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Optimization of Burnishing Parameters by DOE and Surface Roughness, Microstructure and Micro Hardness Characteristics of AA6061 Aluminium Alloy in T6 Condition

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ABSTRACT

Surface finish and surface hardness of the components play vital role in quality of products/components, in general and failure resistance, in particular. One of the finishing process that involve surface plastic deformation and introduces compressive residual stresses and thereby improve fatigue resistance is "Burnishing". Even though the burnishing process is widely employed, its process parameters were not systematically studied till date and not fully established for various important structural materials, including the present material of study the AA6061 aluminium alloy. The burnishing process parameters studied in this investigation include depth of cut, speed, feed, and number of tool passes. The data obtained from systematically conducted burnishing experiments are correlated with theoretical design using Taguchi method. Further, surface characterization was conducted using optical microscopy and XRD studies were employed to estimate the micro hardness and magnitude of residual stress. The study revealed a one-to-one correlation between various burnishing parameters and a peak in all the three parameters, viz. burnishing depth, average micro hardness and compressive residual stress levels at intermediate extent of burnishing (either after first or second pass) in AA6061 alloy.

Keywords - Roller burnishing; surface roughness; microstructure; micro hardness; residual stresses;

I. INTRODUCTION

The performance of a machined component for rotating structural applications largely depends on load bearing capacity, deformation and fracture resistance and more importantly fatigue resistance which all depend to a large extent on the surface topography, hardness, nature of residual stress, strain distribution, as also frictional response. The study of the contact aspects between machine elements is essential due to the fact that more than 70% of provided energy is lost by friction, resulting from the relative movements between the elements [1,2]. Roughness values less than 0.1 µm are required for good aesthetic appearance, easy mould release, good corrosion and fatigue resistance. It is observed that conventional machining methods leave inherent irregularities on surface and it becomes necessary to resort to a series of finishing operations such as grinding, lapping and honing; which processes involve high costs [3,4]. During recent years considerable attention has been paid to the post-machining metal finishing operations, especially burnishing which improves the surface characteristics by plastic deformation of surface layers [5]. Burnishing is economically viable machining process and requires less time and skill to obtain a high quality surface finish [6]. The study of surface finish that results from burnishing is very much essential because the fatigue life, bearing properties and lubrication of a part depends largely upon the appropriate surface finish [7], which ultimately decides the effectiveness of burnishing process. If the surface finish is high, then seizure would occur due to difficulty of maintaining the lubricating oil film. On the other hand, if the surface finish is low, the hills in irregular surface reduce the metal to metal contact and valleys help to retain the film of lubricating oil; but, cannot be below certain level of surface finish as low surface finish leads to high wear and inferior fatigue resistance. In order to increase the life of any part which is subjected to repeated reversals of stress, the working and non-working surfaces of that surface must be given as good surface finish as economical as possible. A constant surface roughness, a desirable feature can be achieved over a wide range of process conditions through hard roller burnishing [8].

Scientific studies conducted till date indicate that burnished surfaces have many advantages over ground surfaces [9,10]. Some of the researchers studied burnishing parameters such as speed, force and burnishing depth and feed rate as well as number of tool passes apart from burnishing tool dimensions in relation to surface roughness and surface hardness [10-14]. Experiments were also conducted to find the distribution of residual stresses and burnishing layer thickness [15-24]. The present work is an attempt to report the results obtained from systematically conducted studies on the effect of external roller burnishing on surface roughness, surface hardness and microstructure as well as micro hardness in case of AA6061 alloy as a function of various burnishing parameters.

II. BUNISHING PROCESS

Specimens were turned and burnished on a lathe machine. The initial work piece material was in the form of round rod of 32 mm diameter. It is turned and finished to 30 mm diameter. These specimens were subjected to surface roughness measurements. The work pieces were prepared with two recesses such that each specimen could be used in two different conditions; namely unburnished and burnished. A portion of the each specimen was left without burnishing for comparison purpose**.** A feed rate of 0.032 mm/rev and spindle speeds of 35.6, 22.6, 14.57, 9.55 and 6.03 m/min were used as **t**he basic burnishing parameters. The basic tools and setups used for burnishing are shown in Figs. 1 and 2 and further details can be obtained from works of Ravindra Babu and co-workers [17-23].

III. EXPERIMENTAL

Fig. 1: External roller burnishing tool used for the conduct of experiments in the present study

III.1. Material

The work piece material is AA6061 aluminium alloy, obtained from standard suppliers. The nominal composition of the alloy is: Al (95.85) – Cr (0.04-0.35) – Fe ((0.7 Max.) – Mg (0.8-1.2) – Mn (0.15 Max.) – Si (0.4-0.8) – Ti (0.15 Max.) – Zn (0.25 Max.) – Cu (0.15-0.4), all in weight %.

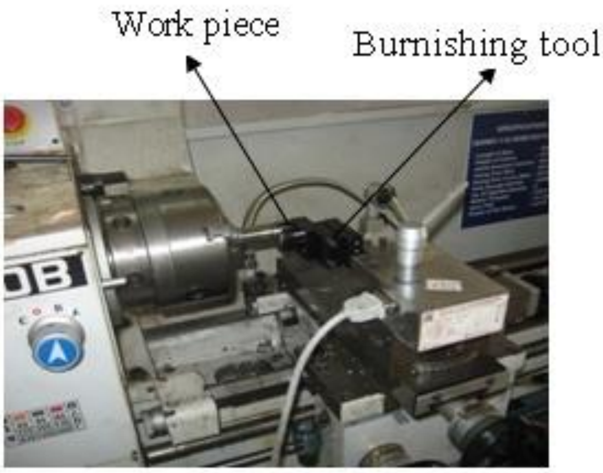


Fig. 2: Burnishing setup used in the present study.

III.2. Surface Roughness

Surface roughness values of the work pieces are noted before and after burnishing by using stylus probe instrument (Model: Mitutoyo SJ-201P). From these data, the surface finish values are also determined before and after burnishing for different burnishing speeds. It is to be noted here that either of surface roughness or surface finish can be used as representative of surface characteristic feature (the lower is surface roughness and higher is surface finish).

III.3. Microstructure

The microstructure of the AA6061 alloy was studied after carefully preparing the burnished surfaces. The depth of burnishing as well as its magnitude with respect to grain width was determined by studying microstructure using image analyzer optical microscope (Model: Leica DMLM Upright). The specimens surfaces for this purpose were prepared by progressive polishing using 0.5 µm diamond paste and then etching the polished surfaces using an etchant containing 25 ml methanol, 25 ml HNO_3, 25 ml HCl and 1 ml HF.

III.4. Micro Hardness

The micro hardness values are obtained as a function of radial distance from burnished surface to the center. A micro hardness machine (Model: Micromet 2100, Buehler Ltd, USA) with Vickers indenter and 500 g indenter load was employed for this purpose.

III.4. Residual Stresses by XRD

The residual stresses were measured using X-ray residual stress analyzer. In this, the lattice distortion creates difference in inter-planar spacing of atoms of the material, which can be measured through X-ray diffracting technique. In this measurement the difference in the inter-planar spacing and subsequent lattice distortion are compared with the standard values of an undistorted metal and the strain is calculated. The strain intern gives the magnitude of residual stress values, when multiplied with elastic modulus.

IV. DESIGN OF EXPERIMENTS (DOE)

Design of experiments (DOE) determines the pattern of observations to be made with a minimum experimental effort, in which effects of multiple factors are studied simultaneously by running tests at various levels. The levels that should be taken, how to combine them, and how many experiments should be run are subjects of importance in DOE. Factors that have direct influence on the performance of the product or process under investigation are classified as: (i) Discrete – those assume known values or status for the level and (ii) Continuous – those can assume any workable value for the factor levels. Minimum number of levels required to make comparison of the performance is two and they determine the influence. An effective DOE provides optimize design using analytical simulation studies; optimum manufacturing process and finally the best assembly method.

IV.1. DOE using Taguchi approach

Design of experiments (DOE) using Taguchi approach is a standardized form of experimental design technique introduced by Fisher, 1990 [24]. DOE with Taguchi approach improves the consistency of performance and saves cost and reduces the time to find the best method without doing the full factorial experiments. In this approach, a fixed number of orthogonal arrays are utilized to handle many common experimental situations. Taguchi has constructed a number of orthogonal arrays to accomplish the experiment design. Each array can be used to suit a number of experimental situations. The smallest among the orthogonal array is L-4 constructed to accommodate three factor two level problems.

IV.2. Experiments with 2- level factors

According to full factorial design (2^k) method of Taguchi technique, one should conduct eight experiments in a standard orthogonal array, for example to optimize the surface finish (Orthogonal arrays are used to design experiments and describe trial conditions). According to Taguchi's approach for the three factors two level problem L-4 orthogonal is the best option. The standard L-4 array is shown in Table 2. This L-4 is the smallest of the arrays developed by Taguchi to design experiments of various sizes. The values obtained for the optimal design for the AA6061 alloy is given in Table 3. The orthogonal parameters of Taguchi method determined from the data given in Table 3, namely the values of A_1, A_2, B_1, B_2 and C_1, C_2. These values determined in the present study for the AA6061 alloy is given in Table 4 and the values of average surface roughness thus determined (see the data included in Table 4) were found to match well with the experimentally obtained values (the experimental variation of surface finish is discussed in the next section).

Table 1: L-4 Orthogonal array for three factors - two level problem (Taguchi technique)

Trial	Factor A	Factor B	Factor C
1	-1	-1	-1
2	-1	+1	+1
3	+1	-1	+1
4	+1	+1	-1

Table 2: Orthogonal array for AA6061 alloy

Depth of cut (mm)	Speed (m/min)	Feed (mm/rev)	R_a (μm)
0.1(-1)	6.03(-1)	0.032(-1)	0.35
0.1(-1)	14.57(+1)	0.095(+1)	0.51
0.3(+1)	6.03(-1)	0.095(+1)	0.35
0.3(+1)	14.57(+1)	0.032(-1)	0.10

V. RESULTS

V.1. Surface Roughness

The values of surface finish, a direct measurement of surface roughness before and after burnishing as a function of burnishing speed and burnishing feed are given in Table 4 and 5, respectively. From these data (Tables 5 and 6 and Figs. 3 and 4) the optimal value of surface finish is found to be 0.12 μm. at all other burnishing conditions, the surface roughness is lower than 0.12 μm. the corresponding optimum burnishing conditions are: 0.2 mm depth of cut, ~14.6 m/min burnishing speed and 2nd burnishing pass.

V.2. Microstructure

The optical micrographs in Fig. 5 clearly show microstructures consisting of equally axed grains of average size 30-40 μm and large amount of intra-granular particles. Mechanically modified layer of varied thickness was found to be present at the surface as a consequence of burnishing values of burnishing depth as a function of extent of burnishing (unburnished, 1st, 2nd and 3rd passes) are marked in the

Table 3: Experimental and theoretical (Taguchi) burnishing parameters, obtained from the present analysis for AA6061 alloy

Surface roughness values, w.r.t						Theoretical (Taguchi) optimum burnishing parameters				Experimental optimum burnishing parameters			
Depth of cut		Speed		Feed		Depth of cut (mm)	Speed (m/min)	Feed (mm/rev)	R_a (µm)	Depth of cut (mm)	Speed (m/min)	Feed (mm/rev)	R_a (µm)
A_1	A_2	B_1	B_2	C_1	C_2								
0.43	0.225	0.35	0.305	0.225	0.43	0.3	14.57	0.032	0.1	0.3	14.57	0.032	0.12

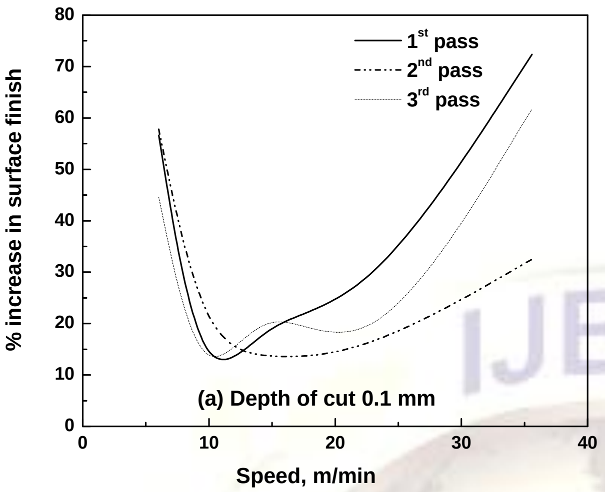
[The values of A_1 is obtained by averaging R_a with (-1) & (-1) Taguchi parameters w.r.t Depth of cut and A_2 is the average of R_a with (+1) & (+1) Taguchi parameters w.r.t force; similarly B_1, B_2 correspond to speed and C_1 and C_2 to feed. The optimal parameters referred to are lower values of surface roughness, which are given later in Table 7]

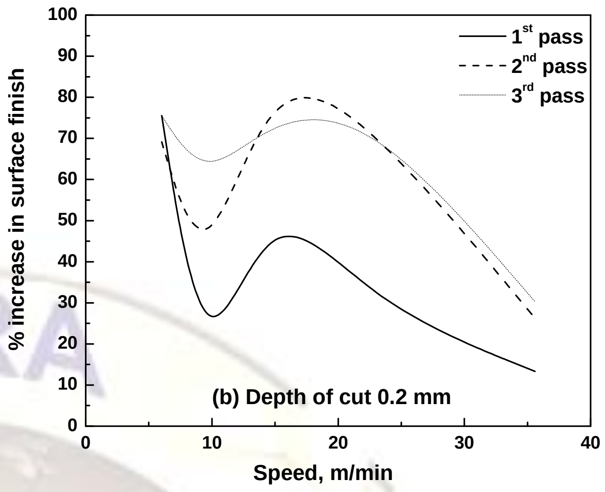
Table 4: Comparison of surface finish values before and after burnishing for a 30 mm diameter work piece of AA6061 alloy as a function of depth of cut and burnishing speed.

Depth of cut (mm)	Burnishing speed (m/min)	Surface finish before burnishing R_a (µm)	Surface finish after burnishing R_a (µm)			% increase in surface finish		
			First pass	Second pass	Third pass	First pass	Second pass	Third pass
0.1	6.03	0.83	0.36	0.35	0.46	56.64	57.82	44.57
	9.55	1.18	1.14	0.99	1.11	3.38	16.1	3.38
	14.57	0.77	0.60	0.51	0.56	22.07	12.98	27.27
	22.6	0.78	0.60	0.67	0.71	23.07	14.10	8.97
	35.6	1.23	0.34	0.83	0.47	72.35	32.52	61.78
0.2	6.03	0.94	0.23	0.29	0.23	75.53	69.14	75.53
	9.55	1.17	1.09	0.78	0.48	6.83	33.33	58.97
	14.57	1.0	0.41	0.12	0.25	59.0	88.0	75.0
	22.6	1.02	0.72	0.26	0.24	29.41	74.50	76.47
	35.6	0.99	0.87	0.73	0.68	13.33	26.26	30.31
0.3	6.03	0.74	0.35	0.58	0.57	52.7	21.62	22.97
	9.55	1.25	0.23	0.16	0.29	81.6	86.5	76.8
	14.57	0.96	0.15	0.13	0.12	84.37	86.45	87.50
	22.6	0.98	0.7	0.62	0.60	28.57	36.73	38.77
	35.6	0.74	0.44	0.32	0.38	40.54	56.75	48.64

Table 5: Comparison of surface finish values before and after burnishing for a 30 mm diameter work piece of AA6061 alloy as a function of burnishing feed.

Burnishing feed (mm/rev)	Surface finish before burnishing R_a (µm)	Surface finish after burnishing R_a (µm)				% increase in surface finish			
		9.55 m/min	14.57 m/min	22.6 m/min	35.6 m/min	9.55 m/min	14.57 m/min	22.6 m/min	35.6 m/min
0.111	1.18	1.11	0.9	1.0	0.34	5.93	23.72	15.25	71.18
0.095	1.17	1.09	0.41	0.72	0.87	6.83	64.95	38.46	25.64
0.063	1.23	0.78	0.12	0.26	0.73	36.58	90.24	78.86	40.65
0.032	0.96	0.23	0.10	0.70	0.44	6.04	89.58	27.0	54.16





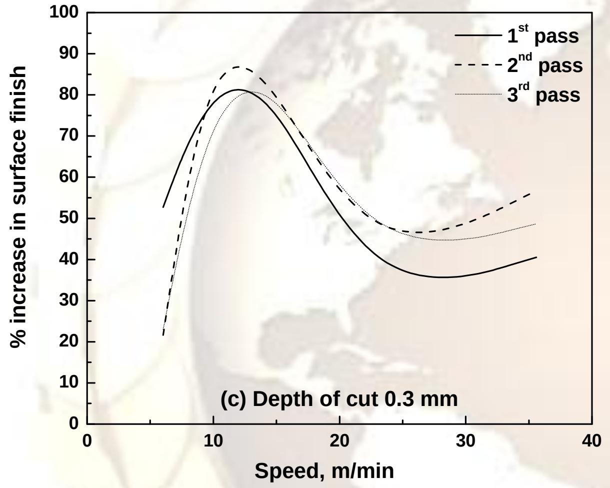


Fig. 3: Variation of burnishing speed with % increase in surface finish for different passes with different depth of cut for AA6061 alloy.

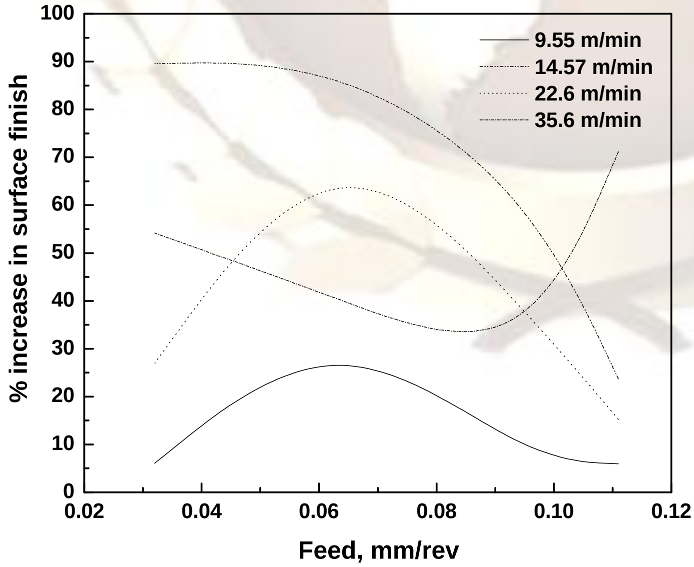


Fig. 4: Variation of burnishing feed with % increase in surface finish at different speeds in AA6061 alloy

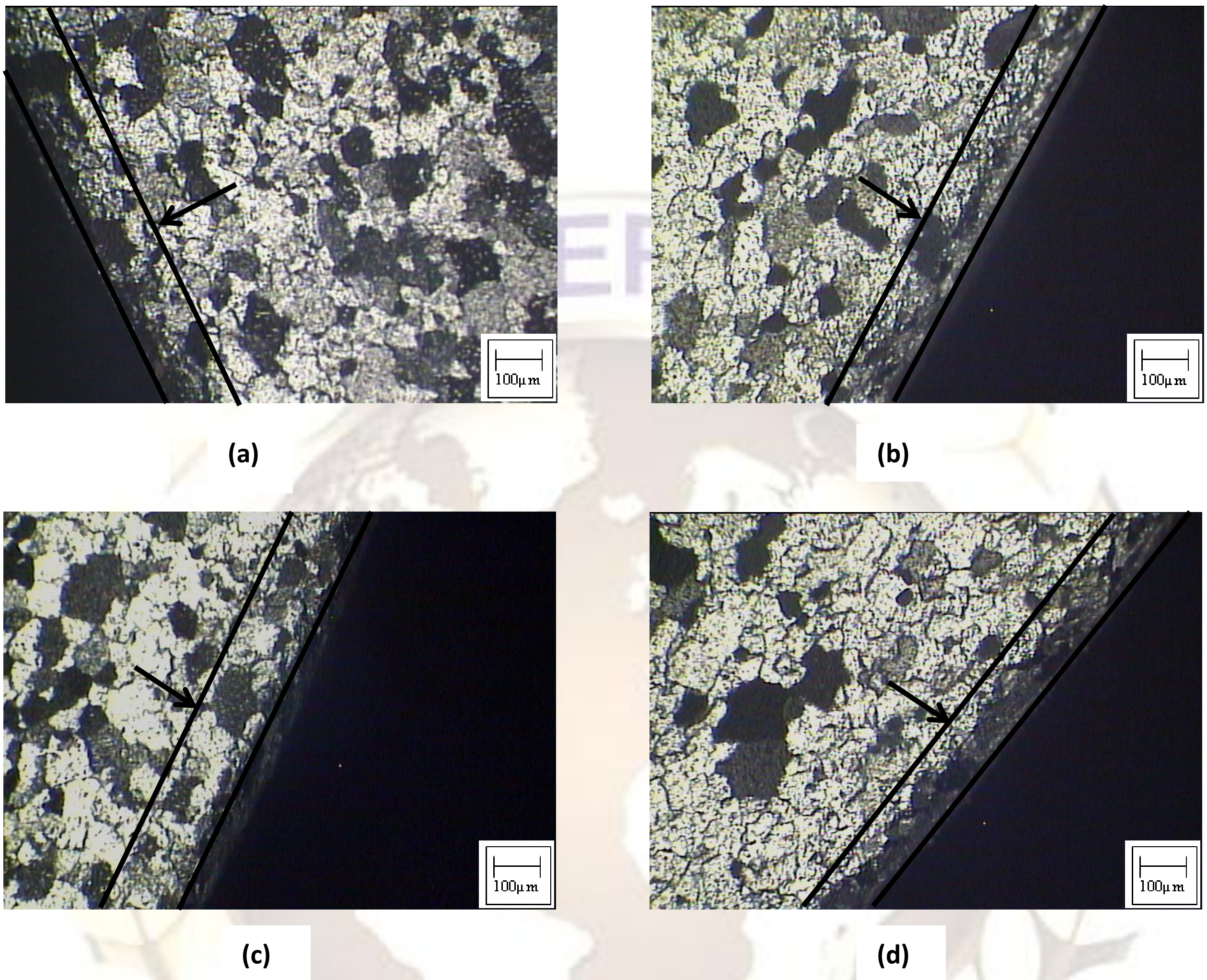


Fig. 5: Optical micrograph of AA6061 alloy showing the depth of burnishing in (a) Unburnished (b) burnished – 1st pass (c) burnished – 2nd pass (d) burnished – 3rd pass condition.

micrographs of Fig. 5 and the data are included in Table 6 clearly shows that maximum burnishing depth happens to occur in 2nd pass. However it should be noted the variation in burnishing depth with extent of burnishing is less pronounced in the present alloy as compared to EN series steels. One should also note that the unburnished material too exhibits certain depth of microstructural modification. This is due to the preburnishing operations such as turning by lathe to prepare the specimens for the burnishing experiments.

Table 6: Variation of burnishing depth and average microhardness values in the burnishing zone for AA6061 alloy. (BB – Before burnishing, B1 – Burnished-1st pass, B2 – Burnished-2nd pass and B3 – Burnished-3rd pass)

Characteristic	Burnishing Process			
	BB	B1	B2	B3
Micro Hardness	89.4	106.8	111.8	98.3
Burnishing layer thickness	180	220	250	230

V.3. Micro Hardness

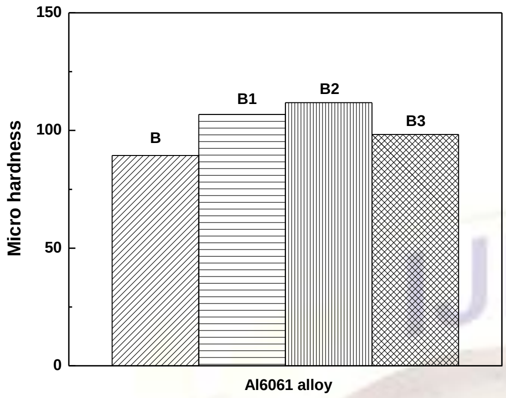


Fig. 7: Correlation of surface micro-hardness with burnishing parameters

The specimens polished to obtain microstructure were further used to determine the variation in micro hardness as a function of distance from the surface. The micro hardness values are found to be almost similar with no systematic variation with the burnishing distance. Hence, an average value of micro hardness is taken as a representative value for each of the experimental condition such as unburnished, burnished-1st pass, burnished-2nd pass and burnished-3rd pass. These data are summarized and included in Table 6 and are shown in Fig. 7. It is interesting to note that maximum burnished depth (as obtained from optical micrographs) also results in highest values of average micro hardness.

5.4 Residual stresses

The residual stresses that are determined by XRD are shown in Fig. 8 as a function of number of passes for the AA6061 aluminium alloy. The data in Fig. 8 show that the residual stresses gradually build up with burnishing and exhibit a peak in residual stresses at 2nd burnishing pass. Following this peak in compressive residual stress, further burnishing results in slight decrease of the order of 15-20% in compressive residual stress. Further the peak in residual stress is found to be of the order of 20% of the yield strength of aluminium alloy AA6061 (based on commonly reported representative yield strength value of 300 MPa). Such an extent of compressive residual stress is found to be of the similar order in other engineering materials studied and reported by the present authors [23].

VI. IMPLICATIONS OF THE STUDY

Aluminium alloys are widely used materials for automobile, aeronautical and aerospace applications. Majority of components and structures made from medium to high strength aluminium alloys fail by fatigue with or without additional damage from corrosion. A few means that can induce compressive residual stresses and there by improve fatigue properties in case of aluminium alloys are pre-straining, shot peening and burnishing. The present study shows that burnishing is a simple and effective means to induce compressive residual stresses. These residual stresses are of the order 20% of the yield strength Hence, a simple process which can contribute significantly to improve the tensile mean stress controlled fatigue resistance in most engineering materials is burnishing. However, one should note that the beneficial effects progressively diminish as the magnitude of compressive residual stress gradually decrease with service or even completely vanish at medium to high temperatures by effective stress relaxation (Malakondaiah and Nicholas, 1994); and, more importantly burnishing process has a major limitation that the compressive residual stress could prove fatally harmful and adversely affect the life in compressive-mean-stress-controlled fatigue and creep [25,26].

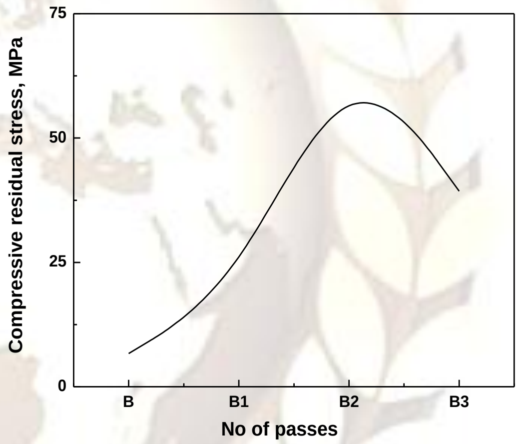


Fig. 8: Variation of magnitude of residual compressive residual stress with burnishing pass in case of AA6061 alloy.

VII. CONCLUSIONS

1. The present study reveals that the burnishing effectively improves surface finish, depth of burnishing, micro hardness and compressive residual stresses.
2. The studies conducted on burnishing till date limit number of passes to a maximum of 4. With the present data where the number of passes are restricted to 3, the aluminium alloy AA6061 shows best surface finish in the second pass (though the third pass doesn't show much degradation in surface finish).
3. Mechanically modified layer of varied thickness was found to be present at the surface as a

consequence of burnishing values of burnishing depth as a function of extent of burnishing (unburnished, 1st, 2nd and 3rd passes). The present study shows that maximum burnishing depth happens to occur in 2nd pass. However it should be noted the variation in burnishing depth with extent of burnishing is less pronounced in the present alloy as compared to EN series steels.

4. The present study revealed one-to-one correlations between burnishing depth, increase in micro hardness and magnitude of compressive residual stresses.

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