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Improving Surface Quality of AA 6351 by the Stiff Burnishing Technique

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Abstract

Burnishing process is used as a surface treatment for increasing the surface quality of circular or flat surfaces. The present paper investigates the effect of different burnishing parameters (speed, feed, depth of penetration and number of passes) on the surface quality of AA 6351. In conventional flexible burnishing tool, when the ball or roller is pressed against the material, gives waviness on the surface of the component, as properties of material throughout the length of the component are not uniform. Proposed stiff roller burnishing tool (Specially designed for CNC Lathe) can avoid these effects due to its high stiffness. Experimental work based on Response Surface Methodology (RSM), using Central Composite Design was carried out. Statistical Analysis of the results shows that the depth of penetration has a substantial effect on surface roughness and depth of penetration, speed and number of passes has significant effect on microhardness. Optimization of burnishing parameters was done to minimize surface roughness and maximize surface hardness using desirability function. Experiments were performed using optimum level of parameters to prove the effectiveness of desirability function and validate the phenomenon.

Keywords: *Stiff Ball Burnishing, surface roughness, surface hardness, desirability function, AA 6351*.

1. Introduction

In the present scenario, industry demands mechanical components with improved strength to weight ratio and good performance with reliability. Conventional methods like honing, lapping, grinding improves the surface finish of the component, which is not sufficient to improve performance with reliability. To improve the reliability of a component, the surface integrity of the component is to be increased. This can be achieved through numerous processes, like burnishing, shot peening, low plasticity burnishing which can improve the surface integrity of the material. In low plasticity burnishing residual compressive stresses are induced on the surface with less amount of cold work, that increases the fatigue life of the component even at high temperature [1]. For a specific material, we need to find optimum burnishing force, which will give us required surface quality. But if the material is changed, we need to find optimum force for that material. On the other hand, if we consider contact pressure between roller and workpiece material, we need to know the diameter of the roller, contact area, roller material, its shape, and size, as well as workpiece material. By considering various industrial applications of burnishing process on various materials, an extensive database of optimum contact pressure for materials is required to be maintained. This is required if one thinks that optimum contact pressure depends on burnishing process parameters and contact pressure. Therefore the focus of the present investigation is the depth of penetration, which the stiff burnishing tool penetrates the roughness valley, based on initial surface roughness, which can give us better surface quality [2]. Surface integrity is the sum of all the elements that describes all conditions existing on or at the surface of the finished workpiece. Surface integrity has two aspects. The first is surface topography which describes the roughness, lay or texture of the outermost layer of the workpiece. The second is surface metallurgy that describes the nature of the component. Burnishing is the cold working process in which rolling part of the tool, ball or roller is rolled over the surface of the component. As a result of rolling of ball or roller over the surface, Hertz contact stresses are developed, which overstep the yield stress, leading to plastic deformation of the surface layer. This increases surface finish and surface microhardness of the component, which in turn increases the surface integrity of the component [3][4]. Thus, the surface integrity has attracted the interest of researchers, e.g., those who want to increase the life of the component. The functional performance of a component, such as a load bearing capacity, wear resistance, fatigue strength depends on surface integrity which includes surface roughness, surface

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hardness, induced compressive stresses and surface topography [5]. Many researchers had studied the effect of different burnishing parameters on, for instance, surface integrity of different materials [6]–[8], surface roughness and microhardness[9]–[12], wear resistance [13][14] and fatigue strength of the different materials, and found that there is improvement in surface finish, surface microhardness, wear resistance, fatigue strength and surface integrity of the material[15]–[17]. Several researchers had optimized burnishing process parameters for enhancing surface quality of material[18]–[21]. However, for optimization of burnishing parameters for a specific material, we need to carry out several experiments with a different combination of burnishing parameters. To minimize the number of experiments Taguchi[22] and RSM[23] were used by many researchers. Dweiri*et al*. [24] used fuzzy modeling for optimization of roller burnishing parameters to improve the surface finish of non-ferrous components. It was observed that as burnishing force increases surface roughness decreases. Revankar[25] investigated optimum burnishing parameters to enhance surface roughness and surface hardness of titanium alloy using Taguchi technique. It was observed that the increase in the burnishing force and number of passes improves the surface finish of the workpiece and the same was the case for hardness but with an increase in speed hardness decreases. RSM and Desirability function was employed for optimization of burnishing parameters and the quadratic model was developed to predict the surface finish of the workpiece [26]. Aluminum alloy is widely used in automobile and aerospace sector due to its properties like high corrosion resistance, high strength to weight ratio. In the present study, AA 6351 was used as a workpiece material. It is most widely used alloy in a wide variety of general applications in small scale industry as well as large scale industries and detailed analysis for burnishing is not found reported. It is also used in pressure vessels, rail and road bridges and can be used in aerospace structure [27].

We need to find out some law in deciding the value of parameters, which will be same for different materials. Here we are concentrating on optimization of the depth of penetration based on initial surface roughness.

2. Stiff Ball Burnishing

Operation of stiff ball burnishing is illustrated in Figure 1. Dynamic behaviour of the burnishing tool is not found reported due to waviness of workpiece surface. Available research does not provide any information on a theoretical or practical aspect of the tool behaviour under real time burnishing process. This is due to the fact that the process is performed on the uneven surface, therefore magnitude of the force acting on the tool cannot be known. Taking into consideration the above fact authors tried to use very high stiffness spring in the tool, so that effect of waviness will not affect the burnishing operation. The depth of penetration is decided based maximum value of Rp (Maximum peak height) on initial surface roughness. The ball is placed on the outer race of the bearing, so that it can rotate freely during burnishing process. The tool is designed in such a way that it will give constant depth of penetration.

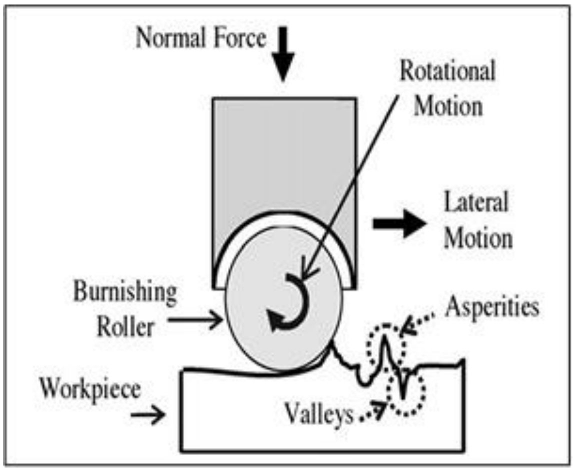

Figure 1. Burnishing Mechanism

3. Experimental Study on Stiff ball Burnishing

Specimens (Size 30mm X 250mm) were prepared on CNC lathe using carbide tip tool having 0.8 mm radius. All burnishing tests were conducted on LMW make CNC lathe having Fanuc Controller at Sandip Institute of Technology and Research Centre, Nashik. Kerosene was used as a coolant. Based on literature review speed, feed, depth of penetration and number of passes were selected as burnishing parameters [28]–[30]. Pilot experiments were conducted, to decide the range of parameters. The experimental work determined the effect of burnishing parameters on surface roughness and hardness. The surface roughness was measured using SURFCOM 130A and surface hardness was measured using Mitutoyo make Micro Vickers Hardness Tester of both turned and burnished surface at Nasik Engineering Cluster (NEC), Nashik. Table 1 shows values of burnishing parameters used.

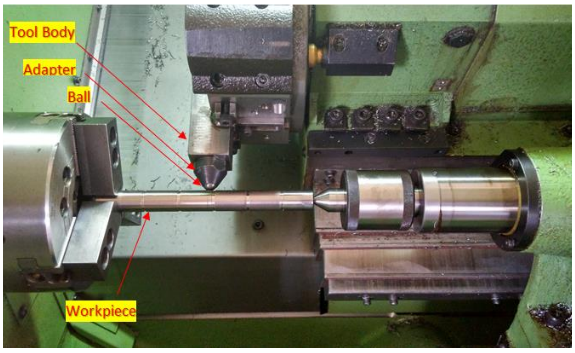

Figure 2. Experimental Setup

Table 1. Burnishing parameters

	Minimum	Intermediate			Maximum
Speed (rpm)	600	700	800	900	1000
Feed (mm/rev)	0.03	0.04	0.05	0.06	0.07
Depth of Penetration(mm)	0.15	0.3	0.45	0.6	0.75
Number of Passes (Units)	1	2	3	4	5

4. Parametric Analysis of Burnishing Process on Surface Roughness and Surface Hardness

In the first stage of the present study based on Response Surface Methodology (RSM) using Central Composite Design (CCD), 30 experiments were conducted using a combination of parameters given in Table 2. The effect of burnishing parameters on the surface roughness and surface microhardness were studied.

Table 2. Design Matrix and Response

Sr No	Speed (rpm)	Feed (mm/rev)	Depth of Penetration (mm)	Number of Passes	Surface Roughness (µm)	Surface Hardness (Hv)
1	1000	0.05	0.45	3	0.063	145.2
2	900	0.04	0.3	4	0.065	143.2
3	900	0.04	0.6	4	0.103	143.8
4	700	0.04	0.3	4	0.067	144.1
5	900	0.06	0.6	2	0.077	143.1
6	800	0.07	0.45	3	0.059	145.8
7	900	0.06	0.6	4	0.079	144.3
8	800	0.05	0.45	3	0.061	146.6
9	600	0.05	0.45	3	0.063	145.3
10	800	0.05	0.45	3	0.06	147.1
11	800	0.05	0.75	3	0.074	145.3
12	700	0.06	0.6	2	0.079	143.8
13	900	0.04	0.3	2	0.068	142.7
14	900	0.06	0.3	4	0.057	144.6
15	700	0.06	0.3	4	0.068	144.2
16	700	0.06	0.6	4	0.0728	142.9
17	700	0.04	0.6	2	0.08	143.5
18	700	0.04	0.6	4	0.079	144.5
19	900	0.04	0.6	2	0.078	144.2
20	700	0.04	0.3	2	0.068	143.8
21	800	0.05	0.15	3	0.063	145.1
22	700	0.06	0.3	2	0.066	144.3
23	800	0.05	0.45	1	0.059	142.1
24	800	0.05	0.45	3	0.061	146.3
25	800	0.05	0.45	3	0.063	146.1
26	800	0.03	0.45	3	0.068	146.5
27	800	0.05	0.45	3	0.059	147.5
28	800	0.05	0.45	3	0.062	147.1
29	800	0.05	0.45	5	0.066	145.5
30	900	0.06	0.3	2	0.068	143.2

ANOVA was used to find the effect of different burnishing parameters on response parameters based on a 95% confidence level. ANOVA for surface roughness quadratic model implied that depth of penetration and quadratic term of, depth of penetration plays an important role in improving the surface finish of the material. Other parameters are found dormant. However, surface microhardness results show that due to a depth of penetration, speed and number of passes (3 to 4) cold work increases which results in, increase in surface hardness. The optimization of burnishing parameters was done using desirability function, to achieve minimum surface roughness and maximum surface hardness. It is found that at speed of 800 rpm, the feed of .05mm/rev., depth of penetration of 0.45 mm and number of passes three, we can get minimum surface roughness and maximum surface hardness. Desirability function value comes 0.814.

Table 3.ANOVA for Response Surface Roughness Quadratic Model

Analysis of variance table [Partial sum of squares - Type III]						
	Sum of		Mean	F	p-value	
Source	Squares	Df	Square	Value	Prob> F	
Model	0.020062	14	0.001433	3.84048853	0.0070	Significant
A-Speed (rpm)	0.000294	1	0.000294	0.7879221	0.3887	
B-Feed (mm/rev)	0.00028	1	0.00028	0.75084867	0.3999	
C-Depth of Penetration (mm)	0.003651	1	0.003651	9.78381276	0.0069	
D-Number of Passes	0.00058	1	0.00058	1.55485081	0.2315	
AB	0.000992	1	0.000992	2.65923709	0.1238	
AC	0.000272	1	0.000272	0.72963195	0.4064	
AD	5.63E-05	1	5.63E-05	0.1507504	0.7033	
BC	0.0004	1	0.0004	1.07200286	0.3169	
BD	0.000676	1	0.000676	1.81168483	0.1983	
CD	0.0001	1	0.0001	0.26800071	0.6122	
A^2	0.000237	1	0.000237	0.63430026	0.4382	
B^2	0.000163	1	0.000163	0.43674545	0.5187	
C^2	0.012168	1	0.012168	32.6106141	< 0.0001	
D^2	6.7E-05	1	6.7E-05	0.17946476	0.6778	
Residual	0.005597	15	0.000373			
Lack of Fit	0.00527	10	0.000527	8.04503817	0.0164	Significant
Pure Error	0.000328	5	6.55E-05			
Core Total	0.025659	29				

The model F-value of 3.84 suggests that model is significant and there is 0.70% chance only that "Model F-Value" this large could occur due to noise. Values of "Prob>F" less than 0.05 indicates that model terms are significant. The "Lack of Fit F-Value" of 8.05 indicates that the lack of fit is significant and there is only 1.64% chance that a "Lack of Fit F-Value" this large could occur due to noise. The value of R^2 is equal to 0.8214. Adequate Precision measures the signal to noise ratio. Signal to noise ratio 9.152 as per present analysis implies an adequate signal to navigate the design space.

The reduced best fitted second order model using least square criteria for surface roughness in coded form is as below:

$$\text{Surface Roughness} = 0.0545 + 0.01333*C + 0.021063*C^2 - 0.005*B*C + 0.0025*C*D - 0.0065*B*D \quad (1)$$

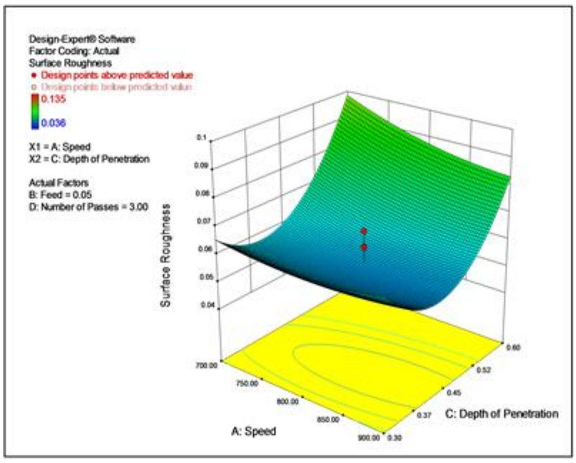

Figure 3. Effect of speed and depth of penetration on surface roughness

Table 4.ANOVA For Surface Hardness Quadratic Model

Analysis of variance table [Partial sum of squares - Type III]						
	Sum of		Mean	F	p-value	
Source	Squares	df	Square	Value	Prob> F	
Model	44.34867	14	3.167762	3.064587	0.0196	significant
A-Speed	0.201667	1	0.201667	0.195098	0.6650	
B-Feed	0.026667	1	0.026667	0.025798	0.8745	
C-Depth of Penetration	0.006667	1	0.006667	0.00645	0.9371	
D-Number of Passes	4.001667	1	4.001667	3.871332	0.0679	
AB	0.25	1	0.25	0.241857	0.6300	
AC	0.7225	1	0.7225	0.698968	0.4163	
AD	0.36	1	0.36	0.348275	0.5639	
BC	1.21	1	1.21	1.17059	0.2964	
BD	0.0025	1	0.0025	0.002419	0.9614	
CD	0.09	1	0.09	0.087069	0.7720	
A^2	10.08107	1	10.08107	9.75273	0.0070	
B^2	3.986786	1	3.986786	3.856936	0.0684	
C^2	10.50107	1	10.50107	10.15905	0.0061	
D^2	25.74107	1	25.74107	24.90268	0.0002	
Residual	15.505	15	1.033667			
Lack of Fit	14.05667	10	1.405667	4.852704	0.0476	significant
Pure Error	1.448333	5	0.289667			
Core Total	59.85367	29				

The model F-value of 3.064 implies that model is significant and there is only 1.96% chance that "Model F-Value" this large could occur due to noise. The "Lack of Fit F-Value" of 4.85 indicates that the lack of fit is significant and there is only 4.76% chance that a "Lack of Fit F-Value" this large could occur due to noise. The value of R^2 is equal to 0.8701. Adequate Precision measures the signal to noise ratio. Our signal to noise ratio 6.526 suggests an adequate signal, to navigate the design space.

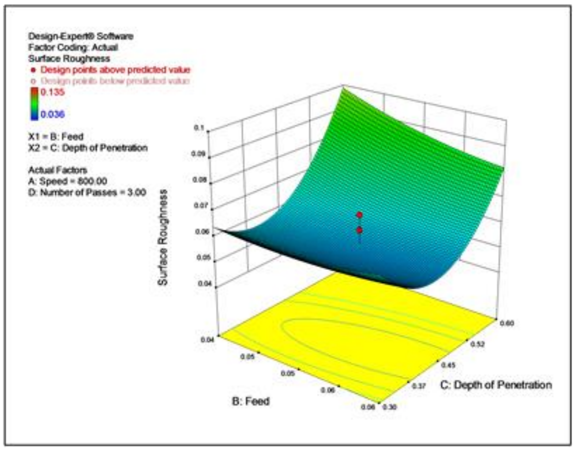

Figure 4. Effect of feed and depth of penetration on surface roughness

The reduced best fitted second order model using least square criteria for surface hardness in coded form is as below:

$$\text{Surface Hardness} = 146.7833 - 0.61875*C^2 - 0.96875*D^2 + 0.0125*B*D + 0.125*A*B + 0.02125*A*C \quad (2)$$

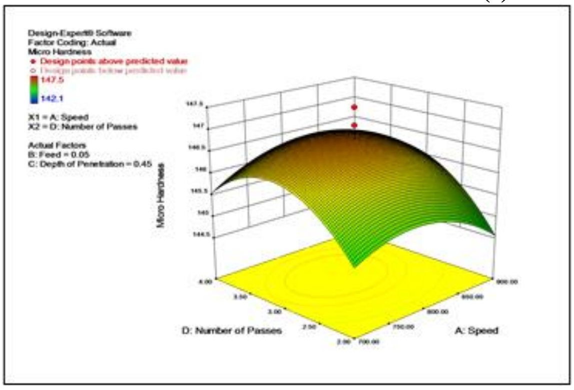

Figure 5. Effect of Number of passes and speed on surface hardness

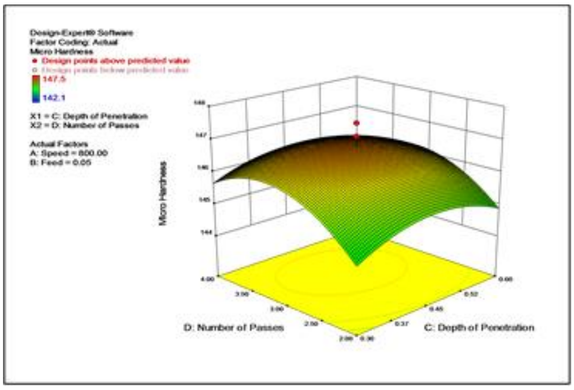

Figure 6. Effect of number of passes and depth of penetration on surface hardness

5. Analysis of the Burnished Surface Quality

5.1. Surface Roughness

In the second stage of the present work, analysis of surface roughness (Ra) was done, in comparison with surface roughness before burnishing. The depth of penetration plays a vital role in improving surface finish. It was observed that depth of penetration equal to 0.8 to 0.9 times Rp (peak value of surface roughness) gives us best surface finish. We were able to get super finished surface having lowest Ra value 0.057 µm, due to stiff burnishing tool.

Figure 7. Surface Roughness Tester

5.2. Surface Microhardness

Depth of penetration creates high pressure and plastic deformation of material takes place, which produces limited cold work region. The thickness of the metal layer formed due to pressure increases as the depth of penetration and number of passes are increased. But after a certain value of the depth of penetration and number of passes surface got damaged. Surface hardness obtained was 147.5. Speed also plays role in improving surface hardness. As speed increases, heat generation between tool and workpiece increases and surface of the workpiece becomes soft. So, after 900 rpm speed, surface hardness decreases.

Figure 8. Surface Microhardness Tester

5.3. Optimization of Burnishing parameters

There are two responses, one is surface roughness and the other is surface hardness. We want to minimize surface roughness and maximize surface hardness. Therefore we optimized burnishing parameters. This was done using Desirability function, using software tool. The value of desirability function came as 0.814. Following Table 5 shows upper and lower limit of burnishing parameters, their weight, and importance of each parameter.

Table 5. Burnishing Parameters Range for Optimization

Name	Goal	Lower Limit	Upper Limit	Lower Weight	Upper Weight	Importance
A:Speed	is in range	700	900	1	1	3
B:Feed	is in range	0.04	0.06	1	1	3
C:Depth of Penetration	is in range	0.3	0.6	1	1	3
D:Number of Passes	is in range	2	4	1	1	3
Surface Roughness	minimize	0.057	0.103	1	1	3
Microhardness	maximize	142.1	147.5	1	1	3

5.4. Validation of Mathematical Models

By using burnishing parameters optimum values again, experiments were conducted to validate mathematical models developed. It was observed that % error is less than 10% in almost all tests. Table 6 shows the results of the validation experiments and % error.

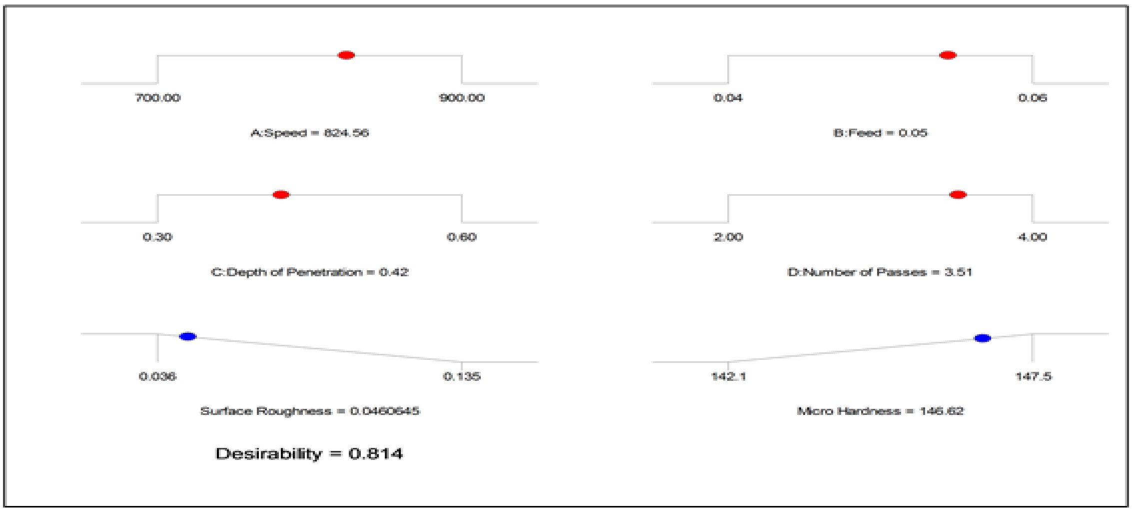

Figure 9. Optimization using Desirability Function

Table 6. Validation Experiments

A	B	C	D	Ra (Measured)	Hv (Measured)	Ra (Predicted)	% Error in Ra	Hv (Predicted)	% Error in Hv
700	0.06	0.6	4	0.078	147.2	0.07434068	4.92236552	145.23855	1.350502329
900	0.04	0.6	4	0.069	149.2	0.07492068	7.902597787	147.03755	1.470678748
900	0.04	0.6	2	0.08	149.1	0.07244068	10.43518642	158.66155	6.026381313
900	0.06	0.3	2	0.063	148.9	0.06102467	3.236936799	155.3416125	4.146739818
900	0.04	0.3	4	0.067	145.6	0.06229467	7.553342846	141.4671125	2.921447556
800	0.05	0.45	3	0.071	146.3	0.067051258	5.88914011	150.5911281	2.849522531
700	0.06	0.3	4	0.063	145.5	0.06174467	2.033098565	140.9431125	3.233139541
700	0.06	0.3	2	0.066	147.8	0.06102467	8.152981409	152.5666125	3.124282844
900	0.06	0.6	4	0.078	146.2	0.07434068	4.92236552	149.28855	2.068845869
900	0.06	0.3	4	0.066	146.4	0.06174467	6.891817545	143.7181125	1.866074814

6. Conclusions

The influence of stiff ball burnishing parameters for improving the surface quality of rotating parts was examined. Along with it, the study of surface roughness and surface hardness achieved was carried out. Based on investigations achieved, subsequent conclusions are drawn:

- The depth of penetration plays important role in enhancement of surface finish up to certain value. As the depth of penetration increases, pressure on the workpiece surface increases and plastic deformation at the surface of the workpiece takes place. Due to this, material will flow into the valleys and we can get the better surface finish. But if it increases beyond a particular limit surface get damaged, as a combination of parameters is giving us required result.
- Burnishing speed, feed, and a number of passes hardly affect the surface roughness. Thus, it is possible to use maximum speed and feed to reduce process time. And we can keep the number of passes as one only. But we can increase speed and feed up to a certain limit, otherwise, the surface may get damaged. There is an interaction between different burnishing parameters used.
- Speed, Depth of penetration and number of passes are critical parameters to enhance surface hardness. But we need to take them at a particular level, as increase or decrease in values can reduce surface hardness. As the depth of penetration and number of passes increases, surface hardness increases, but if values are too high surface will be get damaged, results into increase in surface roughness. Therefore optimum values of burnishing parameters are the key elements to achieve minimum surface finish and maximum surface hardness.
- The depth of penetration is equal to 0.8 to 0.9-times maximum peak height of the surface roughness. This means we can decide the depth of penetration for any material based on initial surface.

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