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Surface Integrity in Turning of Annealed Brass: Hardness Prediction

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The purpose of this study was to obtain a comprehensive understanding of the effects of cutting parameters (depth of cut, feed rate, and cutting speed) on the surface integrity of, in terms of superficial hardening, annealed brass during a turning process. The results indicate that no significant phase transformations occurred for any of the turning conditions evaluated; however, microstructural changes were observed, as well as changes in the superficial hardness were measured. It was found that when the studied cutting parameters increase, the superficial hardness increases, with the cutting speed having less influence (2.56%), and feed rate having the greatest effect (22.67%). Finally, a mathematical expression is proposed, which relates the cutting parameters to the maximum hardness obtained for a given cutting condition.

Keywords brass, cutting speed, depth of cut, feed rate, hardness, turning

1. Introduction

For centuries, turning has been used as a metal cutting process because it is an efficient and precise method of producing close dimensional tolerances and very fine surfaces, and in many cases, it is used as finishing operation in the production cycle.

Surface layers produced by machining are usually plastically deformed and work hardened. The most common changes generated in the work area are due to heat and plastic deformation on the atomic scale, such as phase transformations, dislocations, vacancies, and voids, which alter the surface quality and mechanical properties of the material.

Despite all the researches, several crucial investigations have to be fully assessed to completely understand the experimental relationship, and describe the effect, among surface integrity, turning parameters, and material characteristics. Therefore, the aim of this study is to investigate the superficial changes in the hardness of a workpiece, and develop a simple formulation for the prediction of its maximum value, in turning analysis of annealed brass, taking into consideration the various parameters that can be controlled in the process: depth of cut (d), feed rate (f), and cutting speed (V_c). This mathematical expression can be considered as the starting point for the selection of optimal turning parameters, and the most important—controlling the influence of superficial properties on the operating regime of the piece.

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2. Literature Review

Surface integrity was suggested by Field and Kahles in 1971 (Ref 1) as the build up by the geometric values of the surface, such as surface roughness, and the physical properties, such as microstructures, hardnesses, and residual stresses of the surface and subsurface layers. These characteristics affect the quality of the machined surface which influences the mechanical properties, service life, and functionality of components.

A substantial amount of research has been done on surface integrity of machined parts by means of the residual stresses resulting from the metal removal process, since the study in 1951 by Henriksen (Ref 2), in which he observed that the residual stresses are due to grain deformation, caused by the forces acting between the surface layer and the tool.

Israeli and Papiar (Ref 3) measured the residual stresses caused by single point turning of AISI 4340 steel, showing that a higher feed rate increases the residual tensile forces and the depth of the residual stress layer. Sadat and Bailey (Ref 4) demonstrated that these variables also increase with the depth of cut, but decrease with higher cutting speeds. Saoubi et al. (Ref 5) confirmed most of these results by orthogonal cutting in AISI 316L standard and resulfurized stainless steels, with the only difference being that higher cutting speeds produced an

Nomenclature	
Cu	copper, %
d	depth of cut, mm
f	feed rate, mm/rev
Fe	iron, %
HB	Brinell hardness
Pb	lead, %
S_u	ultimate strength, kg/mm^2
S_y	yield strength, kg/mm^2
R^2	determination coefficient
R^2_{adjust}	adjust determination coefficient
V_c	cutting speed, m/min
Zn	zinc, %

increase in residual stresses, and a diminution of the thickness of the tensile layer.

Few authors have investigated the changes in hardness and mechanical properties due to the variables involved in turning process. The earliest quantitative evidence of work hardening caused by machining was reported in 1926 by Herbert (Ref 6), using a Pendulum hardness test; he observed that in lathe turning, an obtuse angle tool would harden the chip more, thus indicating a greater hardening of the work surface.

Later, Digges (Ref 7) reported that the amount of work hardening in turning of steels was influenced equally by changes in the feed rate or depth of cut, within a given area of cut, and it was not affected by changes in cutting speed. It was also confirmed that the maximum hardness obtained at the surface decreased with increasing carbon contents of the steel.

The changes in hardness and mechanical properties due to the finishing turning operation of AISI 4340 steel was subject of study by Sadat (Ref 8). Microhardness, measured in the surface section of the piece, showed little variation and was the same as that of the bulk material. In particular, the influence of the feed rate was negligible.

Other research by Sasahara (Ref 9), using 0.45% C steel as test material for the cutting process, demonstrated that for tool corner radii of 0.2 and 0.8 mm the hardness on the machined surface becomes higher with a smaller radius. In addition, the feed rate did not affect the surface hardness, for values between 0.05 and 0.4 mm/rev.

Recently, in 2008 Javidi et al. (Ref 10) applied different feed rates in turning of quenched and tempered 34CrNiMo6 steels. It was reported that plastic deformation of the grain boundaries was found at the first 3-4 μm of the subsurface layer. They also confirmed that, no significant variation in hardness was observed beneath the machined surface produced by different cutting conditions.

3. Experimental Procedure

Starting from a round bar of brass (60.59% Cu, 34.90% Zn, 3.92% Pb, and 0.59% Fe) with a diameter of 22.23 mm, which was selected because it has a high strain hardening index, cylinders of approximately 300 mm in length were cut.

3.1 Heat Treatment

The samples were annealed for 1 h after reaching a temperature of 650 °C, to allow the crystallographic recovery of the material and thus obtain a strain free structure with a lower hardness value. The mechanical properties obtained are shown in Table 1.

3.2 Turning Process

For turning of the specimens, all the cutting tests were carried out with a numerically controlled lathe, using a DNMG insert with a nose radius of 0.8 mm, and were preformed dry, without cutting fluid.

Table 1 Mechanical properties of the annealed brass

S_y, MPa	S_u, MPa	HB
130.33	305.97	70

The experiments were planned using the Design of Experiments technique (Ref 11), and were conducted in a $3 \times 3 \times 2$ factorial arrangement of variables, with three levels of depth of cut, three levels of feed rate, and two levels of cutting speed, as shown in Table 2.

Single longitudinal cutting passes were performed, with a fixed length of cut of 25 mm, and the cutting speed was kept constant by the lathe controller, which varied the rotation speed depending on the tool position in radial direction.

In order to guarantee equal conditions for all the experiments, and ensure the absence of changes in the surface properties of the material due to the tool wear (Ref 12), the insert's cutting edge was changed for each experiment.

3.3 Preparation of Metallographic Specimens

The machined samples were cut perpendicularly along the longitudinal direction, at a fixed distance of 20 mm from the bar edge.

To describe the changes caused by the turning process, the near-surface microstructure of the turned face and the bulk material were recorded by metallographic tests conducted in accordance with the ASTM E3-80 standard, using conventional metallographic equipment, with 40% HNO_3-60% water and an attack time of 5 s.

3.4 Microhardness Measurements

Vickers microhardness sweep along the radii was made with a Shimadzu model 4046 hardness tester for the study of the changes in superficial hardness caused by the turning process.

The indentations were made at different radial distances, with increments from the surface of 0.5 mm, in a pattern as drawn in Fig. 1. Measurements were made until a constant value of hardness and equal to the initial hardness of the material was achieved. For each hardness measurement, a load of 100 gf was applied for 30 s.

In order to take an average of the hardness measured, three indentations were made for each distance of the sweep, discarding the values that were considerably outside the range demarcated by the other measures.

3.5 Construction of the Mathematical Expression

By means of the multiple linear regression method (Ref 13), a mathematical expression is derived. Several empirical models were employed to construct the expression to select the one that best represents the experimental data (Ref 14). In the formulation, the independent variables correspond to depth of cut (d), feed rate (f), and cutting speed (V_c), while the hardness HB represents the response variable.

4. Results and Discussion

As was expected, machining had an influence over the conditions of the subsurface microstructure of the worked

Table 2 Parameters used in the turning of the samples

d, mm	f, mm/rev	V_c, m/min
2	0.05	20
4	0.15	…
6	0.25	70

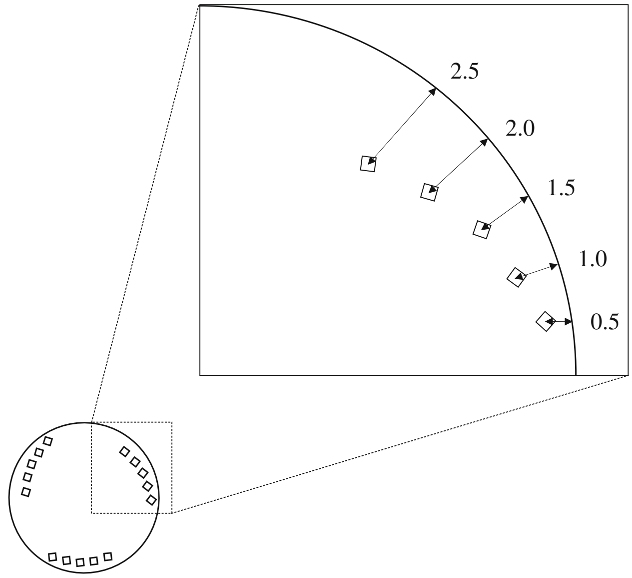

Fig. 1 Schematic view of microhardness indentations

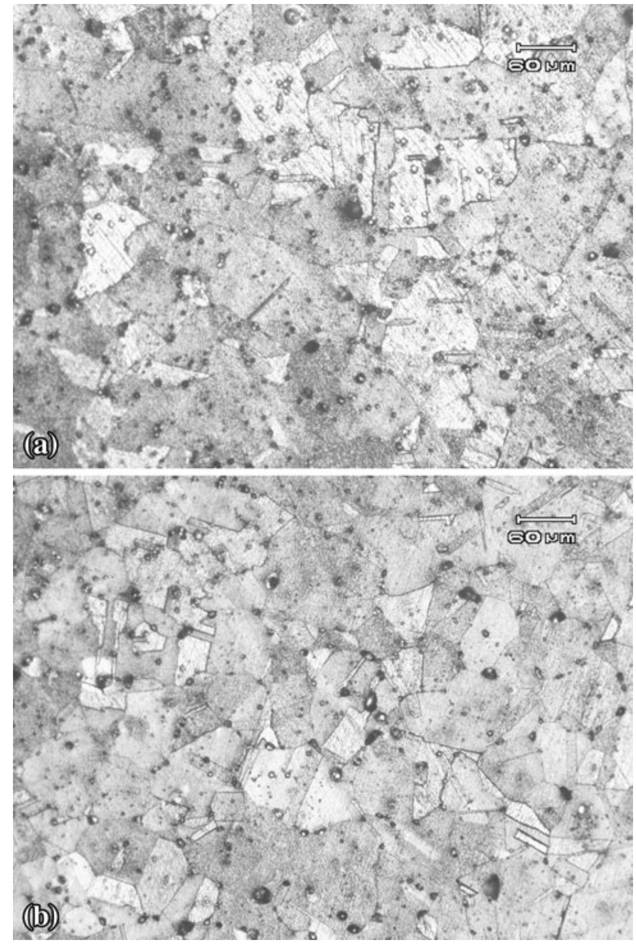

Fig. 2 Microstructure present on the surface of a brass specimen: (a) after the annealing heat treatment; (b) after turning under severe conditions (d = 6 mm, f = 0.25 mm/rev, V_c = 70 m/min)

pieces, caused by the high quantity of heat and plastic deformation introduced. Figure 2(b) shows the resulting microstructure at the surface of a specimen turned under severe conditions, where a light increment in the amount of twins as compared with the after annealed sample (Fig. 2a) is seen, which in less degree is representative of the behavior observed for all evaluated conditions.

Figure 3 shows cascade shape curve of hardness along the radii, with a maximum point occurring near the surface, gradually decaying until reaching a constant at the core of the sample. Values for the maximum hardness increase between 6.14 and 35.71% compared with the annealed condition, proving the superficial hardening that takes place as a consequence of the turning process, which is caused by the above described microstructural changes, plastic deformation, and residual stresses introduced into the material.

Previous studies (Ref 15), report that the primary hardening mechanism in machining was the rapid heating and cooling cycle with mechanical deformation being secondary. In the case of the material used in this study, the cooling speed was too slow to reach the phase transformation, leaving the severe plastic deformation caused by the surface tearing as the tool advances as the main source for microstructure changes and work hardening at surface and subsurface layers.

The influence of the depth of cut on the superficial hardening is shown in Fig. 4. The average maximum hardness were plotted since it is more representative and is the value exposed to the external conditions on a piece in operation.

The slopes of the curves indicate a very light increment in the superficial hardness with the cutting depth. The general tendency obtained in all the evaluated conditions for the hardness is to increase, with a maximum difference value of 6.67%, which corresponds to a fixed cutting speed of 70 m/min and feed rate of 0.05 mm/rev.

The depth of cut has greater influence on the tangential cutting force, consequently, when the depth of cut changes the increase of the axial force is not significant, thus having a minor contribution to the subsurface deformation and the hardening of the material in axial direction (Ref 16, 17).

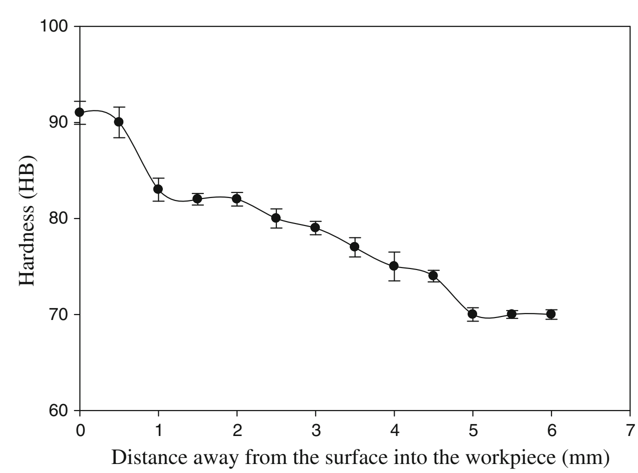

Fig. 3 Representative curve of the changes of superficial hardness caused by turning a specimen with the parameters of: d = 2 mm, f = 0.25 mm/rev, V_c = 70 m/min

In Fig. 5, showing plots of the superficial hardness as a function of the feed rate of the tool, we observe that similar to the previous parameter which increased with a good linear trend, surface hardness increases constantly with higher feed

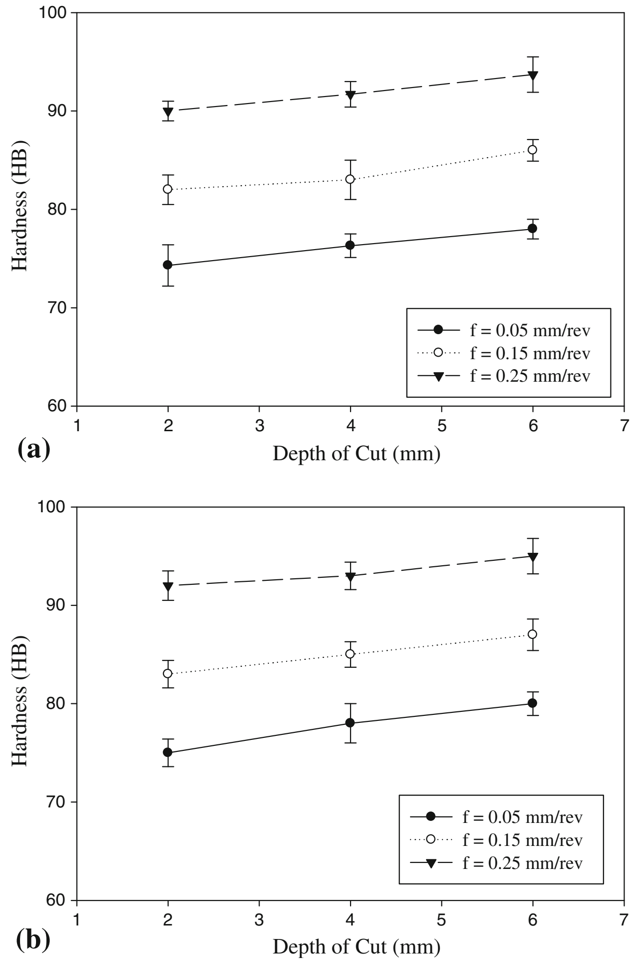

Fig. 4 Graph of average maximum Brinell hardness vs. depth of cut for turned annealed brass, with a cutting speed of (a) 20 m/min; and (b) 70 m/min

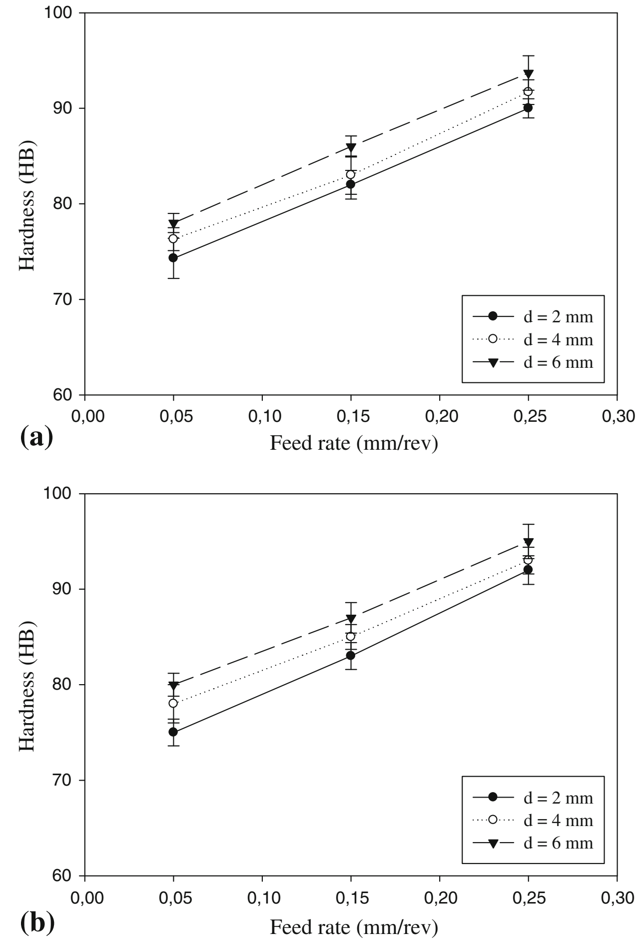

Fig. 5 Graph of average maximum Brinell hardness vs. feed for the turned annealed brass, with a cutting speed of (a) 20 m/min; and (b) 70 m/min

rates, but rising in a much greater slope than the depth of cut. The maximum measured hardness difference in all the evaluated conditions was 22.67%, for a fixed cutting speed of 70 m/min and depth of cut of 2 mm.

This is because the increasing feed rate generates higher cutting forces and, therefore, more plastic deformation; it also increases the compressive stress values in the sub-surface and the thickness of the tensile layer (Ref 17). Thus, the tool effect on the workpiece gains importance, causing the augmentation of the compressive zone in the region situated below the cutting edge, and these result in a more severely work-hardened layer (Ref 16).

Figure 6 shows that the superficial hardness of the material for all the evaluated conditions increases with the cutting speed, with a maximum hardness difference of 2.56% observed for a fixed feed rate of 0.05 mm/rev and depth of cut of 6 mm.

The influence of cutting speed is explained by the increase in chip speed flow in the cutting zone leading to a greater heat evacuation, the remaining heat is introduced in the workpiece and tends to increase with cutting speed, producing tensile stresses at the surface. In addition, at higher cutting speeds, the strain rate also increases, leading to compressive stresses, because of the additional mechanical work introduced in to the process (Ref 17). The final result is achieved by the counteraction of these opposing phenomena, causing a small increase in the cutting energy in this zone, which is only sufficient to lightly affect the workpiece surface region (Ref 18).

Comparing the curves in Fig. 4-6, the feed rate is the parameter that has more influence, and cutting speed has least influence, on the superficial hardening caused by the turning process, which is evident from the more-, and the less-inclined slopes of the curves, respectively.

Based on these results, several mathematical adjustments were studied to generate a mathematical expression that would be a reliable representation of the variation in the hardness as function of the different cutting parameters.

The expression that best represents the experimental data obtained for the annealed brass was the following:

$$\mathrm{HB} = 67.84 + 77.07f + 1.00d + 0.03V_c \qquad \text{(Eq 1)}$$

$$S = 1.1235 \quad R^2 = 0.9739 \quad R^2_{\mathrm{adjust}} = 0.9627$$

This expression was selected because, as can be observed, the values represented by R^2 and R^2_{adjust} are higher than 96%. Since these coefficients correspond to the amount of variance in the outcome that the model explains, it means that the fit describes 96.27% of the total variation in the data, indicating excellent goodness-of-fit, and thus a high level of reliability (Ref 13).

The standard error of estimates (S) approximate to one, which reports a linear trend for the surface hardness values

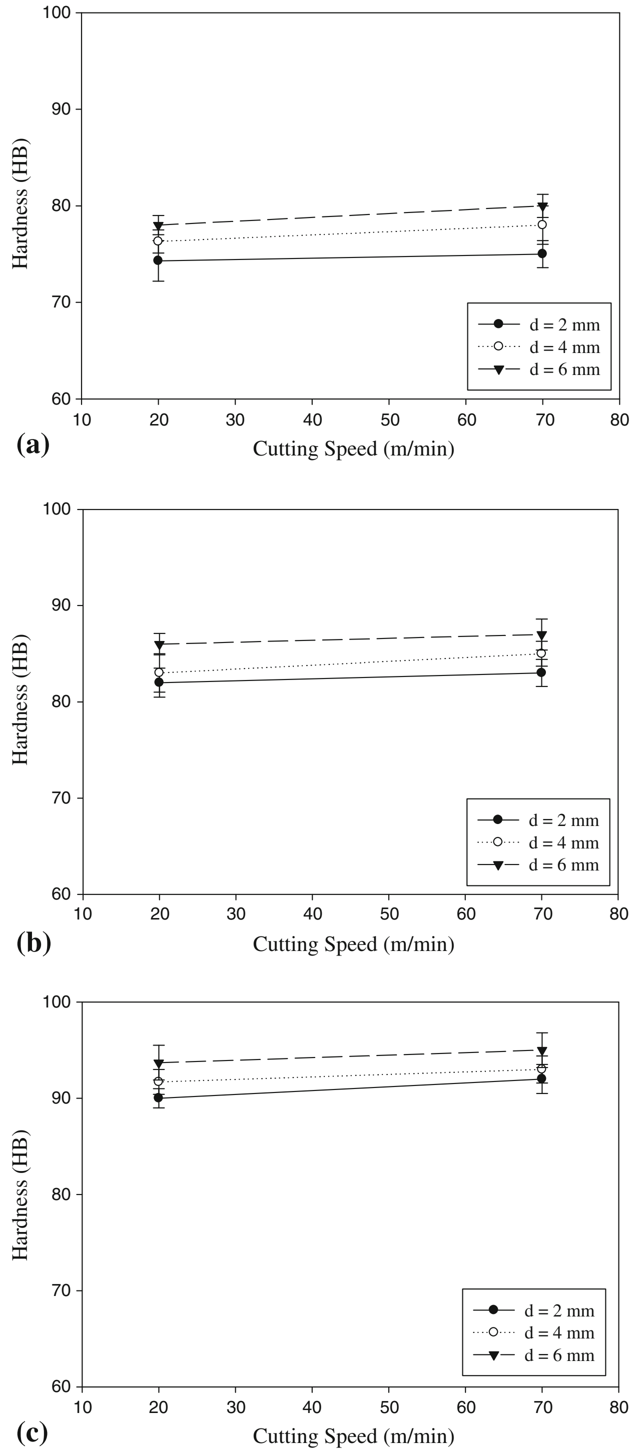

Fig. 6 Graph of average maximum Brinell hardness vs. cutting speed for the turned annealed brass, with a feed of (a) 0.05 mm/rev; (b) 0.15 mm/rev; and (c) 0.25 mm/rev

fitting between the limits, as in the ideal case, which indicates that this model is consistent with the experimental values (Ref 14).

As observed in Eq 1, it was verified that the coefficients of each variable are consistent with the analysis of Fig. 4-6, where the feed rate has the greatest effect on the superficial hardening, followed by the depth of cut, and at last, the cutting speed.

5. Conclusions

This article presents an investigation on the relationship between turning cutting parameters and workpiece surface integrity. All factors were found to have a significant influence on the surface hardness. Specifically, the following conclusions can be drawn:

(1) The superficial hardening of the material was shown by the microstructural change and the plastic deformation caused by the chip outburst.
(2) The maximum value for superficial hardness increases between 6.14 and 35.71% compared with the annealed condition, when the depth of cut, feed rate, and speed increase.
(3) When comparing the influence of the turning parameters, the feed rate has the greatest effect (22.67%) on the superficial hardening relative to the depth of cut (6.67%) and cutting speed (2.56%).
(4) The mathematical expression that offers the best description of the hardness superficial maximum as function of the cutting parameters is the Eq 1.

References

1. M. Field and J. Kahles, Review of Surface Integrity of Machined Components, *Ann. CIRP*, 1971, **20**, p 153–163
2. E. Henriksen, Residual Stresses in Machined Surfaces, *Trans. ASME*, 1951, **73**, p 69–76
3. A. Israeli and R. Papiar, Residual Stress Profile in Machined Parts, *J. Test. Eval.*, 1981, **9**(6), p 348–353
4. A.B. Sadat and J.A. Bailey, Residual Stresses in Turned AISI, 4340 Steels, *Exp. Mech.*, 1987, **27**(1), p 80–85
5. R. Saoubi, J. Outeiro, B. Changeux, J. Lebrun, and A. Morao, Residual Stress Analysis in Orthogonal Machining of Standard and Resulfurized AISI, 316L Steels, *J. Mater. Process. Technol.*, 1999, **96**, p 225–233
6. E.G. Herbert, Work-Hardening Properties of Metals, *Trans. ASME*, 1926, **48**, p 705
7. T.G. Digges, Effect of Lathe Cutting Conditions on the Hardness of Carbon and Alloy Steels, *Trans. ASME*, 1932, **54**, p 49–57
8. A.B. Sadat, Effect of High Cutting Speed on Surface Integrity of AISI, 4340 Steel During Turning, *Mater. Sci. Technol.*, 1990, **6**, p 371–375
9. H. Sasahara, The Effect on Fatigue Life of Residual Stress and Surface Hardness Resulting from Different Cutting Conditions of 0.45%C Steel, *Int. J. Mach. Tools Manuf.*, 2005, **45**, p 131–136
10. A. Javidi, U. Rieger, and W. Eichlseder, The Effect of Machining on the Surface Integrity and Fatigue Life, *Int. J. Fatigue*, 2008, **30**, p 2050–2055
11. D.C. Montgomery, *Design and Analysis of Experiments*, 6th ed., John Wiley and Sons, New York, 2004
12. A.R.C. Sharman, J.I. Hughes, and K. Ridgway, An Analysis of the Residual Stresses Generated in Inconel 718TM When Turning, *J. Mater. Process. Technol.*, 2006, **173**, p 359–367
13. D.C. Montgomery and E.A. Peck, *Introduction to Linear Regression Analysis*, 3rd ed., John Wiley and Sons, New York, 2001
14. D. Peña, *Estadística; Modelos y Métodos* (Statistics; Models and Methods), 3rd ed., Alianza Editorial S.A., Madrid, 2001 (in Spanish)
15. Y.K. Chou, Surface Hardening of AISI, 4340 Steel by Machining: A Preliminary Investigation, *J. Mater. Process. Technol.*, 2002, **124**, p 171–177
16. P. Dahlman, F. Gunnberg, and M. Jacobson, The Influence of Rake Angle, Cutting Feed and Cutting Depth on Residual Stresses in Hard Turning, *J. Mater. Process. Technol.*, 2004, **147**, p 181–184
17. F. Gunnberg, M. Escursell, and M. Jacobson, The Influence of Cutting Parameters on Residual Stresses and Surface Topography During Hard Turning of 18MnCr5 Case Carburised Steel, *J. Mater. Process. Technol.*, 2006, **174**, p 82–90
18. M. Jacobson, P. Dahlman, and F. Gunnberg, Cutting Speed Influence on Surface Integrity of Hard Turned Bainite Steel, *J. Mater. Process. Technol.*, 2002, **128**, p 318–323