Superficial Hardening in the Plane Grinding of AISI 1045 Steel

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This work outlines the influence of cutting parameters on the superficial hardening of AISI 1045 steel during a grinding process. The parameters are infeed (d), workpiece velocity (v), and cross feed (s). Microstructural changes are also presented. A mathematical expression was obtained that relates the parameters to the maximum hardness obtained for a given cutting condition. No significant microstructure transformations were observed for any of the grinding conditions evaluated; however, changes in the superficial hardness were measured. It was found that when the studied cutting parameters increase, the superficial hardness increases.

Keywords AISI-1045, cutting parameters, grinding, hardness

1. Introduction

Grinding is a metal cutting process, which for many centuries only existed in workshops in the form of sharpening. Over the years it was perfected until it became a quick, efficient, and precise method of producing very fine surfaces.

It is well known that this process requires very high energy compared with other machining processes. In any grinding process, virtually all the energy is dissipated as heat in the cutting area. Most of the heat that is generated in the work area is due to friction and plastic deformation. This heat can cause a significant increase in the temperature of the workpiece, giving rise to several types of damage to the workpiece and the wheel.

A substantial amount of research has been done on heat transfer during the grinding process, such as the studies by Snoeys and Peters[1] and Malkin.[2] A model was later developed that used the heat transfer associated with the workpiece, chip, and fluid, and eliminated the need to specify the energy fragment that enters the workpiece or the convective coefficient of the heat flow.[4]

Recent research[4,5] reveals that the heat flow in each of the elements is not uniform in the work area and proposes a model of temperature distribution.

The changes in hardness and mechanical properties due to the grinding process have also been studied. Microhardness, measured along the section of the piece, shows marked variations in hardness in the material due to the violent heating and cooling of the surface, and the creation of residual stresses in the material.[6]

Other research[7,8] demonstrates that the residual stresses are caused mainly by: (1) martensite transformation in areas near the surface; (2) the plastic flow of the material on the surface and adjacent areas due to thermal stresses caused by the heat generated during the process; and (3) plastic deformation due to the cutting forces of the grains on the surface of the piece. Plastic deformation close to the surface is related to grinding parameters, such as size of abrasive grain, speed of the piece, infeed, and properties of the material.[9] Additionally, the depth of the damage caused in the material during the grinding process was determined by metallographic observation and microhardness. Guest[10] concluded that when the speed of the piece and the infeed increase, the surface temperature rises.

The grinding process causes changes in the mechanical properties of the surface of the workpiece. The most common changes are phase transformations, introduction of residual stresses, and plastic deformation, which alter the properties of the material. The surface finish and superficial properties have to be controlled by adjusting the cutting parameters of the grinding. Finally, and most important, is the influence of these changes on the operating regimen of the piece.

This work studies the superficial changes in the hardness of a workpiece caused by the grinding of AISI 1045 steel, taking into consideration the various parameters that can be controlled in the process; infeed (d), workpiece velocity (v), and cross feed (s).[11]

2. Experimental Procedure

Starting from a cylindrical bar of AISI 1045 steel (0.455%C and 0.82%Mn) with a diameter of 25.4 mm, disks of approximately 6 mm in thickness were cut with sufficient coolant and

Nomenclature	
C	carbon (%)
D	infeed (mm)
HB	Brinell Hardness
Mn	manganese (%)
S	cross feed (mm/pass)
S_u	ultimate strength (MPa)
S_y	yield strength (MPa)
R^2	determination coefficient
R^2_{adjust}	adjust determination coefficient
V	workpiece velocity (m/min)

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Table 1 Mechanical Properties of the Annealed AISI 1045 Steel

S_y, MPa	S_u, Mpa	HB
412	588	206

Table 2 Dimensions of the Abrasive Wheel Used in the Grinding Process

External Diameter, mm	Internal Diameter, mm	Thickness, mm
355	127	38

operating parameters to ensure the absence of changes in the surface properties of the material.

2.1 Heat Treatment

After producing the samples, annealing heat treatment was applied to allow the crystallographic recovery of the material and thus obtain a ferrite and pearlitic structure and a lower hardness value.

The treatment involved maintaining the samples in an oven for 1 h after reaching a temperature of 860 °C, followed by cooling inside the oven. The mechanical properties obtained are shown in Table 1.

The measurements of the reference Brinell hardness were made in a traverse section of the sample to eliminate any possibility of the preferential orientation of the phases affecting the measurements, which were then compared with the results obtained after the grinding process.

2.2 Grinding Process

All the experiments were conducted with a Carborundum (Untd. Carborundum & Electrite Work, Benátky N. Jiz., Czechoslavakia) type A36M5V42 grinding wheel of the dimensions shown in Table 2.

The external surface of the wheel was cleaned with a diamond tip before each experiment to guarantee that it was in the best condition (i.e., with a very sharp plane cutting surface to guarantee equal conditions for all the experiments).

A horizontal-spindle machine (Fig. 1), Grand Rapids model 480 (Gallmeyer & Livingston Co., Grand Rapids, MI), was used for the grinding processes, with a fixed rotation wheel speed of 1750 rpm that converts to an average speed of 32.5 m/s due to the size of the abrasive wheel.

The parameters and experimentation levels used for the tests are shown in Table 3.

A random combination of the cutting parameters given above was used in the tests, producing a total of 27 combinations with three repetitions each.

For each sample, successive cutting passes (partial depths) were made to a total depth of 1 mm, to guarantee removal of any irregularity or variation in the surface of the samples. An abundant quantity of water-soluble oil coolant was used during the entire process.

2.3 Preparation of Metallographic Specimens

For the metallographic analysis, the samples were cut perpendicularly along the grinding plane in the cutting direction.

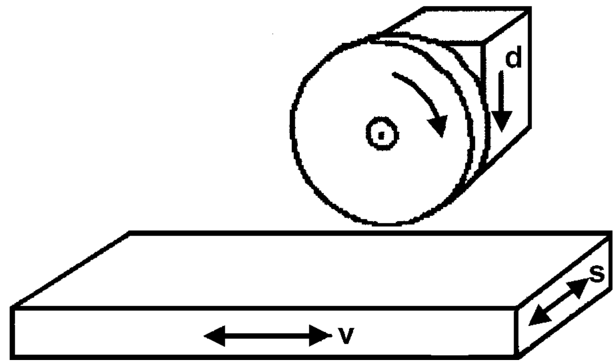

Fig. 1 Schematic view of a horizontal-spindle machine with the parameters used

Table 3 Parameters Used in the Plane Grinding of the Samples

Experimental Level	Low	Medium	High
V, m/min	7.63	13.63	25.83
s, mm/pass	3.5	6.0	11.0
d, mm	0.0075	0.0125	0.0175

The tests were conducted in accordance with the ASTM E3-80 standard, using conventional metallographic equipment, with picral 4% and an attack time of 15 s.

The near surface microstructure of the ground face was recorded to describe the influence or changes caused by the grinding process.

2.4 Microhardness Measurements

For the study of the changes in superficial hardness caused by the grinding process, a Vickers microhardness sweep in the traverse section of the ground area was made with a Shimadzu (Shimadzu, Kyoto, Japan) model 4046 hardness tester. The conditions for the measurements were a load of 100 gf for 15 s.

The indentations were made in the traverse area of the samples, with a separation of 0.5 mm, covering the entire surface (i.e., from one face to the other of the sample).

Three indentations were made for each distance of the sweep to take an average of the hardness measured.

The average was calculated by discarding the values that were considerably outside the range demarcated by the other measures; if the measures were outside but close to a range, indentations were made until a representative sample was found.

2.5 Construction of the Mathematical Expression

The mathematical expression is derived by the multiple linear regression method.[12] In the expression, the hardness HB represents the answer variable while the independent variables correspond to infeed (d), workpiece velocity (v), and cross feed (s). Several empirical models were used to construct the expression to select the one that best represents the experimental data.[13]

3. Results and Discussion

For the evaluated conditions, the metallographic and hardness analysis gave the following results.

It was expected that the microstructure of the worked pieces would present some changes, at least in the conditions where a higher quantity of heat is introduced; however, this was not the case. Under all conditions, both soft and severe, the structures before and after the machining were unchanged. Figure 2 shows the resulting pearlitic and ferritic microstructure of a specimen ground under severe conditions, which is representative of the annealing heat treatment.

Previous studies[14] report that the superficial hardening occurs due to the martensite transformation, due to the cooling of the material of the piece with a type of quench at the surface. In the case of the material used in this work, two possible situations could have occurred: (1) the temperature needed to produce the martensitic transformation was not reached, or (2) more probable, the cooling speed was too slow to reach the area of martensitic formation.

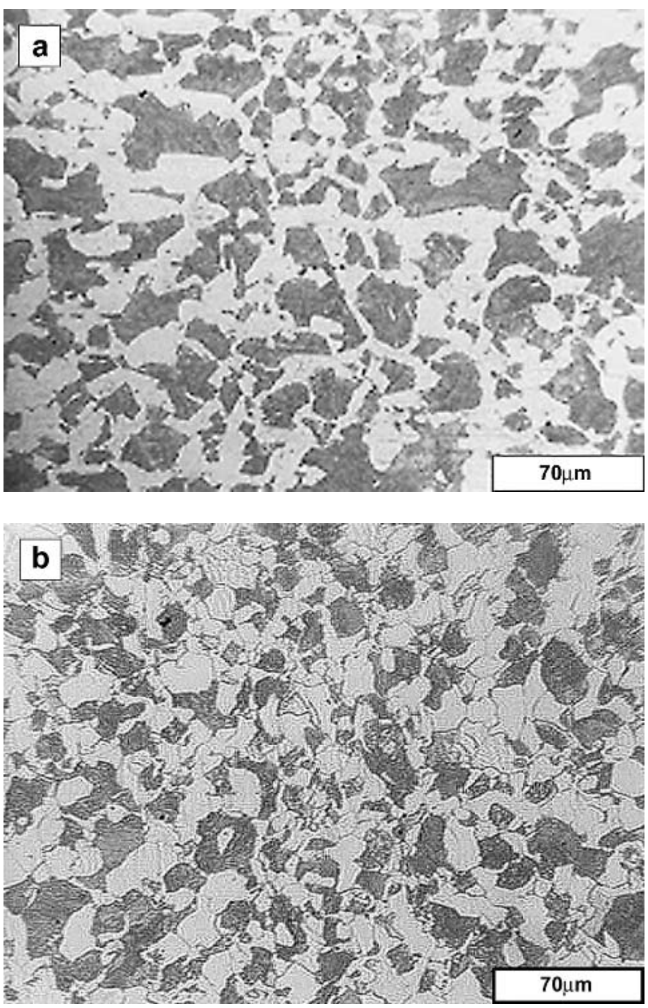

Fig. 2 Pearlitic (dark zones) and ferritic (clear zones) microstructure present on the surface of an AISI 1045 specimen: **(a)** after the annealing heat treatment; **(b)** after grinding under severe conditions (v = 25.83 m/min, s = 11 mm, d = 0.0175 mm)

This is explained by the fact that the AISI 1045 is a low hardenability steel. The TTT diagram of AISI 1045 steel shows that due to the low percentage of carbon and the absence of other elements, the cooling curve for the martensite transformation should be almost vertical (i.e., a high freezing speed is necessary).

Figure 3 shows that due to the grinding process, a superficial hardening of the material takes place that could be caused by microstructural changes, plastic deformation, and residual stresses introduced into the material.

The curve has roughly a cascade shape. A maximum point of hardness occurs on the surface, which gradually decays as it penetrates the material until reaching a constant that corresponds to the hardness of the core of the annealed sample.

If the superficial hardening of the samples is not due to the microstructural transformations caused by the cutting process, it must be considered that the removal of the material produces a severe plastic deformation.

Depending on the operating conditions, changes will take place in the quantity of heat produced, plastic deformation, and residual stresses induced, because these vary with the quantity of material removed during the process.

Figure 4 shows the influence of the infeed on the superficial hardening. To construct the graphs, the average maximum values of hardness were plotted from sweepings of hardness made in all the samples. The average maximum value was used since it is more representative and is the value exposed to the external conditions on a piece in operation.

The curve of the graphs shows the increase in the superficial hardness as the infeed increases, because a higher value represents more material haulage, which implies a higher penetration of each grain in the surface of the piece at the time of the cut. Consequently, the contact area between the grain and the piece increases, and the cut forces required for the outburst of the chip also increase.

This generates an increase in the energy consumed during the cutting process, which increases the residual stresses and hardens the material. This behavior agrees with previous re-

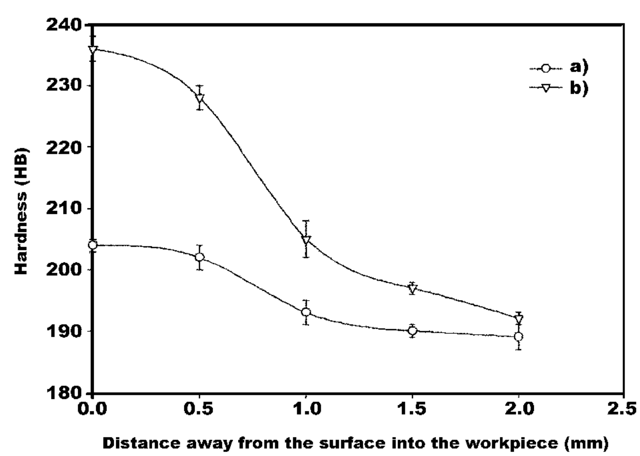

Fig. 3 Representative curve of the changes of superficial hardness caused by grinding a specimen with the parameters of **(a)** low level (v = 7.63 m/min, s = 3.5 mm, d = 0.0075 mm); and **(b)** high level (v = 25.83 m/min, s = 11 mm, d = 0.0175 mm)

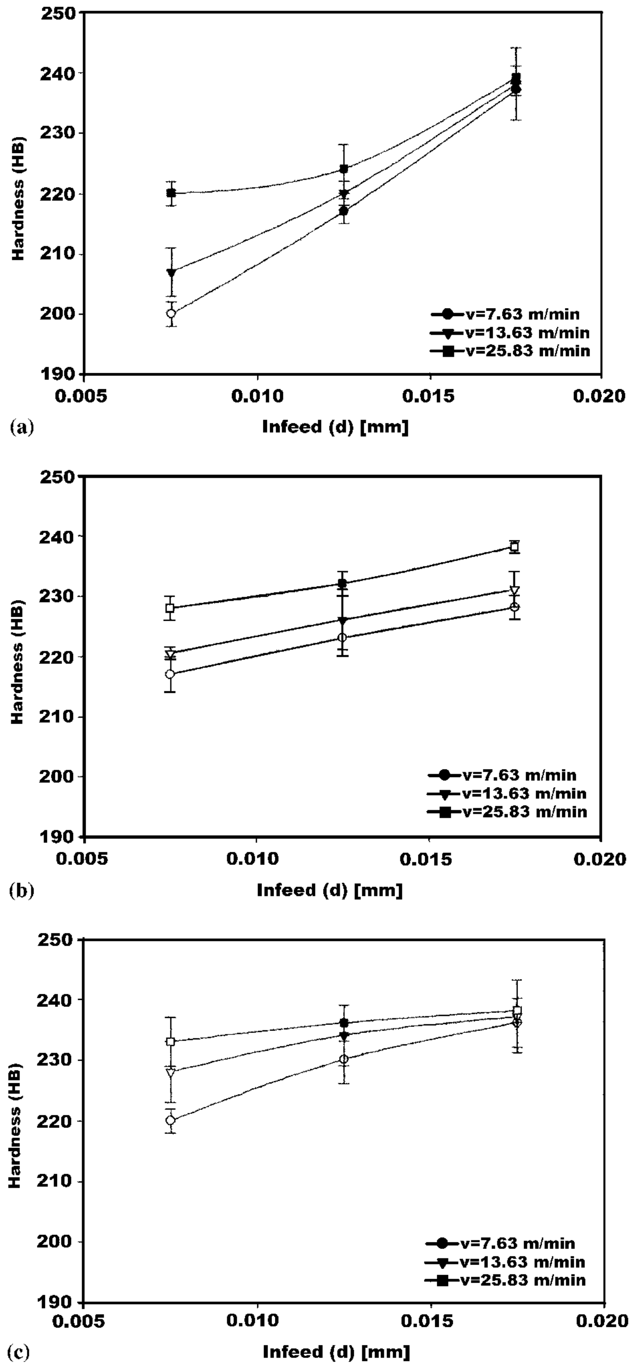

Fig. 4 Graph of average maximum Brinell hardness vs infeed for the AISI 1045 steel, with a cross feed(s) of **(a)** 3.5 mm, **(b)** 6 mm, and **(c)** 11 mm

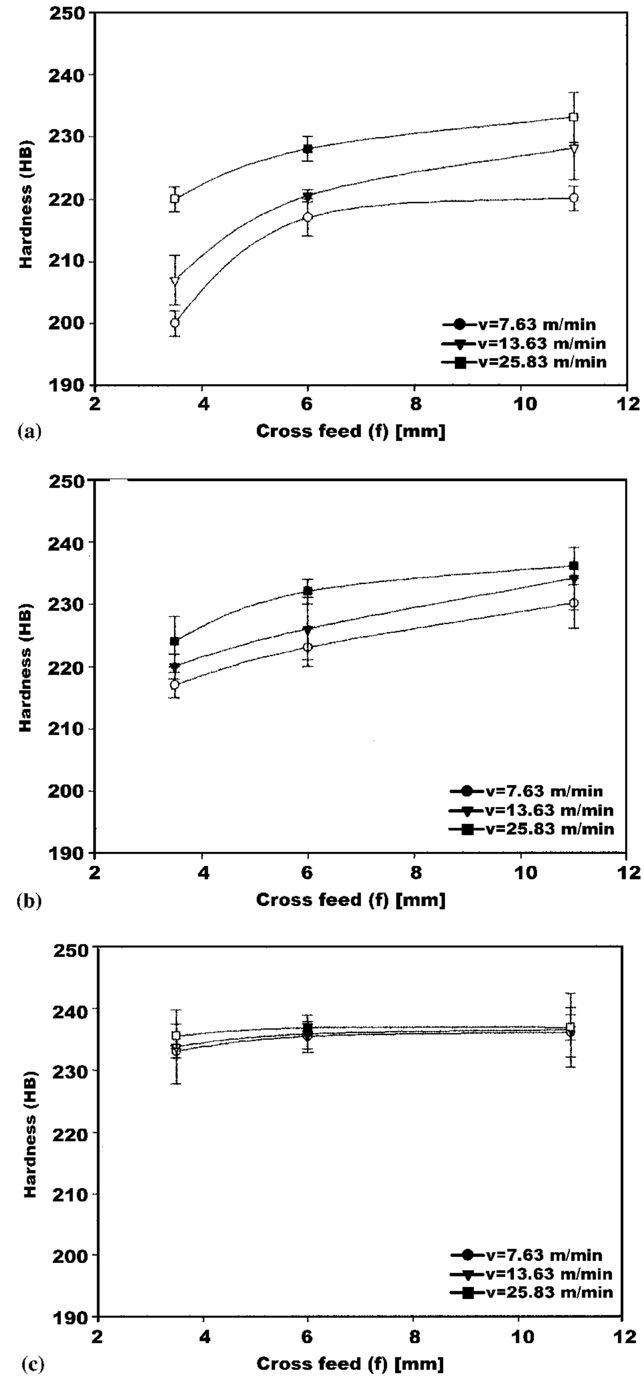

Fig. 5 Graph of average maximum Brinell hardness vs cross feed for the AISI 1045 steel, with an infeed (d) of **(a)** 0.0075 mm, **(b)** 0.0125 mm, and **(c)** 0.0175 mm

search[6,15] where an increase in residual stresses resulted from an increase in the infeed during the grinding of the steel.

The general tendency of the hardness is to reach a value of 238 HB, which corresponds to the maximum hardness obtained in all the specimens. This indicates that there is an infeed limit after which the effects of changes in speed on the piece do not affect the change in superficial hardness, which could be because the force required to continue deforming, and therefore hardening, is no longer produced by the contact between the piece and the active grains.

Comparing the slopes of the curves in Fig. 4 with the other parameters, the infeed has more influence on the superficial hardening caused by the grinding process.

In Fig. 5, which plots the superficial hardness in function of the cross feed of the worktable, the increase in the hardness follows the increase in the values of the cross feed.

Contrary to the previous parameter, which increased with a good linear trend, the increase in hardness in the cross feed occurs in two stages. In the first stage (3.5-6 mm), the increase is marked, and the curve rises more quickly; in the second stage (6-11 mm), the growth is much slower, and in some cases levels out and stabilizes.

The cross feed is the measure of the section or width of the wheel that has been assigned to make the cut. The smaller this is, the weaker the force needed to cut due to the small contact area where the material will be removed.

A higher cross feed implies an increase in the cutting area, and therefore a stronger cutting force, which in turn means an increase in the removal of material and therefore an increase in the plastic deformation and the hardening of the material, which is consistent with previous research.[16]

The trend of the curves is explained by the number of passes that the wheel must make to complete a sweep of the entire surface of the material. The more cutting passes, the more waste caused on the abrasive grains, which lose their capacity to remove material. Therefore, the plastic deformation is greater and the temperature increases, due to the increase in the friction between the piece and the blunt grains, which is shown as a positive slope on the graph. When the number of passes is lower, the grains retain their capacity for chip removal; therefore, a higher cross feed has less influence on the increase in the hardness. It does not produce large plastic deformations or marked temperature increases, which is why the graph tends to stabilize.

Figure 6 shows that the superficial hardness of the material increases with the speed of the workpiece, results that are consistent with previous research.[9,10]

At low speeds, the amount of work done for the same quantity of grains decreases, which decreases the contact pressure between the tool and the piece, and weakens the cutting force and the traction generated by the slip of the grains across the surface. This leads to a less plastic deformation and a decrease in the friction; as a result, slower workpiece speeds increase the superficial hardness of the piece, but not to any great extent.

When the speed of the workpiece is increased, the traction of the grains on the surface tends to increase, which leads to a higher chip removal and an increase in superficial hardness. In conclusion, the workpiece speed is the parameter that has least influence on the superficial hardening caused by the grinding process, which is evident in the less inclined slopes of the curves in comparison with the other parameters.

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 a function of the different cutting parameters.

The expression that best represents the experimental data obtained for the AISI 1045 steel was the following:

$$HB = d^{0.0354}\, e^{(4.38+83.7d+2.62s-1.07v-187*s+76.3d*v)}$$

$$S = 0.01385 \quad R^2 = 93.0\% \quad R^2_{adjust} = 90.5\% \qquad \text{(Eq 1)}$$

This expression was selected because, as can be observed, the values represented by the coefficients R^2 and R^2_{adjust} are higher than 90%, and the standard deviation (S) has a very low value, which indicates that this model is adjusted to the experimental values.[13]

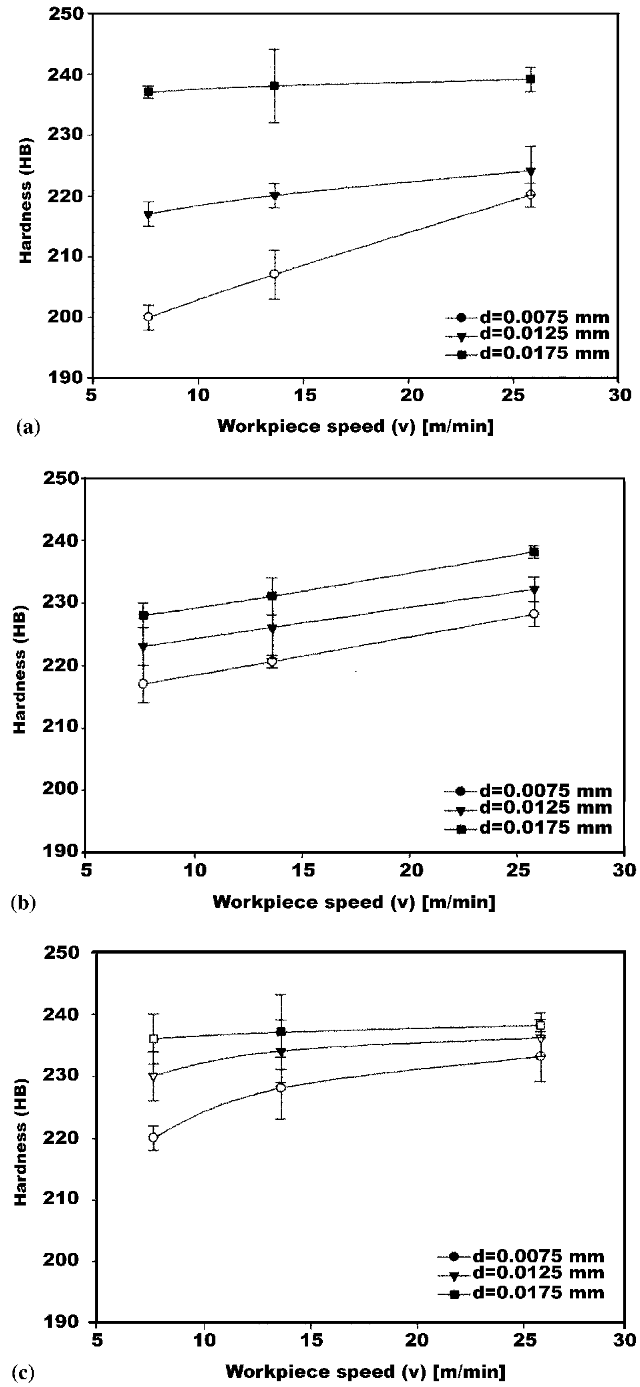

Fig. 6 Graph of average maximum Brinell hardness vs workpiece speed for the AISI 1045 steel, with a cross feed(s) of **(a)** 3.5 mm, **(b)** 6 mm, and **(c)** 11 mm

As Fig. 7 and 8 show, the dependability of the expression is completely proven. The normal probability plotting (Fig. 7) reports a linear trend for the residual values fitting between the limits, and the mean and standard deviation approximate zero and one, respectively, as in the ideal case.[17]

The graph of the residuals versus the fitted values (Fig. 8) has the shape of a symmetrical cloud without defined geometry

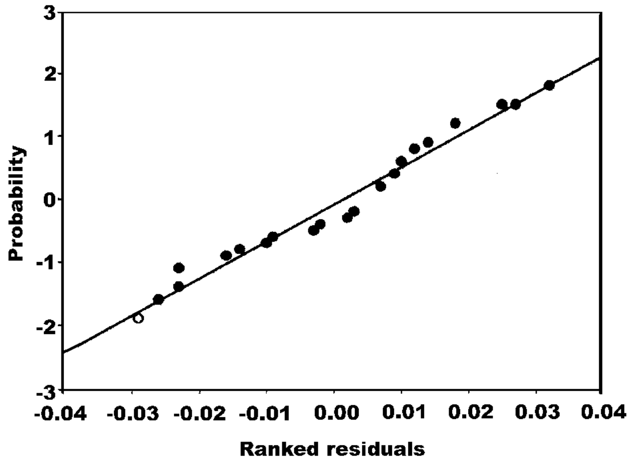

Fig. 7 Normal probability plot for the mathematical expression (Eq 1)

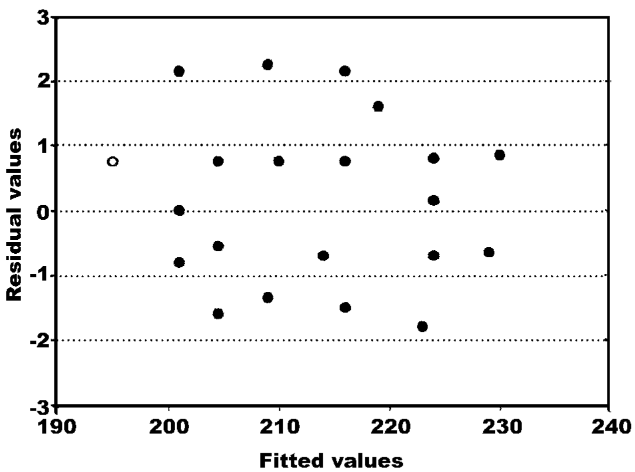

Fig. 8 Residual vs fitted values plotted according to the mathematical expression (Eq 1)

with respect to line zero, which suggests that the model fulfills the hypothesis of normal residuals.[18]

4. Conclusions

In relation to the AISI 1045 steel and the grinding conditions evaluated in this work, the following conclusions were reached.

- The superficial hardening of the material was shown by the plastic deformation caused by the chip outburst rather than by microstructural transformations.
- When the cross feed, workpiece speed, and infeed increase, the superficial hardness also increases.
- At higher infeeds, the workpiece speed did not influence the superficial hardness.
- When comparing the plane grinding parameters, the workpiece speed has less influence on the superficial hardening than the cross feed or the infeed, which had most effect.
- Equation 1 was selected as the mathematical expression that offers the best adjustment to the hardness superficial maxim as function of the cutting parameters.

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