speed and Working Gap.

II. Magnetizing Current is the most contributing factor out of the three factors and can be utilized to manipulate the magnetic field existing near the tooltip. By increasing the current supply, the strength of the magnetic field can be controlled. An increase in magnetizing current increases the % reduction in residual stress. Its contribution towards % reduction in residual stress is 58.24 %.

III. The working gap is the second largest contributing factor and as the working gap goes on increasing the % reduction in residual stress starts decreasing.

IV. Initially the rise in tool rotational speed enhances the % reduction in residual stress rate but its contribution is minimal and after reaching a particular speed further increases in tool rotation speed do not produce any positive effect on the % reduction in residual stress.

V. It can be concluded that by using ball end magneto-rheological finishing process using Pulse DC power supply (with a duty cycle 0.16)with a magneto-rheological fluid having the composition as 20 % Magnetic face (having 4% Nano CIP and 16% Micro CIP CS grade), 45% Cutting face (SiC of 800 mesh size) with 55% Carrier fluid (20 % AP-3 Grease and 80% Heavy duty Paraffin oil) on volume % basis the residual stress in EN-31 work-piece can be reduced 61.96%.

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7. **Abbreviations used in Graphs and Data Tables**: WG: Working gap, TRS: Tool Rotational Speed, MC: Magnetizing Current, RSR: Residual Stress Reduction, MRF: Magneto-rheological Fluid, BEMRF: Ball End Magneto-rheological Finishing and % Δ RSR: % Reduction in Residual Stress

References

F. Iqbal and S. Jha, "Closed Loop Ball End Magnetorheological Finishing Using In-situ Roughness Metrology," Experimental Techniques, vol. 42, no. December 2018, p. 659–669, 2018.

A. Mishra and T. Prasad, "Residual Stresses Due to a Moving Heat Source," International Journal of Mechanical Sciences, vol. 27, no. 9, pp. 571-581, 1985.

A. J. Perry, J. A. Sue and P. J. Martin, "Practical measurement of the residual stress in coatings," Surface and Coatings Technology, vol. 81, pp. 17-28, 1996.

K. Jian and X. Peng, "Cylindrical Magnetorheological Fluid Variable Transmission Controlled by Shape-Memory Alloy," Science and Technology of Nuclear Installations, vol. 2012, no. Special Issue, 2012.

S. Jha and V. K. Jain, "Design and development of the magnetorheological abrasive flow finishing (MRAFF) process," International Journal of Machine Tools and Manufacture, vol. 44, no. Issue 10, pp. 1019-1029, 2004.

A. K. Singh, S. Jha and P. Pandey, "Performance analysis of ball end magne-torheological finishing process with MR polishing fluid," Materials and Manufactur-ing Processes, vol. 30, no. 12, pp. 1482-1489, 2015.

A. Kumar, N. Kumar and M. S. Niranjan, "Synthesis and Characterization of Magnetorheological Fluids," International Journal of Innovative Technology and Exploring Engineering (IJITEE), vol. 9, no. 6, pp. 272-277, 2020.

M. S. Shunmugam and M. Kanthababu, Advances in Unconventional Machining and Composites, Singapore: Springer Science and Business Media, LLC, 2020.

S. Peter, S. Andreas, C. Helmut and M. Svea , Neutrons and Synchrotron Radiation in Engineering Materials Science: From Fundamentals to Applications, 2nd Edition, Verlag : Wiley-VCH Verlag GmbH & Co. KGaA., 2017, p. 488.

M. Singh and A. K. Singh, "Parametric Optimization for Nano-Finishing of the External Cylindrical Surfaces Using Rotating Core Magnetorheological Finishing Process," in International Manufacturing Science and Engineering Conference, College Station, Texas, USA, 2018.

M. S. Niranjan and S. Jha, "Statistical analysis of magnetorheological ball end finishing parameters using response surface methodology," International Journal of Manufacturing Technology and Management, vol. 30, no. july 2016, pp. 240-252, 2016.

M. S. Niranjan and S. Jha, "Optimum selection of machining parameters in ball end magnetorheological finishing process," International Journal of Precision Technology, vol. Vol.5, pp. 217-228, 2015.

E. H. J., L. H. S., Y. K., D. J. and S. F. T., "Experimental characterization of dynamic heat exchanger behavior," International Journal of Heat and Mass Transfer, vol. 121, no. June, pp. 933-942, 2018.

K. Manjesh, N. S. Y. Hari, K. Abhinav and . D. Manas, "An overview of magnetorheological polishing fluid applied in nano-finishing of components," Journal of Micromanufacturing, vol. April 2021, no. April, 2021. .

H. Li, I. Jönkkäri, E. Sarlin and F. Chen, "Experimental Comparison of Constitutive Models for Magnetorheological Fluids Under Different Conditions," Brazilian Journal of Physics, no. September, 2021.

S. M. T, "Effect of friction stir processing on electrical conductivity and corrosion resistance of AA6063-T6 Al alloy," Proceedings of the Institution of Mechanical Engineers Part C Journal of Mechanical Engineering Science, vol. 222, no. 7, pp. 1117-1123, 2008.

L. Wei, F. Meriem , H. Fan, H. Xuanhong, Z. Jun and H. Hua, "Mixed hemimicelle solid-phase extraction based on magnetic halloysite nanotubes and ionic liquids for the determination and extraction of azo dyes in environmental water samples," Journal of Chromatography A, vol. 5551, no. May, pp. 10-20, 2018.

S. R. N., D. M. , Y. B. K. and G. O. A., "Methods of measuring residual stresses in components," Materials & Design, vol. 35, no. March, pp. 572-588, 2012.

C. Kumari, C. K. Chak and V. V. Vani, "Experimental investigations and optimization of machining parameters for Magneto-rheological Abrasive Honing process," Materials and Manufacturing

Processes, vol. June 2020, no. Online, pp. 1622-1630, 2020.

P. M. Pandey, P. Kumar and V. Sharma, Advances in Production and Industrial Engineering, Heidelberg NY 5: Springer Science and Business Media LLC, 2021.

H. M. Aldawsari, N. R. Naveen, N. A. Alhakamya and ors, "Compression-coated pulsatile chronomodulated therapeutic system: QbD assisted optimization," Drug Delivery, vol. 29, no. 1, pp. 2258-2268, 2022.

A. K. Singh and K. P. Singh, "Response surface optimization of nitrite removal from aqueous solution by Fe3O4 stabilized zero-valent iron nanoparticles using a three-factor, three-level Box-Behnken design," Research on Chemical Intermediates, vol. 42, no. 3, p. 2247–2265, 2015.

F. Iqbal and S. Jha, "Experimental investigations into transient roughness reduction in ball-end magneto-rheological finishing process," Materials and Manufacturing Processes, vol. 32, no. 2, pp. 224-231, 2019.

N. Khatri, J. X. Manoj, V. Mishra, H. Garg and V. Karar, "Experimental and simulation study of nanometric surface roughness generated during Magnetorheological finishing of Silicon," Materials Today: Proceedings, vol. Volume 5, no. 2 Part-1, pp. 6391-6400, 2018.

Z. Alam, D. A. Khan and S. Jha, "A study on the effect of polishing fluid volume in ball end magnetorheological finishing process," Materials and Manufacturing Processes, vol. 33, no. 11, pp. 1197-1204, 2017.