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EFFECT OF BURNISHING FORCE AND FEED ON THE DEPTH OF THE SURFACE HARDENED LAYER IN PLANE SURFACE BALL BURNISHING

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ABSTRACT :-

In an experimental analysis study, a blend of burnishing parameters was varied to obtain their optimum values to produce the finest surface integrity in plane surface burnishing process. The physical depth of the micro hardened surface layer was also evaluated at the obtained optimum values of the parameters. The analysis was undertaken on ball burnished plane surface, mild carbon steel M1044, using a milling machine and a purpose designed and manufactured burnishing tool. The effects of burnishing feed and force on both surface smoothness and hardness together and on the depth of the hardened surface layer of the work pieces material were observed and investigated. The results indicated that plane burnished surface finish and hardness improvements of around (89 %) and (70 %) respectively were obtainable at the optimum values of the mentioned parameters. Around 35 μm physical depth of the hardened surface layer was the result at the obtained optimum burnishing force and feed values of about 7.8Kgf and 107 mm/min respectively.

KEYWORDS : Plane Surface Burnishing, Ball Burnishing, Surface roughness; Surface hardness; Depth of the Surface Hardened Layer.

تاثير قوة الصقل والتغذية على عمق الطبقة السطحية المتصلدة في صقل سطح المستوي

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الخلاصة :-

في دراسة عملية تحليلية ، تم تغيير مزيج مؤشرات الصقل لغرض الحصول على قيمها المثلى التي تنتج افضل نوعية للسطح فى عملية الصقل السطحى المستوى . كما تم تقييم العمق الفعلي للطبقة السطحية المتصلدة عند القيم المثلى للموشرات التي تم ايجادها. أجري التحليل في الصقل الكروي لسطح المستوي على الفولاذ الطري (M1044) باستخدام ماكينة تفريز وأداة صقل صممت وصنعت لهذا الغرض .

تم ملاحظة و تحرى تاثيرات كل من قوة الصقل والتغذية على النعومة السطحية والصلادة السطحية معا وعلى عمق الطبقة السطحية المتصلدة لمعدن المشغولة. اشارت النتائج أنه فى عملية الصقل السطحى المستوى يمكن الحصول على حوالى (89%) و (**70**%) تحسين فى نعومة و صلادة السطح على التوالي عند القيم المثلى للمؤشرات المذكوره. اظهرت النتائج ان العمق الفعلي للطبقة السطحية المتصلدة هو حوالي **35** مايكرومتر عند القيم المثلى لقوة الصقل والتغذية التى تم الحصول عليها وهي 7.8Kgf و 107 mm /min على التوالي .

1. INTRODUCTION :-

Burnishing is a forming and finishing treatment, which is commonly used as a post machining process to enhance some mechanical and physical properties of the work piece, which includes surface finish and hardness [M.M El-Khabeery et.al. 2001, M. Némat et.al. 2000, and Ubeidulla Al-Qawabeha et.al. 2009]. Burnishing is a plastic deformation process under cold working conditions and is performed by pressing a hard and highly polished ball against the work piece surface. The tool surface finish and hardness must be superior to that of the work piece. The work piece is driven by the feed motion while the ball rotates with the milling machine spindle rotation and with the work piece as a result of friction. This creates a high compressive stress in the peaks of the surface finish that in turn lands the flow of the material and hence the plastic deformation.
The literature appraisal revealed that the burnishing process offers some additional specific advantages in comparison with precision cutting processes [Ismail Ovali et.al. 2011, and M. Némat et.al. 2000]. The most noticeable features of the process are the superior surface finish and hardness improvements with the creation of a surface hardened layer [Hamid Hamadache et.al 2014, L. N. López de Lacalle et.al. 2006 and Yinggang Tian et.al. 2007]. Other burnishing benefits and features include improved visual appearance of the burnished work piece [Ubeidulla Al-Qawabeha et.al. 2009 and W. Grzesik et.al. 2013], improving fatigue strength [Adel M. Hassan et.al. 2000, and Lothar Wagner et.al. 2011], improving wear resistance [Ubeidulla F. Al-Qawabeha et.al 2013], improving corrosion resistance [Adel M. Hassan et.al. 2000], increasing compressive residual stress [Feng Lei Li et.al.2012, and M.M El-Khabeery et.al. 2001] and the overall improvements of the mechanical and physical properties of the surface layer of the burnished work piece [Lothar Wagner et.al. 2011, M. Némat et.al. 2000, and Ubeidulla F. Al-Qawabeha et.al 2013]. In a ball burnishing process of 36 Cr Ni Mo 6 steel, Hamid Hamadache et.al. 2014 used a metallographic observation and some measurement of micro-hardness to show that “the depth of penetration strengthened by plastic surface deformation (PSD) reaches 100 μm”.
The aim of this paper is to assess and determine experimentally the effect of burnishing force and feed on the surface finish, surface hardness and the depth of the surface hardened layer in plane surface mild carbon steel M1044. This includes obtaining the optimum values of these parameters that offers both the best surface finish and improved surface hardness. The aim is also to obtain the physical depth and extent of the hardened layer at the above optimum values under the experimental conditions used. These parameters are regarded to be the dominant factors that affect the surface structure [Feng Lei Li et.al.2012, and M. Némat et.al. 2000]. To the best of the authors’ knowledge, no previous optimisation and effect studies have been found in the literature review with the chosen parameters in plane surface ball burnishing, at the selected specification of mild steel and within the experimental boundary used.

2. EXPERIMENTAL DETAILS :-

2.1 Burnishing Tool

A ball-burnishing tool was purposely designed and fabricated specifically to fit the vertical spindle of the MF 1 Knuth milling machine, which was used for the experimental work. Due to the flexible design of the burnishing tool that inherited the spindle rotation motion; the ball could also rotate freely (due to friction) with the work piece horizontal feed motion, be changed, cleaned and lubricated during the process. A pre-calibrated spring was used to support the ball against shocks, sticking effects due to friction and heat, and importantly for the measurements of the applied burnishing force (Pz). Pz is the vertical downward force in Z axis direction (figure 2a). The spring calibration (compression test) was carried out by using INSTRON 1195 Tension machine. The relation between the applied compression force and the spring displacement is shown in Figure 1, which is used to find the applied burnishing force (Pz) in Kgf for each vertical tool displacement in mm. The ball has the following composition and specification: high chromium-carbon steel, En 31 alloy, 1%C, 1.4%Cr, 0.2%V; measured Vickers hardness number (HV) > 750 Kg/mm^2, measured surface roughness Ra of 0.03 µm and 10.3 mm in diameter [Ministry of Planning 2015, and Metals Handbook 1985].

2.2 Work Piece Material

Mild carbon steel M1044 was used as the material type for the work piece specimen. The material is widely available and has good formability and machinability characteristics.
The mechanical properties and the indicative partial composition of the work piece material used are shown in Table 1, beside their chemical composition and the AISI (American Iron and Steel Institute) equivalent notation [Ministry of Planning 2015, and Metals Handbook 1985].

2.3 Burnishing Conditions

A range of burnishing parameters and the work piece specification values were chosen and applied for the experimental part of the investigation. Table 2 shows the data with other burnishing conditions and variables.
These settings were selected in order to study the influence of process parameter variations on the work piece surface finish (Ra), micro hardness (HV) and on the depth of the surface hardened layer (d). For each experiment, either burnishing force or feed was varied within its range shown.
Specific burnishing conditions are illustrated with the figures (3 to 9) of the results section.

2.4 Experimental Procedure

The burnishing process was carried out on plane surface cuboid shape work piece, which was held by a vice that fastened to the milling machine table (Figure 2 a). By using a milling cutting tool, the work piece was then milled to a flat surfaces cuboid shape with the dimensions shown in Table 2. The upper face of the cuboid work piece was then partitioned into several equally-sized rectangular segments (A to J in Figure 2 b).

The ball-burnishing tool was held in the milling machine’s spindle tool holder and with the above work piece setting; each segment was burnished and used as a medium for a different burnishing condition. The first segment (M) was reserved (un-burnished) as a reference milling condition, from where the initial surface finish (Rai) and initial surface hardness (Hvi) were obtained. Drops of light engine oil were used as a lubricated coolant between the tool and the work piece during the process. In order to prevent the presence of any alien particles in the burnishing zone, the work piece and the tool were cleaned regularly during the burnishing process. A new ball was used after each 3 passes of the tool to maintain the high surface quality of the ball and hence to reduce effects of any ball scratches on the work piece surface. The surface finish and hardness for each burnished segments (A to J in Figure 2 b) were measured after 3 tool passes, several readings from burnished surfaces were taken in burnishing feed direction (X axis) and at a right angle to that (Y axis). The average of these reading was considered to be the final value. Vickers hardness test was used to obtain the Vickers numbers (HV). Surface roughness measurements of (Ra) were carried out by using Pocket Surf instrument that has 0.01 µm reading accuracy.

3. RESULTS AND DISCUSSIONS :-

3.1 Effect of Burnishing Force (Pz) on Surface Roughness (Ra), Surface Hardness (HV) and on the Depth of the Surface Hardened Layer (d)

The effect of the burnishing force (Pz) on the surface roughness, surface hardness and on the depth of the surface hardened layer is shown in Figures 3, 4 and 5 respectively. It is important to highlight that the burnishing force (Pz) is the applied vertical force of the tool (ball) in Kgf on the work piece surface on the (Z) axis (Figure 2 a). This force causes the tool penetration in the work piece surface. The optimum feed and force values are the values at which the best surface finish and hardness were obtained under the experimental conditions, procedures, tools and materials used in this paper.

Figure 3 shows that up to the optimum force value of around 8 kgf, the surface roughness decreases with the increase of the applied force Pz to reach its best value of 0.4 µm.

Beyond these optimum values, the surface roughness Ra increases with further increase of the applied force Pz. This could be due to the lump of metal in front of the tool becoming large, as the region of the plastic deformation widens which damages the already burnished surface and hence increases the surface roughness.

Figure 4 shows the directly proportional relationship between the applied force (Pz) and surface hardness (HV) under the boundary of the experimental conditions used. The surface hardness increases with an increase of the applied force. This is typically due to the increase of the tool pressure causing an increase in metal flow, which leads to an increase in the amount of deformation and more surface valleys being filled and hardened.

Figure 5 also illustrates the directly proportional relationship between the applied force (Pz) and the depth of the surface hardened layer (d). Increasing the applied force increases the depth of the surface hardened layer, within the boundary of the experimental conditions used. It is apparent that increasing the applied force has a physically similar effect on the depth of the surface hardened layer as on the surface hardness magnitude itself. This is due to the more surface valleys being filled as mentioned above in figure 4. Also the increased force leads to an increase in the internal compressive residual stresses in the surface layer, which in turn increases the surface hardness and the depth of the hardened layer.

3.2 Effect of Burnishing Feed (f) on Surface Roughness (Ra), Surface Hardness (HV) and on the Depth of the Surface Hardened Layer (d)

The effect of the burnishing feed on the surface roughness, surface hardness and on the depth of the surface hardened layer is shown in Figures 6, 7 and 8 respectively. It is noteworthy to highlight that the burnishing feed is the speed in (mm/rev) in the (X) axis direction (figure 2 a) at which the milling machine table travels during the burnishing process, where the tool is in contact with the work piece.

The effect of the burnishing feed (f) on the surface roughness (Ra) is illustrated in figure 6. The surface roughness decreases with the increase of the burnishing feed until the optimum feed of around 100 mm/min which provides the best Ra value of 0.5 µm, beyond this the surface roughness increases again.

Figure 7 shows surface hardness increases with the increase of the burnishing feed until the feed value reaches around 50 mm/min and then decreases slightly until the feed value of around 100 mm/min. Further increase in the feed beyond the 100 mm/min value causes significant decrease in the surface hardness under the experimental conditions used.

The increase in surface roughness and the significant decrease in surface hardness beyond the optimum feed value of around 100 mm/min are probably due to chattering occurring at higher feeds. This means that there is less deformation time available for the tool to smooth out more roughness and to harden the surface layer.

Figure 8 illustrates that the effect of the feed on the depth of surface hardened layer is akin to that on the surface hardness. Similar to the surface hardness, the depth of the layer increases with the increase of the burnishing feed until the feed value of approximately 50 mm/min. This then decreases slightly until the feed value reaches around 100 mm/min, after which a sharp drop occurs. This proves the directly proportional relationship between the surface hardness and the depth of the surface hardened layer, meaning the harder the surface, the deeper the layer becomes.

3.3 Optimum Values

The aim of this study was to obtain optimum values of force and feed that provide both the best surface finish and improved surface hardness under the experimental conditions used. The aim was also to obtain the physical depth and extent of the hardened layer at the above mentioned optimum parameters values. The surface hardness and the depth of the hardened layer could be further improved with forces beyond the optimum force value and feeds below the optimum feed value, as the graphs confirm under the experimental conditions used. But those further improvements would however, be at the expense of achieving the best surface roughness . Consequently, the optimum parameters values are considered to be 7.8 Kgf force and approximately 107 mm/min feed, which obtained the best surface roughness (Ra) of 0.4 µm, an improved surface hardness (HV) of about 280 kg /mm^2 and a depth of the surface hardened layer of about 35 µm. These results indicate that, compared to the initial Rai and Hvi values, an improvement of about 89% in surface roughness and around 70% in surface hardness are applicable by plane surface ball burnishing under the experimental conditions used in this study.

Figure 9 shows the hardness magnitude and depth of the surface hardened layer at the optimum burnishing parameters values. The highest burnished hardness occurs at the top surface of the work piece, at a depth of the layer (d) close to zero and gradually decreases towards the centre of the work piece, until it reaches the initial work piece pre burnished hardness value of 165 Kg /mm^2. The depth of the surface hardened layer is considered to be the vertical distance from the edge of the work piece surface in the downward direction (Z axis) represented by (d) in (figure 2 b). Thus, the depth of the hardened layer is found to be about 35 µm at the optimal process parameters of force and feed.

4. CONCLUSIONS :-

- The plane surface ball burnishing demonstrated its capabilities as a finishing process to improve the surface structure of the milled mild carbon steel M1044 work piece.
- The results confirmed the impressive effect of the burnishing force and feed parameters on the surface roughness, surface hardness and the depth of the surface hardened layer.
- Optimum force and feed values were found to be about 7.8Kgf and 107 mm/min respectively, under the experimental conditions used.
- The burnishing process produced at the above optimum values about 89% surface finish improvement and 70% surface hardness improvement compared to their initial values and generated a surface hardened layer of about 35 µm depth
- Maximum surface hardness improvement value occurs at the surface of the work piece, where the depth of the hardened layer (d) is close to zero. The hardness value decreases towards the centre of the work piece until equal to the initial hardness, where the maximum depth of the surface hardened layer is.
- Force is directly proportional to both the surface hardness and the depth of the hardened layer. This means enhanced surface hardness and depth improvements are possible, but at the expense of the best surface roughness.
- Increasing burnishing force beyond its optimum value leads to an increase in surface hardness and the depth of the hardened layer, but undesirably it also increases the surface roughness.
- Increasing burnishing feed beyond its optimum value has negative effects as it increases the surface roughness and decreases both the surface hardness and the depth of the surface hardened layer.

Table (1). The composition and mechanical properties of the specimens

Metals	**(AISI) Specifications**	**Indicative partial Composition**	**Strength MPa**	**Hardness HV Kg/mm^2**
Mild Carbon Steel	M1044	0.502% C, 0.371% Mn, 0.047% P, 0.019% S, 0.511% Si, 0.083% Cu, 0.093% Cr, 0.053% Ni, Remainder Fe%.	Ultimate 550 Yield 310	165

Table (2). Burnishing conditions

1- Work piece	Plane surface cuboid. Length 110mm, width 50mm and 10mm height
2- Number of tool passes (NTP)	3
3- Burnishing force (Pz)	**Variable**: Range from 1 to 15 Kgf in increments of 1 Kgf.
4- Burnishing feed (f)	**Variable:** Range from 27 to 264 mm/min (27, 50, 80, 107, 134, 168, 219, 240, and 264 mm/min)
5- Spindle speed (v)	1460 rpm
6- Burnishing condition	lubricated (light engine oil).

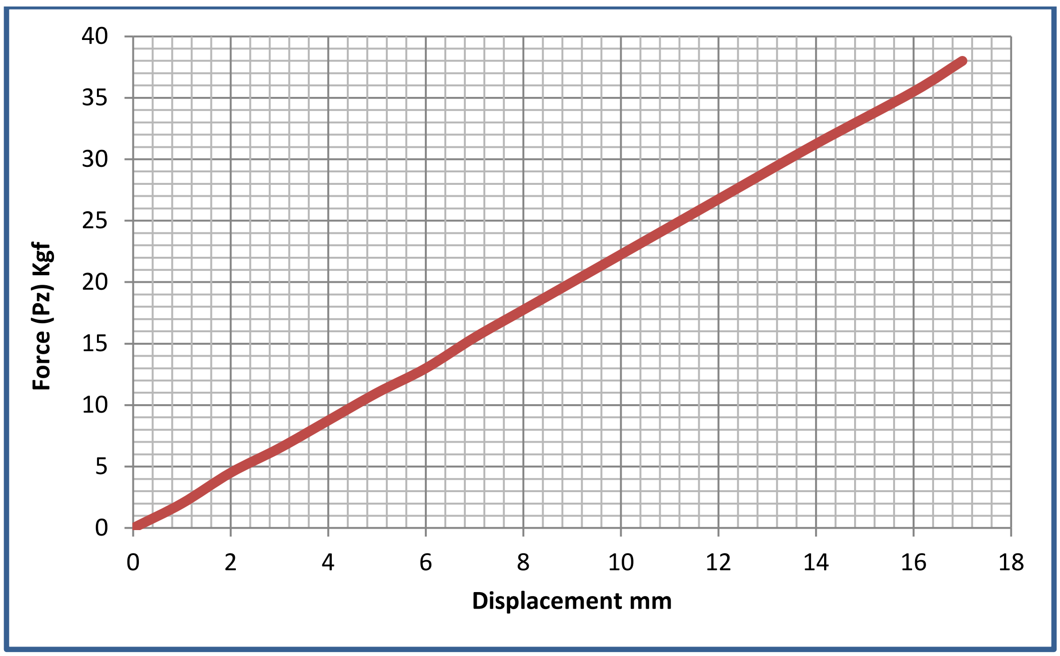


Figure (1). The spring's force / displacement relationship

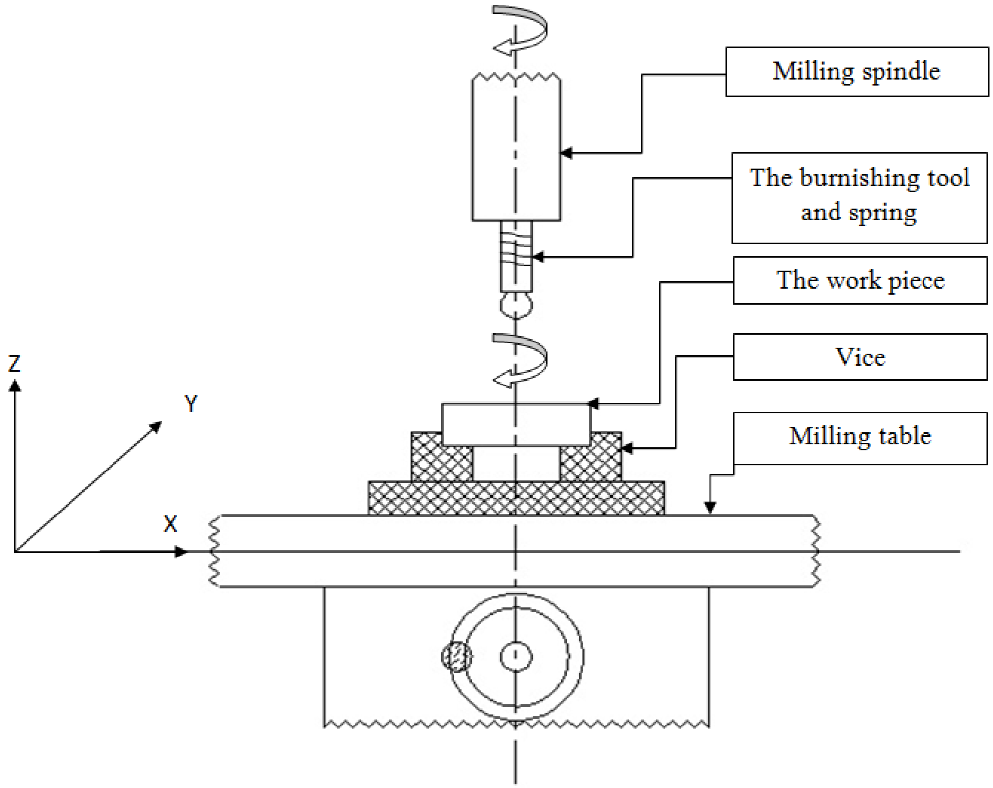
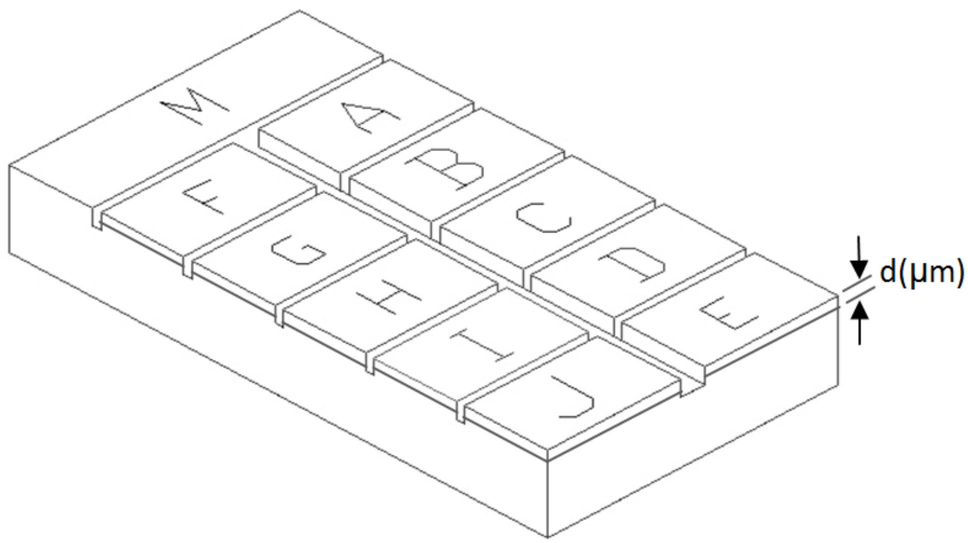


Figure (2 a). The experimental setup



M is the reference (un-burnished) milling segment. **A-J** segments are for different burnishing variables. The depth of the surface hardened layer is denoted by **d** in µm.

Figure (2 b). The experimental work piece

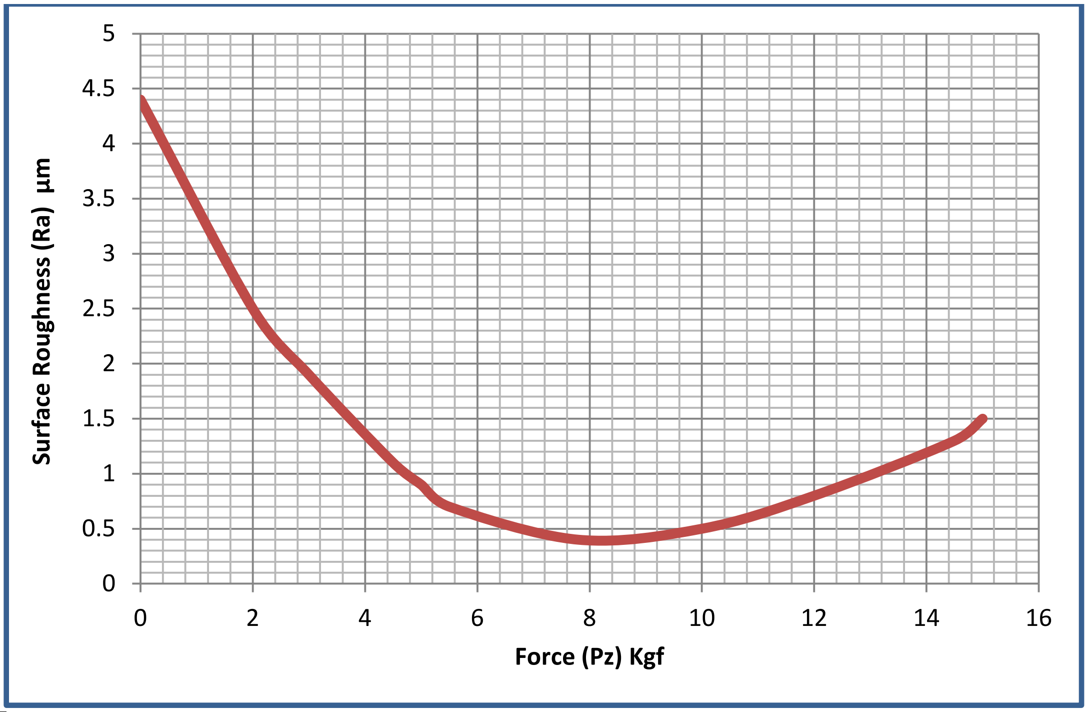


Figure (3). Effect of burnishing force (Pz) on surface roughness (Ra) at v = 1460 rpm, f = 107 mm min^{-1}. Initial surface roughness (Rai) = 4.4 µm, Initial surface hardness (Hvi) = 165 Kg mm^{-2}

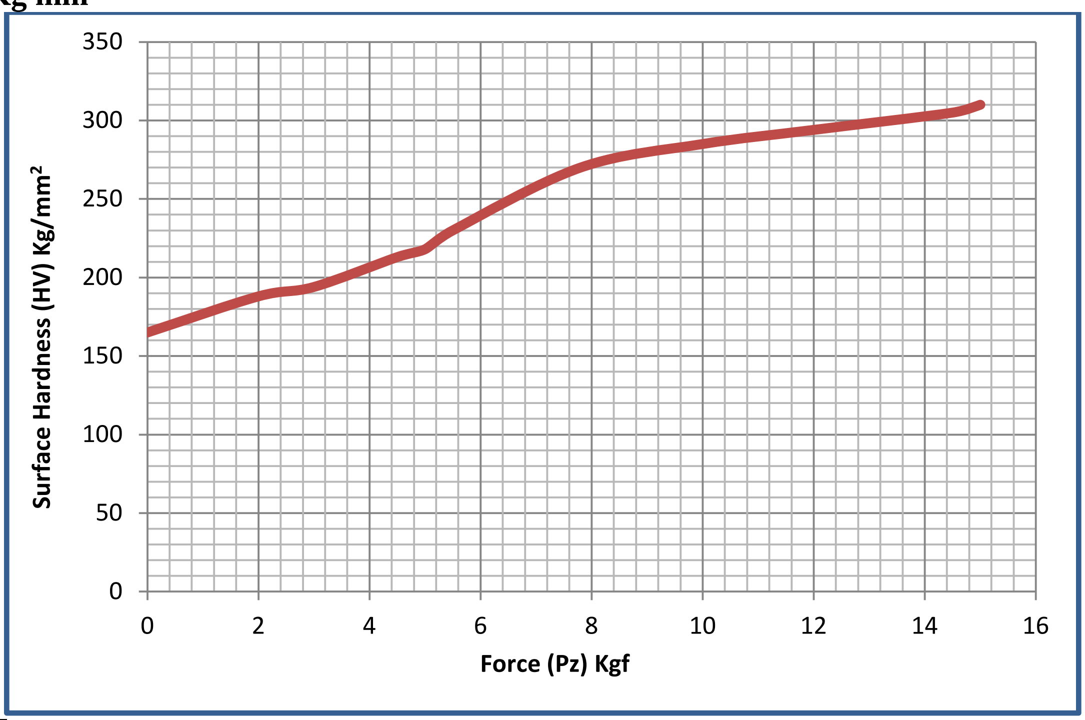


Figure (4). Effect of burnishing force (Pz) on surface hardness (HV) at v = 1460 rpm, f = 107 mm min^{-1}. Rai = 4.4 µm, Hvi = 165 Kg mm^{-2}

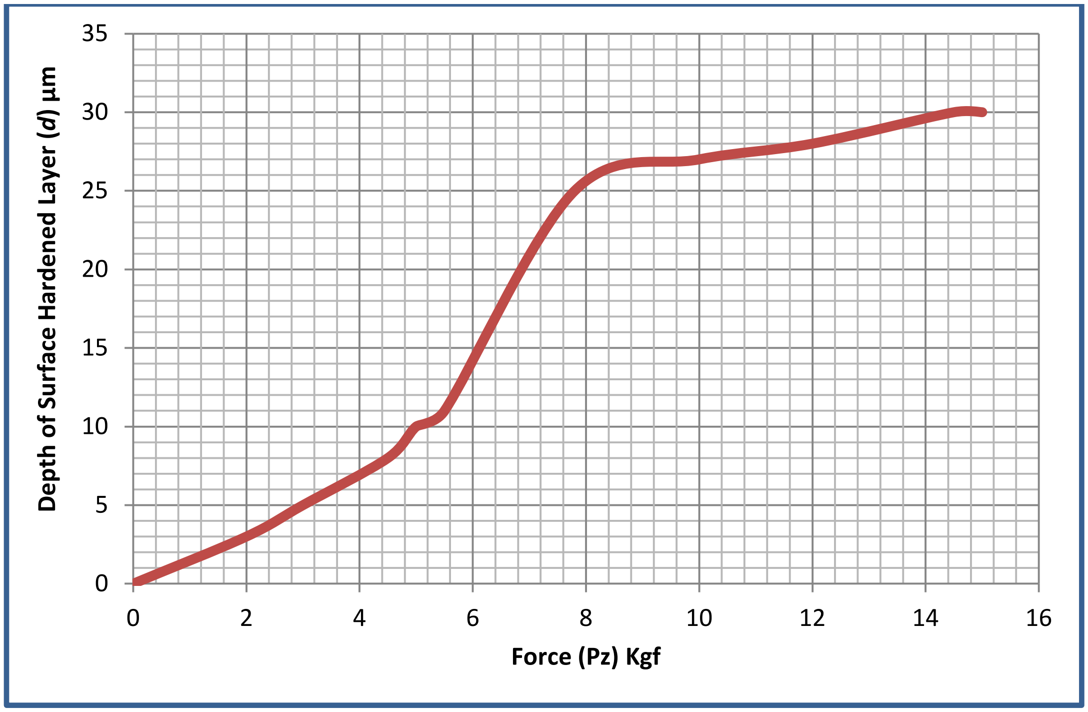


Figure (5). Effect of burnishing force (Pz) on depth of the surface hardened layer (d) at v = 1460 rpm, f = 107 mm min^{-1}. Rai = 4.4 µm, Hvi = 165 Kg mm^{-2}

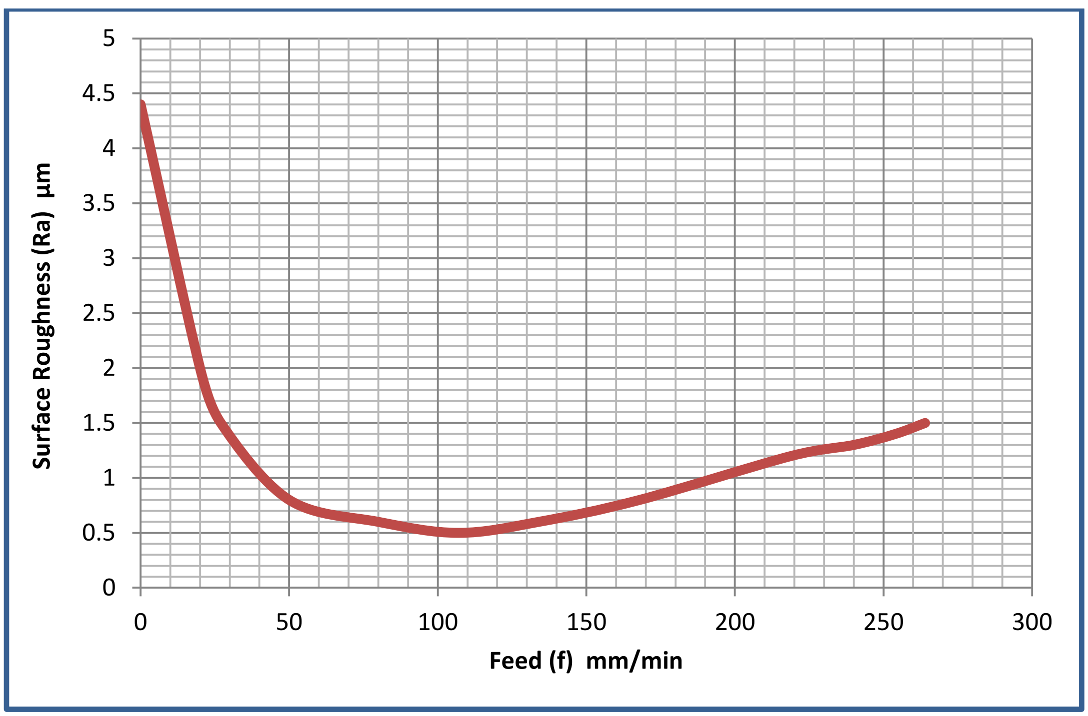


Figure (6). Effect of burnishing feed (f) on surface roughness (Ra) at v = 1460 rpm, Pz = 7.8Kgf. Rai = 4.4 µm, Hvi = 165 Kg mm^{-2}

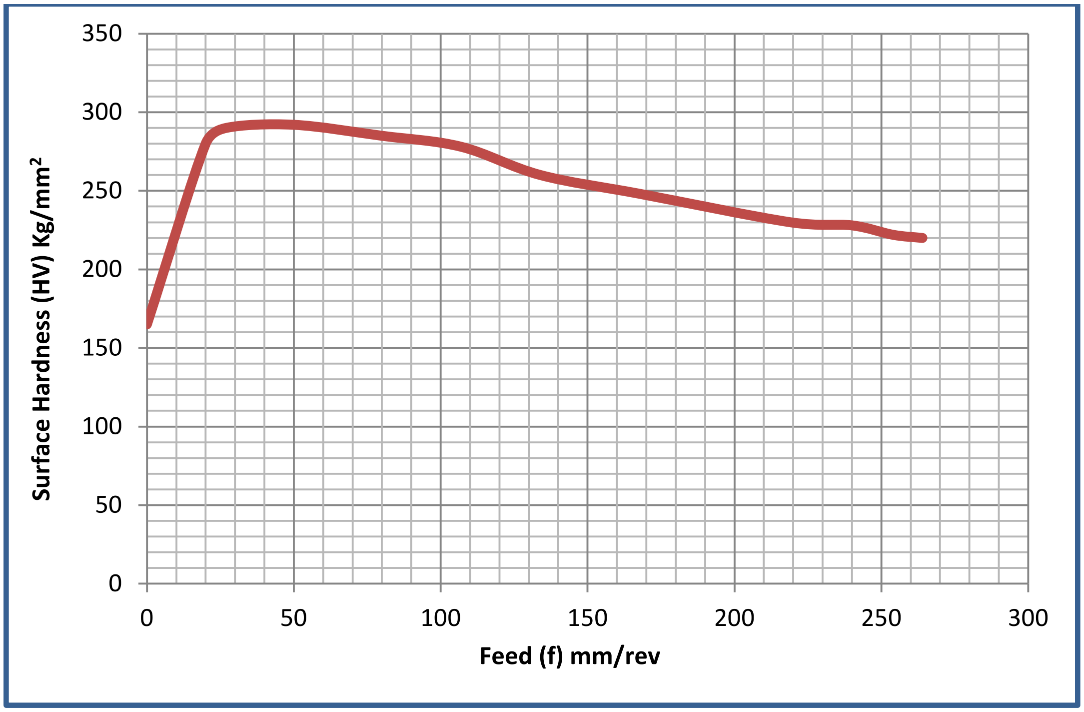


Figure (7). Effect of burnishing feed (f) on surface hardness (HV) at v = 1460 rpm, Pz = 7.8Kgf. Rai = 4.4 μm, Hvi = 165 Kg mm^{-2}

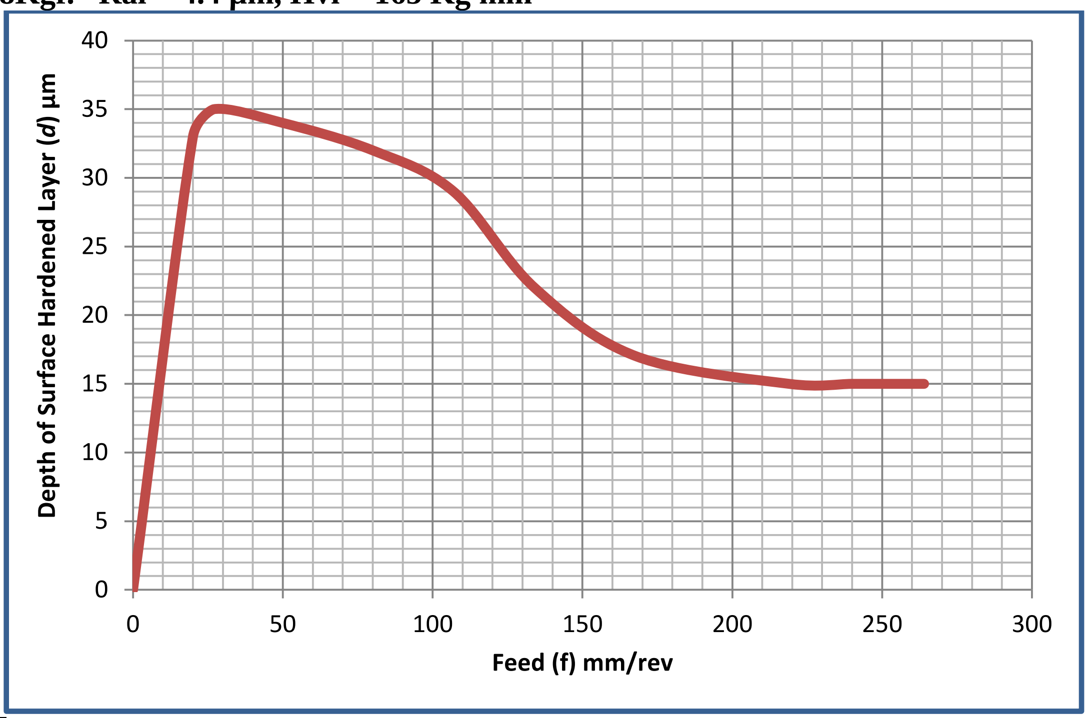


Figure (8). Effect of burnishing feed (f) on the depth of the surface hardened layer (d) at v = 1460 rpm, Pz = 7.8Kgf. Rai = 4.4 μm, Hvi = 165 Kg mm^{-2}

Figure (9). The depth of the hardened layer at the obtained optimum values of Pz = 7.8Kgf and feed (f) = 107 mm/min, at v = 1460 rpm, Rai = 4.4 µm, Hvi = 165 Kgmm^{-2}

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