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Experimental Investigation into Residual Stress in Ball End Magne-Torheological Finishing

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ABSTRACT

Ball end magnetorheological finishing (BEMRF) is a novel finishing process used to finish variety of surfaces ranging from flat, curved, complex, two dimensional, three di-mensional and non linear. The residual stress and surface finish play an important role in overall efficiency and durability of the components. The present work is aimed to relieve the residual stress of work-piece surface with the improvement in surface finish using pulse DC power supply (PDCPS) in BEMRF process. The preliminary experiments have been conducted on flat EN-31 steel with and without pulse DC power supply (WPDCPS). The process parameters during experiments were considered as magnetiz-ing current (MC) of 2.5A, tool rotational speed (TRS) 500 rpm, and working gap (WG) 1.5 mm with finishing time 35 minutes and 55 mm/minute feed rate given to the work-piece. The responses such as residual stress and surface roughness have been measured before and after experimentation. Residual stress of EN-31 surface was measured with X-ray residual stress analyzer using Cosα method. It has been observed that the residual stress was found reduced from 130 to 66 MPa and surface roughness was reduced drastically with the use of pulse DC power supply in BEMRF process. After preliminary experi-mentation, the statistical analysis with design of experiment has been conducted with pulse DC power supply on EN-31 steel to visualize the effect of various process parame-ters on residual stress using RSM technique.

Keywords: BEMRF; Residual stress; Surface finish; Duty cycle; Pulse DC power

NOMENCLATURES

%ΔRS	percentage reduction in residual stress [μm]TRS tool rotation speed[rpm]	
WG	working gap[mm]MC	magnetizing Current [A]
RS	Residual stress [MPa]Ra	Surface roughness [μm]
PDCPS	Pulse DC power supplyFMF	Fluctuating magnetic field

INTRODUCTION

Residual stresses (RS) plays an important aspect in finished product and these stresses are those stresses which are remain in a solid material after machining. Residual stress is generally undesirable in the machined components. The functional behavior and efficien-cy of machined components can be enhanced with the relieve of residual stresses (Paul, A., Akash, P. Savio, 2015). The study of residual stress is important for overall part quality. The effect of machining parameter on residual stress (RS) was analyzed by performing the experiments on stainless steel (AISI 304) (Jang, D.Y., 1996). The RS Measurement on the finished surface was done using X-ray diffraction technique and it was observed that sharpness of tool influences the surface residual stress significantly (Henriksen, E.K. 1951).FEM model was developed to study residual stress due to moving heat source and it was predicted that residual stresses in grinding process are generated by thermal and mechanical abrasion only (Mishra, A., and T. Prasad. 1985). Conventional finishing processes like lapping, honing, grinding etc. produce residual stress, burrs and damage of subsurface of the components. It is essential to achieve surface roughness in nano level or beyond nano level to get desired quality finishing processes assisted by magnetic field are Magnetic abra-sive finishing (MAF) (S. Ahmad et. al. 2021), Magnetorheological jet finishing (MRJF) (Kordonski,W.I. et.al 2006), Magnetic float polishing (MFP) (Komanduri, R. 1996), Magnetorheological finishing (MRF) (Kordonski, W.I., and Jacobs, S.D. 1996), Rota-tional magnetorheological abrasive flow finishing (R-MRAFF) (Das, M. et.al 2012), and ball end magnetorheological finishing (BEMRF) (Singh, A.K. et. al 2012).

The finishing forces in Magnetorhelogical Finishing (MRF) can be controlled by ap-plied magnetic field and hence final surface finish. The wear occurs in nano finishing by the selective mechanical abrasion in MR finishing while in case of grinding the wear occurs due to both thermal and mechanical abrasion. This mechanical abrasion is respon-sible for finishing of work-piece. The RS produced due to machining, and damage of surface or subsurface in grinding or lapping processes. The sub surface damage is linked with a layer of material in residual stress. The damage of surface or subsurface and residual stresses present in the work-piece was removed effectively by the use of MRF process (Steven, R. A., 2001). MRF process neglects subsurface damage. A highly viscous semi-solid shape is formed at the end of finishing tool in Magnetorhelog-ical finishing. The semi solid MR fluid shape moves over any kind of work-piece sur-face during finishing (Sidpara A.,Jain, V.K.; 2012). BEMRF process is a variant of mag-netorheological finishing process for novel finishing. MR polishing fluid used at the tip of the finishing tool formed a highly viscous semi solid hemi spherical ball in the pres-ence of magnetic field. MR polishing fluid is a mixture of carbonyl iron particles (CIPs) and micronsized abrasives (Saraswathamma, K. et.al 2015). MR fluid behaves like a semi solid ball when continuous DC power supply is given to electromagnetic coil. The MR fluid semisolid hemi spherical ball is formed at the tip of tool. This hemi spherical ball acts as a finishing tool and has the capability for finishing a variety of typical work-piece surfaces.

In advancement of BEMRF process, a PDCPS was used to magnetize the electromag-net coil in order to produce fluctuating magnetic field (FMF) at the tip of ball end magne-torheological finishing tool. Fluctuating magnetic field (FMF) density is operated by switching the DCPS ON and OFF alternatively termed as Duty cycle. The Duty cycle results in orientation change of abrasive particles which has more finishing capability as compared to Continuous DCPS was used to magnetize the electromagnetic coil. BEMRF process is used with continuous DCPS (WPDCPS) and has no FMF at the tip of tool due to which no fresh active abrasive grains come with work-piece surface. Pulse DC power supply is used in BEMRF process in which fresh active abrasive grains or changed orientation of active abrasive grains are responsible for finishing effi-ciently with the surface. BEMRF process used with pulse DC power supply was called Pulsed BEMRF(PBERMF) process. It was observed that the better surface finish is achieved with PBEMRF as compared to continuous DCPS using BEMRF process at same process parameters (Singh, H. et. al 2020).

The pulse DC power supply was also used in magnetic abrasive finishing (MAF) for advancement of this process. The continuous DC power supply and pulsating DC power supply was used in MAF process. It was observed that better surface finish has been found with pulse DCPS as compared to continuous DCPS at same process parameters (Jain, V.K. et. al 2008).

In the paper, the experiments were performed on EN-31 steel with PBEMRF and con-ventional BEMRF process to see the effect on residual stress (RS) and surface rough-ness at same process parameters of 1.5 mm working gap, 500 rpm tool rotational speed and 2.5A magnetizing current.

EXPERIMENTAL PROCEDURE

A PDCPS based BEMRF set up called PBEMRF has been indigenously designed and developed. The various parts of experimental setup of pulse ball end magnetorheo-logical finishing (PBEMRF) setup including residual stress analyzer is shown in fig. 1. PBEMRF process generate fluctuating magnetic field at the tip of magnetorheological finishing tool. The orientation of abrasive particles is changed during experiments which enhence the surface finishing capability on the work-piece. This ultra surface finishing achieved at low temperature in PBEMRF process may improve surface quality with reduction in residual stress.

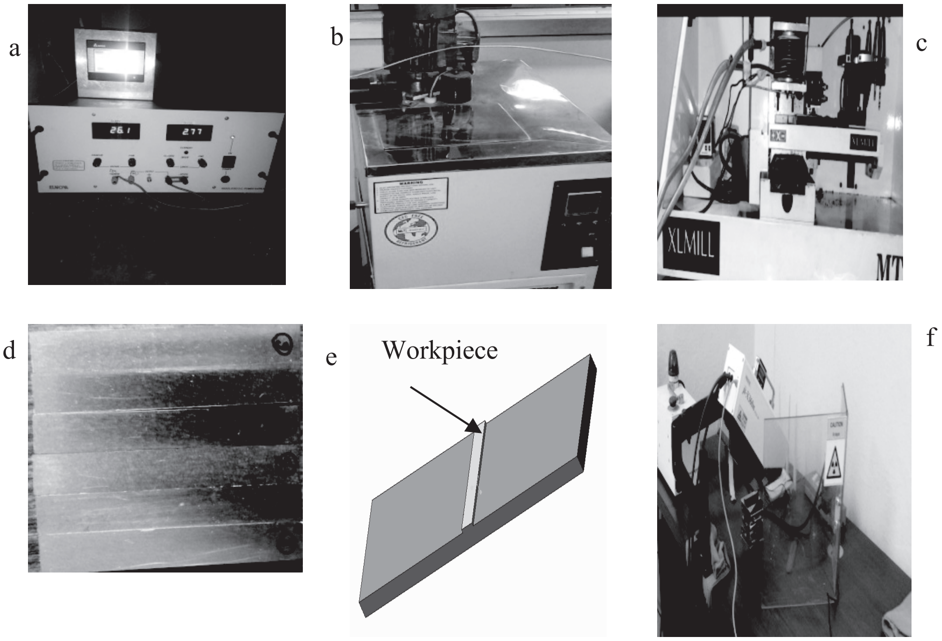


Figure 1. (a) Pulse DC power supply (b) Chiller for cooling the finishing tool (c) BEMRF setup (d) EN-31Surface after Finishing (e) Schematic of die with work-piece (f) X-ray residual stress analyzer

In continuous DC power supply based BEMRF process, the orientation of abrasive particles do not change during experiments. The use of pulse DC power supply in BEMRF process provide higher reduction in residual stress and improve subsurface damage (SSD). The Semi solid ball behaviour with BERMF process or PBEMRF pro-cess is shown in fig.2a and fig. 2b respectively.

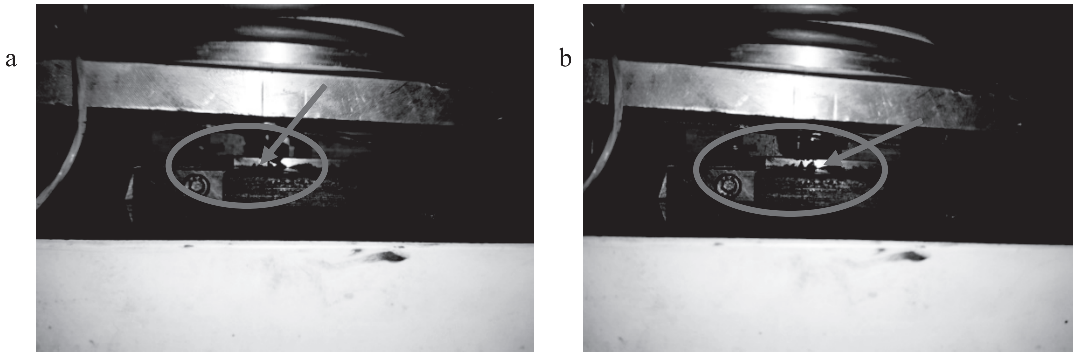


Figure 2. Schematic of wear behaviour in (a) BEMRF process (b) PBEMRF process

PRELIMINARY EXPERIMENTATION

The experiments were conducted at magnetizing current 2.5 A, tool TRS 500 rpm, WG 1.5 mm and duty cycle 0.16 in PBEMRF process (Singh, A.K. et al 2015 - Singh, A.K et. al 2013). Conventional BEMRF process used for finishing was carried out at MC 2.5 A, TRS 500 rpm and WG 1.5 mm. Duty cycle was found on the basis of pulse on and pulse off time. In the same manner, the residual stress of grinded surface before BEMRF pro-cess and after conducting experiments with BEMRF process were measured using x- ray residual stress analyzer. Thereafter percent reduction in residual stress (%ΔRS) was cal-culated. In the present work, Cosα method has applied to measure the residual stress of machined surface of EN-31 steel made by the PBEMRF and BEMRF technique. The comparative results of residual stress and surface roughness after conducting experi-ments with BEMRF process with and without pulse are shown in table 1& 2 respectively.

The %ΔRS and %ΔRa is calculated as

$$\%\Delta RS \; = \frac{(Initial\ residual\ stress - Final\ residual\ stress)}{Initial\ residual\ stress} \times 100$$

$$\%\%\Delta Ra = \frac{(Initial\ roughness - Final\ roughness)}{Initial\ roughness} \times 100$$

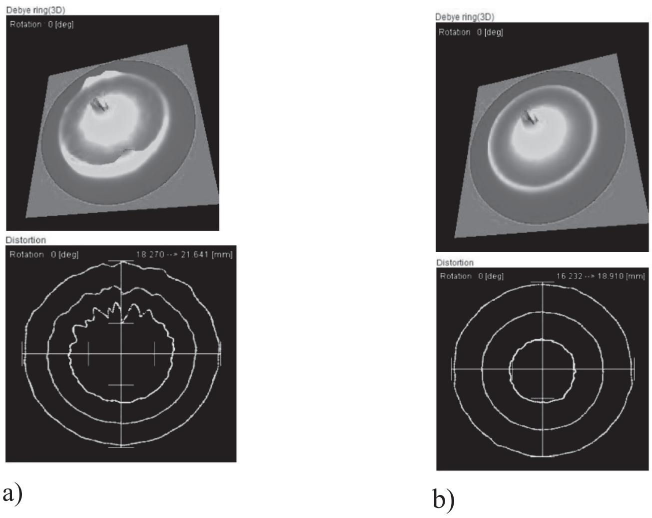
Table 1. Preliminary experiment for residual stress and surface roughness with pulse DC power supply in BEMRF

S. No	Duty cycle	MC(A)	TRS (rpm)	WG (mm)	Initial Residual Stress	Final Residual Stress	%ΔRS	Initial Surface roughnes	Final Surface roughness	%ΔRa
.1	0.16	2.5	500	1.5	127	70	44.88	.189	.114	39.68
.2					124	71	42.74	.203	.127	37.43
.3					130	66	49.23	.196	.120	35.20

Table 2. Preliminary experiment for residual stresses and surface roughness without pulse DC power supply

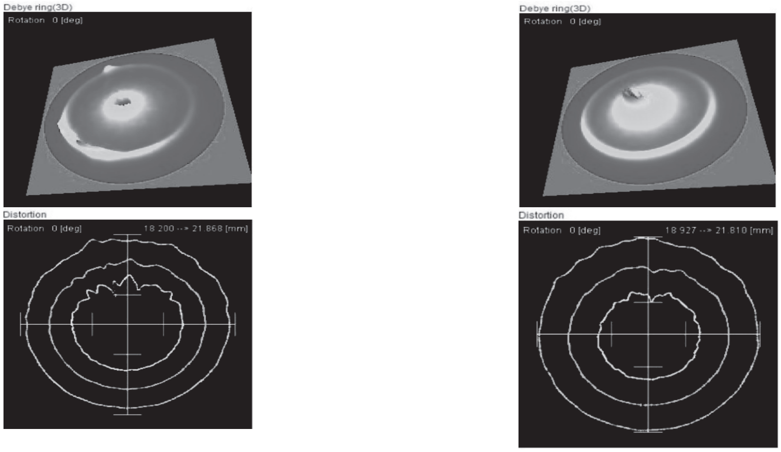
S.No	MC (A)	TRS (rpm)	WG(mm)	Initial Residual Stress	Final Residual Stress	%ΔRS	Initial Surface roughness	Final Surface roughness	%ΔRa
1.	2.5	500	1.5	116	86	25.86	0.193	0.166	13.98
2.	2.5	500	1.5	129	92	28.68	0.191	0.156	18.32
3.	2.5	500	1.5	142	103	27.46	0.188	0.154	18.08

The residual stress of initial grinded work-piece was measured efficiently by detecting the full Debye ring data from a single incident X-ray angle (35o) as shown in fig. 3(a) and 4(a). Figure 3 and 4 shows the Debye ring 3(D) and Distortion ring taken under normal incidence. The Debye ring of grinded work-piece has higher irregularity and the ring was not seen clearly which represent texture of surface (Ogawa,D. et.al 2019) is shown in fig.3a & fig 4a. The Debye ring and Distortion ring of finished surface using pulse DC power supply using BEMRF process which has less irregularity and debey ring was seen clearly due to fine surface of work-piece as shown in fig.3b. Debye ring and Distortion ring of finished surface by without pulse DC power supply using BEMRF process as shown in fig.4b which has less uniform ring than finished surface with pulse power supply in BEMRF process. The Debye ring represents the texture of surface. The full width at half-maximum (FWHM) is minimum for the grinding surface of work-piece and FWHM is increased when finishing is done without pulse DC power supply in BEMRF process.



a) b)

Figure 3. Debye ring (3D) and Distortion ring of (a) initial grinding work-piece at 130 MPa, FWHM= 3.31 degree (b) work-piece surface at 66 MPa, FWHM=3.52 with Pulse DC power supply in BEMRF.



a) *b)*

Figure 4. Debye ring (3D) and Distortion ring of (a) initial grinded work-piece at 129 MPa, FWHM= 3.28 (b) work-piece surface at 92 MPa, FWHM= 3.50 Without pulse supply in BEMRF.

In fig. 5 and 6 x-axis Cosα represents cos of azimuth angle of Debye sheerer ring and y-axis represents strain (εα1). The residual stress was measured by the inclination angle of bend. The measured value of residual stresses after grinded surfaces of EN-31 are ob-served as 130 MPa, 129 MPa respectively which is shown in fig.5a and 6(a). The resid-ual stress of finished surface was reduced to 66 MPa with pulse DC power supply in BEMRF process as shown in Fig.5b. The residual stress graph shown by fig.5b repre-sents that residual stress was reduced drastically with the pulse DC power supply in BEMRF process. However, the residual stress was reduced without pulse in BEMRF process as shown in fig.6b but that reduction in residual stress was lesser than reduction in residual stress with pulse DC power supply in BEMRF processes at same process parameters.

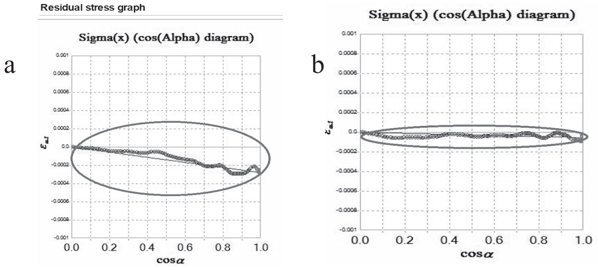


Figure 5. Residual stress graph of (a)initial grinded surface at 130 MPa (b)Finished sur-face by pulse BEMRF at 66 MPa

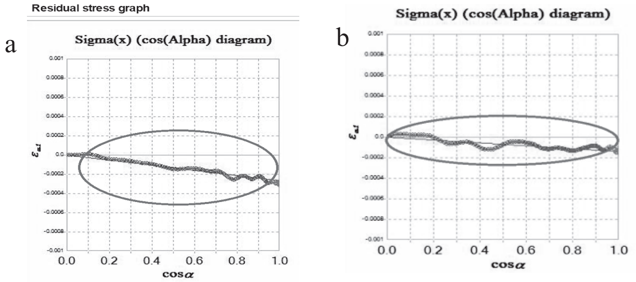


Figure 6. Residual stress graph of (a) initial grinding at 129 MPa (b)Finished surface by without pulse BEMRF at 92 MPa

The optical microscopic views of finished surface are obtained by conducting the exper-iments with PBEMRF and without pulse BEMRF process. From fig 7a, it is observed that the surface texture was found less improved by using without PDCPS as compared to surface texture obtained by using PBEMRF process.

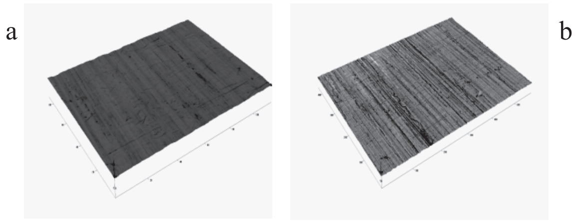


Figure 7. 3D optical microscopic texture (a) finished with PBEMRF process (b) finished without pulse BEMRF process

Scanning electron micrographs (SEM) of the work-piece surface are given in fig.8 at 50 μm resolution and 1200X magnification. Initial surface with clear lays is shown in fig.8a . Fig. 8b shows that better surface finished obtained with pulse BEMRF process as compared to surface finish obtained by BEMRF process without pulse as shown in Fig. 8c.

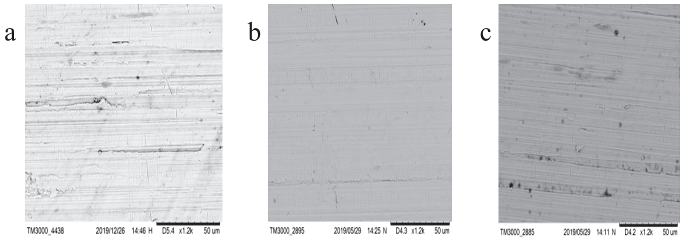


Figure 8. SEM graph of (a) Pre finished (grinded) surface texture (b) finished surface with pulse BEMRF process (c) finished surface without pulse BEMRF process.

Atomic force microscopy (AFM) images are shown in fig. 9. The more lays are seen by the grinded surface (pre finish) as shown in figure 9a. The density of lays is 0.301 (/µm^2) and means height of peak is 5.454 (°). The surface texture produced with BEMRF as shown in fig.9b is quite unlike from the fig.9a because without pulse BEMRF finished surface has very fine lays. The surface texture is produced with pulse BEMRF process has more fine lays as shown in fig.9c as compared to surface texture obtained by BEMRF process without pulse DC power supply. The density of the lays and mean height of peak are 9.250 (/µm^2) and 2.426 (°) respectively obtained with pulse BEMRF process.

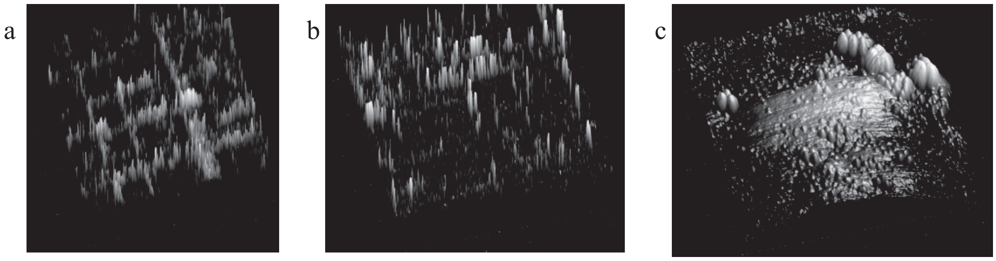


Figure 9. AFM images of EN-31 steel surface (a) pre finished (grinded) surface (b) Fin-ished surface by BEMRF process without pulse (c) Finished surface by pulse BEMRF process.

A drastic reduction in residual stresses was observed after conducting the preliminary experimental study on EN-31 steel . Surface roughness of the work-piece also reduced considerably after pulse BEMRF process. Residual stress was relieved from the work-piece 130 MPa to 66 MPa in pulse BEMRF process.

In order to analyze the effects of various process parameters on residual stress, detailed experiments were conducted on EN-31steel surface by considering three process pa-rameters at five levels as provided in table 3.

Table 3. Level and ranges of process parameter

S No	**Process parameter**	**Units**	**Levels**				
			-2	**-1**	**0**	**1**	**2**
1	Magnetizing Current	A	1.5	2	2.5	3	3.5
2	Tool rotational speed	rpm	300	400	500	600	700
3	Working gap	mm	0.5	1	1.5	2	2.5

DESIGN OF EXPERIMENT

Experiments were performed on the basis of preliminary study using the response surface methdology (RSM) under central composite design (CCD). Five levels with three process parameters were considered for statistical analysis using response surface methodology to find out the response on percent reduction in residual stress. The results of output responses using PBEMRF process are shown in table 4.

RESULT ANALYSIS AND DISCUSSION

Residual stresses of work- piece are taken by X-ray residual stress analyzer. Table 4 shows the percentage reduction in residual stress on EN-31 steel surface through PBEMRF process.

Table 4. Design and result of output response (% Reduction in Residual Stress)

Std order	**Run order**	**Magnetizing current (A)**	**Rotation of central core (rpm)**	**[1] Working gap (mm)**	**% Reduction in Residual Stress** (%ΔRS)
16.	1	2.5	700	1.5	51.58
12.	2	3	400	1	52.50
4.	3	2.5	300	1.5	37.44

1.	4	3.5	500	1.5	54.11
10.	5	2	400	1	24.61
14.	6	3	600	2	39.69
15.	7	3	400	2	38.82
13.	8	2.5	500	1.5	44.4
17.	9	2	400	2	22.6
20.	10	2.5	500	2.5	21.34
6.	11	1.5	500	1.5	15.89
7.	12	2	600	2	28.03
11.	13	2.5	500	1.5	42.57
5.	14	2	600	1	36.9
9.	15	2.5	500	0.5	50.92
2.	16	2.5	500	1.5	48.91
3.	17	3	600	1	56.27
19.	18	2.5	500	1.5	47.58
18.	19	2.5	500	1.5	45.57
8.	20	2.5	500	1.5	44.78

In DOE, the large F-value for the model has only 0.01% possibility to occur due to noise. These terms A,B,C, and AC , C2, A2 are found to be significant with reduced model of ANOVA as shown in table 5.

Table 5. Anova For Percent Reduction In Residual Stress (%ΔRs)

Source	**Sum of Squares**	**DOF**	**MSE**	**F-value**	**p-value**	
Model	**2591.17**	**6**	**431.86**	**43.89**	**< 0.0001**	**Significant**
A-current	1436.03	1	1436.03	145.93	< 0.0001	

B-rotation	160.28	1	160.28	16.29	0.0031	
C-working gap	628.76	1	628.76	63.89	< 0.0001	
AC	46.95	1	46.95	4.77	0.0479	
A^2	207.35	1	207.35	21.07	0.0005	
C^2	167.68	1	167.68	17.04	0.0012	
Residual	127.93	13	9.84			
Lack of Fit	101.76	8	12.72	2.43	0.1714	not significant
Pure Error	26.16	5	5.23			
Cor Total	2719.10	19				

The actual equation for percent reduction in residual stress (%ΔRS) is given as

$$\%\Delta RS = -129.065 + 89.58*A + 0.031*B + 41.9*C - 9.69*AC - 11.22*A2 - 10.09*C2$$

From the statistical analysis using analysis of variance (ANOVA) the regression model has been developed. In this section the effect of process parameters such as MC,WG and TRS are explained.

Effect of Magnetizing current on percent reduction in residual stress

Figure 10(a) explain that the %ΔRS is improved with increase in the magnetizing current at various tool rotation speed (TRS) with the constant working gap(WG) 1.5 mm. Magnetizing current (MC) is found as the most effective contributing parameter for reduction in residual stresses from ANOVA table 4. The contribution of MC in % ΔRS is 54.25 %.The Magnetic flux density of MR fluid at the tip of finishing tool can be enhanced by the increasing the current supply. This residual stress is relieved from the work-piece with pulse BEMRF process due to the pressure generated by group of fresh abrasive particles in the finishing zone.

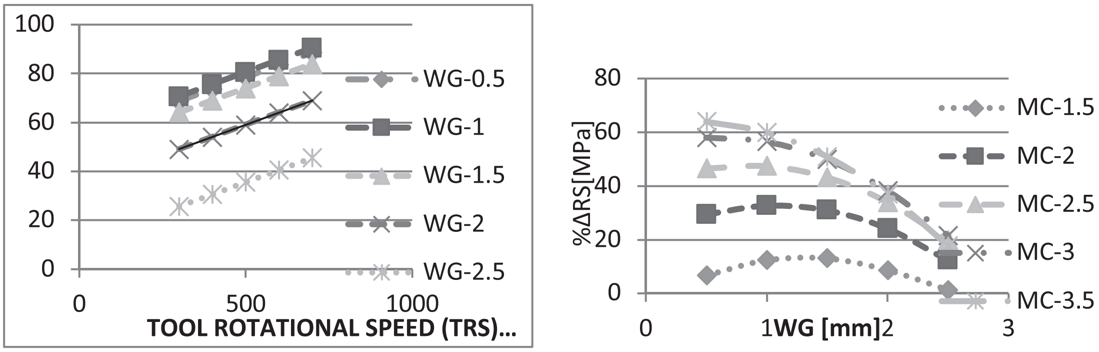
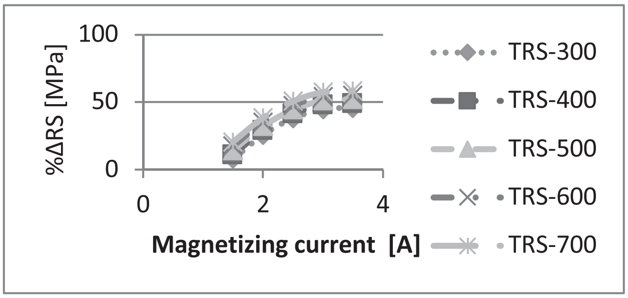


Fig.**10** Effect of (a) MC (b) TRS (c) WG on %ΔRS

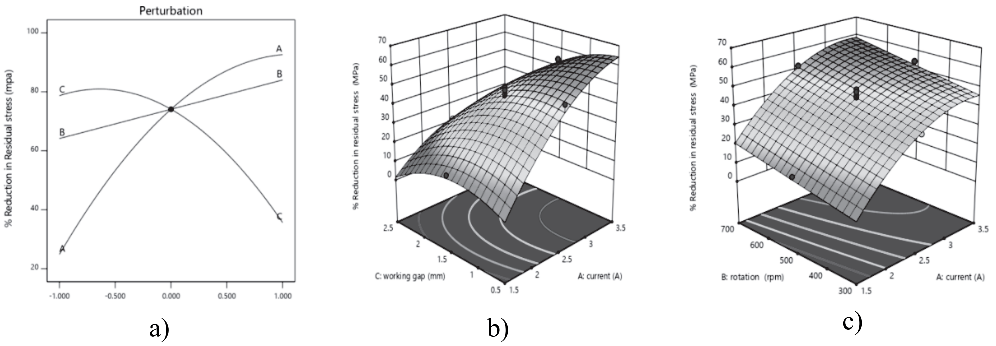


Effect of TRS on % ΔRS

It is observed from the figure 10(b) as the TRS (rpm) increases %ΔRS slightly increases at various working gap (WG) with constant MC 2.5 A. It is noted from table 5 that the TRS is the least contributing process parameter on % ΔRS with 16.29 F-value.

Effect of working gap (WG) on percent reduction in residual stress

The gap between the work-piece surface and tip of finishing tool is known as working gap (WG). It is observed from Fig. 10(c) that the %ΔRS decreases with the increase in WG at constant TRS 500 rpm. The contribution of WG in %ΔRS is found as 63.89 F- value and maximum %ΔRS is observed at WG of 0.5 mm.



a) b) c)

Figure 11. a) Perturbation diagram for %ΔRa (A - current, B –tool rotation speed, C- working gap), b& c) The %Δ Ra with 3D surface.

CONCLUSION

The statistical analysis using response surface methodology was done to see the effect of various process parameters using pulse DC power supply in BEMRF process on percentage reduction in residual stresses (%Δ RS). It is observed that the better percent reduction in residual stress was achieved with PDCPS in BEMRF process as compared to BEMRF process without PDCPS. The surface finish obtained with pulse BEMRF process has very fine surface texture than surface finish surface obtained by BEMRF process without pulse DC power supply. The percent reduction in residual stress is found as 49.23% at 0.16 duty cycle with PDCPS in BEMRF process while 28.68% without PDCPS in BEMRF process. AFM image of EN-31 workpiece has better surface texture using pulse supply as compared to without pulse supply in BEMRF process. The residual stress was relived from the work-piece surface significantly using pulse supply in BEMRF process. The %ΔRS is found increased with increase in the MC and was observed to be maximum at 3.5A. The Magnetizing current was most effective process parameter on %ΔRS. Rotation speed of central core was least contributing parameter on percentage reduction in residual stress. As the tool rotation speed (rpm) increases, the percentage reduction in residual stress slightly increases and observed maximum at 700 rpm. The WG was the second most effective parameter in finishing of EN-31 steel. The %ΔRS is found decreased with increase in working gap and observed maximum at 0.5 mm.

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