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# Surface hardness prediction based on cutting parameters in turning of annealed AISI 1020 steel

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**Abstract**
The influence of various cutting parameters, cutting speed ($Vc$), feed rate ($f$), and depth of cut ($d$) on the surface hardness developed by turning annealed AISI 1020 steel using carbide insert tools was investigated. It was shown from the measured results that hardness increases with the increase in all the studied parameters. An analysis of variance (ANOVA) was employed to determine the contributions of each parameter on the response variable. From the results, it was found that cutting speed has the most significant role in producing surface hardness (69.2 %) followed by feed rate (24.4 %), while the depth of cut has the lesser effect (6.4%). Finally, a simple equation is proposed, for the prediction of the values of surface hardness, which accounts for the effects of process parameters.

*Keywords*: AISI 1020; ANOVA; cutting speed; depth of cut; feed rate; surface hardness; turning.

# Predicción de la dureza superficial en base a los parámetros de corte en el torneado de acero AISI 1020 recocido

**Resumen**
La influencia de varios parámetros de corte, velocidad de corte ($Vc$), velocidad de avance ($f$), y la profundidad de corte ($d$) en la dureza superficial desarrollada por torneado en acero AISI 1020 recocido utilizando herramientas de insertos de carburo fue investigada. Se demostró a partir de los resultados medidos que la dureza aumenta con el aumento en todos los parámetros. Se empleó un análisis de varianza (ANOVA) para determinar las contribuciones de cada parámetro estudiado en la variable de respuesta. A partir de los resultados, se encontró que la velocidad de corte tiene el rol más importante en la producción de dureza superficial (69.2 %), seguido de la velocidad de avance (24.4 %), mientras que la profundidad de corte tiene el efecto menor (6.4 %). Finalmente, se propone una ecuación simple, para la predicción de los valores de dureza superficial, que representa los efectos de los parámetros del proceso.

*Palabras clave*: AISI 1020; ANOVA; velocidad de corte; profundidad de corte; velocidad de avance; dureza superficial; torneado.

## 1. Introduction

Turning is a process whereby a single cutting edge is used to remove small chips of material from a rotating workpiece to create a cylindrical shape. After the process, the surface layers are deformed and hardened. The hardness of a material is the property that enables it to resist permanent plastic deformation, which is usually measured by indentation. For designers, this is important in analyzing corrosion resistance, and fatigue crack initiation on components during their applications. Therefore, attention must be paid to when selecting cutting parameters.

Several studies have demonstrated that a lower cutting speed increases the values of surface hardness on turning of AISI 304 - stainless steel [1], 12-Mn austenitic steel [2] and duplex stainless steel [3]. However, a deviation from this conclusion was reported for titanium based alloy Ti-64 [4], as less hardness resulted when decreasing the cutting speed. Additionally, on AISI 316 austenitic stainless steel [5] it was confirmed that this parameter has no significant effect on hardness.

The influence of feed rate on surface hardness in turning has also been investigated. For example, many authors agree that this cutting parameter has negligible influence on the

hardness of AISI 316 austenitic stainless steel [5], AISI 4340 steel [6], AISI 1045 steel [7] and 34CrNiMo6 alloy steel [8]. While other studies suggest that higher feed rates have an impact on increasing the surface hardness on turning of AISI 304 - stainless steel [1], titanium based alloy Ti-64 [4] and nickel-based alloy IN-718 [9]. Meanwhile, the result from a study conducted on 12-Mn austenitic steel [2] has shown that hardness increases as feed rates are lower.

In literature, some efforts have been made to analyze how the depth of cut affects the surface hardness. In most cases, it was found that higher values of hardness are obtained by increasing this cutting parameter on turning of AISI 304 stainless steel [1], AISI 316 stainless steel [5] and nickel based alloy INCONEL 718 [9].

Despite this research, few works have assessed the impact of individual cutting parameters on surface hardness, to determine which may have more, and which may have less. The depth of cut was found to have more influence on hardness after turning AISI 316 austenitic stainless steel [5], while on the other hand, cutting speed has a significant influence on titanium based alloy Ti-64 [4].

The prevailing literature indicates that the effect of cutting parameters on surface hardness is still not well understood. Therefore, this study is concerned with the relation of turning cutting parameters, cutting speed ($Vc$), feed rate ($f$), and depth of cut ($d$) as input variables on the surface hardness of annealed AISI 1020 steel, and the development of a simple mathematical expression for the prediction of its value.

## 2. Experimental procedure

The workpiece material for this work consisted in cylinders of 31.75 mm in diameter and 170 mm in length, cut from a round bar of commercial AISI 1020 steel (0.18 ± 0.01% C, 0.035 ± 0.001% S, and 0.40 ± 0.01% Mn). To achieve a homogenized microstructure, the samples were annealed at 910 °C for 1 h, followed by slow cooling inside the furnace.

The specimens were machined 15 mm in length from the edge by turning in a numerically controlled lathe; all performed with an abundant supply of water-soluble oil as coolant and using ISO code - DCMT11T308MU grade TN2000 coated carbide inserts. For each experiment, a new insert's edge was used, which not only ensures same cutting conditions, but also avoids the presence of changes in the properties near the surface of the material due to the tool wear [10].

Three factors were considered for evaluation and arranged by using a technique of variables [11], with three levels of feed rate, three levels of depth of cut, and two levels of cutting speed for 18 combinations in total. The limit values shown in Table 1, were restricted by the lathe, and were selected based on previous experience with AISI 1020 steel [12].

After turning, the samples were cut perpendicular to the axis direction of the bar, within the machined length. The cross-sectional areas were then prepared according to ASTM E3-11 standard metallographic techniques [13].

Table 1.
Input parameters and their levels.

| Level | d (mm) | f (mm/rev) | Vc (m/min) |
|---|---|---|---|
| 1 | 1 | 0.05 | 20 |
| 2 | 2 | 0.15 | - |
| 3 | 3 | 0.25 | 70 |

Source: The authors

The Vickers microhardness profile was measured for each sample on the cross-section starting from the edge along the radius to the center, with 70 µm spacing. For each distance, five indentations at randomly chosen locations were made, discarding the extreme values. Finally, three measurements were used to calculate the average value of hardness. A Buehler Vickers tester was used and tests were carried out at a load of 200 gf for 15 s according to ASTM E384-11 standard [14].

The results obtained from the average maximum hardness were treated using statistical parametric analyses of variance approach (ANOVA) with Minitab. In the analysis, the microhardness (HV) represented the dependent variable, while the depth of cut ($d$), feed rate ($f$) and cutting speed ($Vc$) were the independent variables. This analysis was carried out for a confidence level of 95%. The significance level was based on the P-value [15] as:

Insignificant if $P > 0.10$
Mildly significant if $0.05 < P < 0.10$
Significant if $P < 0.05$

Then, a Pareto-Anova analysis was performed to determine the relative importance of each parameter and their percentage contribution.

Finally, using multiple linear regression methods [15], a statistical mathematical model was derived for the prediction of the maximum surface hardness.

## 3. Results and discussion

The graph on Fig. 1 shows the microhardness profiles measured along the radii for tests with low and high-level limits on each evaluated parameter. This tendency was the same for the other combination of conditions.
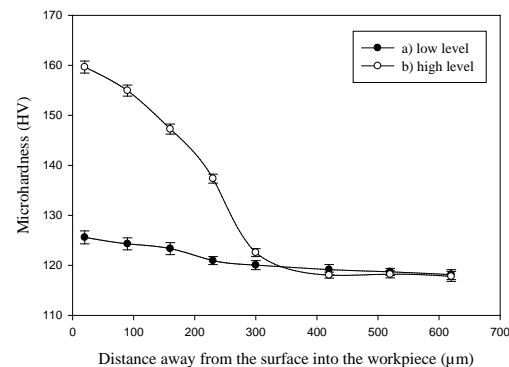


Figure 1. Microhardness profiles through depth after turning, a) low level (v = 20 m/min, f= 0.05 mm/rev, d = 1 mm), and b) high level (v = 70 m/min, f= 0.25 mm/rev, d = 3 mm).
Source: The authors

Table 2.
Experimental runs with measured surface average hardness

| Trail No. | Vc (m/min) | F (mm/rev) | d (mm) | HV |
|-----------|------------|------------|--------|-------|
| 1 | 20 | 0.05 | 1 | 125.6 |
| 2 | 20 | 0.05 | 2 | 126.8 |
| 3 | 20 | 0.05 | 3 | 132.5 |
| 4 | 20 | 0.10 | 1 | 128.0 |
| 5 | 20 | 0.10 | 2 | 130.0 |
| 6 | 20 | 0.10 | 3 | 136.0 |
| 7 | 20 | 0.15 | 1 | 135.1 |
| 8 | 20 | 0.15 | 2 | 141.3 |
| 9 | 20 | 0.15 | 3 | 146.0 |
| 10 | 70 | 0.05 | 1 | 142.0 |
| 11 | 70 | 0.05 | 2 | 144.0 |
| 12 | 70 | 0.05 | 3 | 147.0 |
| 13 | 70 | 0.10 | 1 | 149.0 |
| 14 | 70 | 0.10 | 2 | 150.0 |
| 15 | 70 | 0.10 | 3 | 153.0 |
| 16 | 70 | 0.15 | 1 | 156.0 |
| 17 | 70 | 0.15 | 2 | 158.0 |
| 18 | 70 | 0.15 | 3 | 159.0 |

Source: The authors

As expected, the curves describe a cascade shape, with higher values of hardness on the surface of the samples. Then as the depth below the surface reaches the bulk material, the hardness decreases to a value that becomes steady-state. This is due to the severe plastic deformation at the surface, and residual stresses introduced in the material after the tearing by the tool during the cutting process.

Table 2 shows 18 set of cutting parameters listed as per orthogonal array with corresponding surface average hardness values.

Influence of feed rate on the average maximum values of microhardness is shown in Fig. 2. The maximum hardness was studied since it is more significant and is the value exposed to the higher loading conditions on a component in service.

It can be observed that in every test, microhardness increased with the increase in feed rate. This is consistent with the findings of previous researchers [1,4,9]. The reason might be that as feed increases, cutting force also increases, as higher resistance is exerted the tool propagation [16]. The results obtained showed a minimum and maximum difference in hardness for fixed cutting speed and depth of cut, of 7% and 11% respectively.

An analysis of Fig. 3 indicates that an increase in depth of cut causes greater average maximum values of hardness. These results are consistent with previous experiments [1,5,9]. This trend suggests that an augmentation in the value of the depth of cut leads to an increase of the cutting forces, resulting in a more severely work-hardened surface layer [16]. A very small increment in the hardness with the depth of cut is indicated by the slopes of the curves, resulting in differences values of 2% and 8%, corresponding to fixed cutting speed and feed rate.

From Fig. 4 it can be observed that as cutting speed increases, the average maximum values of hardness also increase. This is consistent with previous works [4]. This fact is related to the increase in the cutting energy in the surface region, which is sufficient to increase the surface stresses,

leading to hardening as a result of the introduced deformation [17]. The experimental results show that measured hardness differences corresponding to a fixed feed rate and depth of cut have values between 9% and 17%.
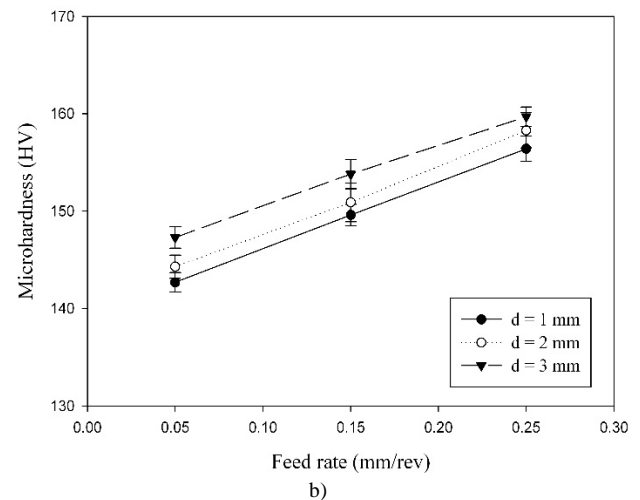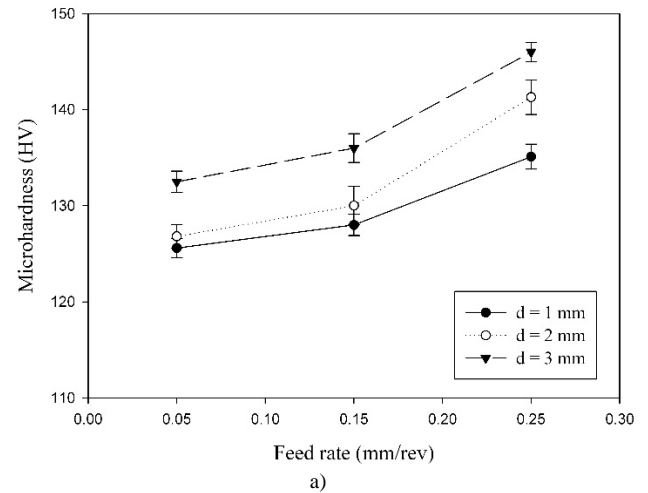


a)



b)

Figure 2 Microhardness plotted against feed rate for the turned annealed AISI 1020 steel, with a cutting speed of (a) 20 m/min; and (b) 70 m/min
Source: The authors

A statistical analysis of experimental data using the analysis of variance (ANOVA) for maximum values of microhardness was calculated and is presented in Table 3. The results obtained show significant ($P<0.05$) effects for the depth of cut ($d$), feed rate ($f$) and cutting speed ($Vc$) on the hardness values. Additionally, F-test decides whether the parameters are significantly different. A larger F-value shows the greater impact on the machining performance characteristics [18]. Larger F-values are observed for speed as 477.59.
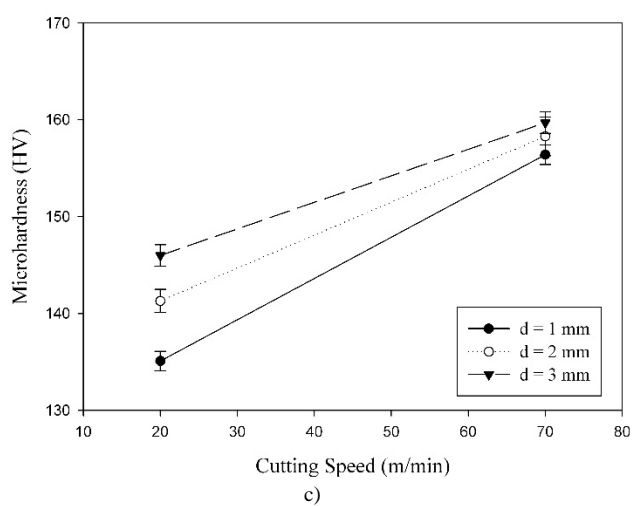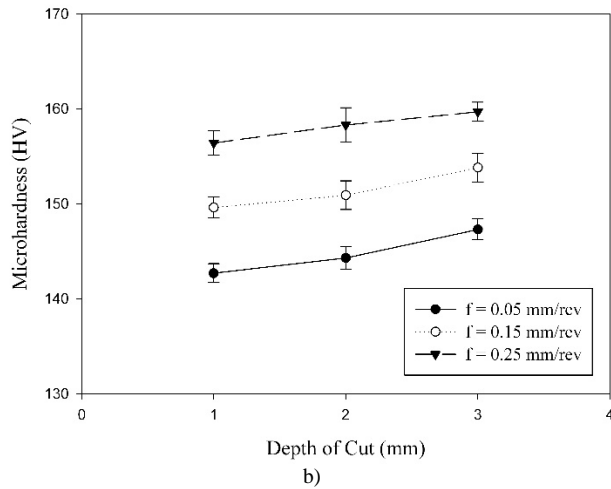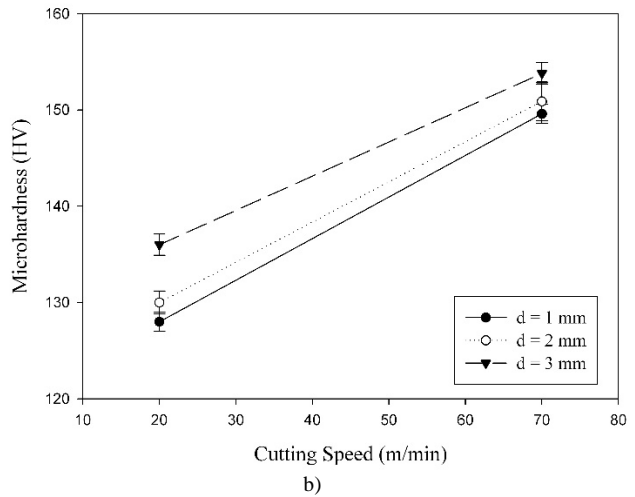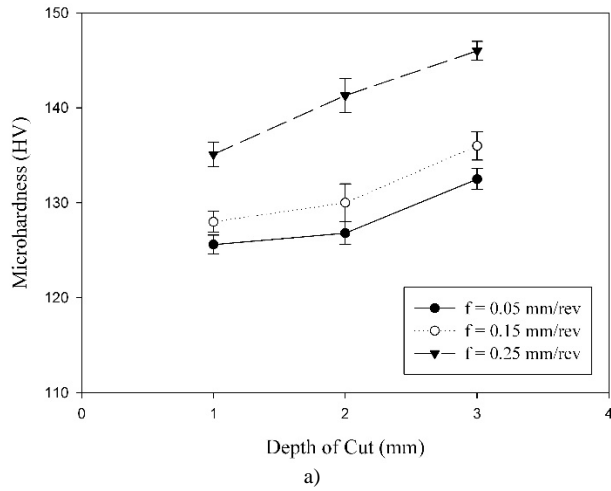
a)



b)



b)

Figure 3 Microhardness plotted against depth of cut for turned annealed AISI 1020 steel, with a cutting speed of (a) 20 m/min; and (b) 70 m/min
Source: The authors



c)

Figure 4 Microhardness plotted against cutting speed for the turned annealed AISI 1020 steel, with a feed rate of (a) 0.05 mm/rev; (b) 0.15 mm/rev; and (c) 0.25 mm/rev
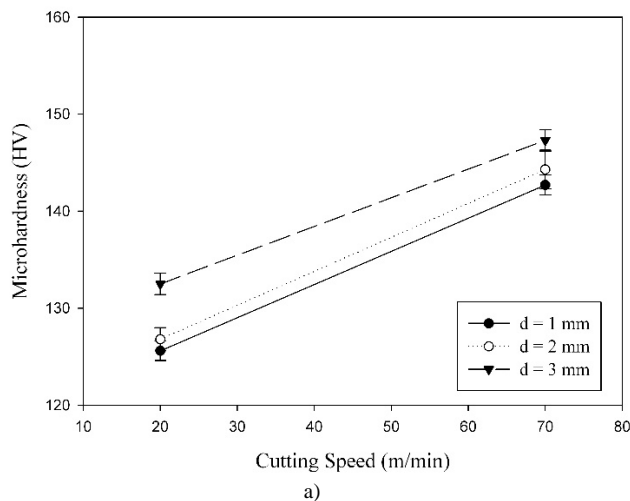Source: The authors



a)

Table 3.
ANOVA for surface microhardness.

| Source of variance | Degrees of freedom | Sum of squares | Mean squares | F - value | P - value |
|---|---|---|---|---|---|
| Vc | 1 | 1424.00 | 1424.00 | 477.59 | 0.00 |
| f | 2 | 501.53 | 250.77 | 84.10 | 0.00 |
| d | 2 | 131.74 | 65.87 | 22.09 | 0.00 |
| Error | 12 | 35.78 | 2.98 | | |
| Total | 17 | 2093.06 | | | |

Source: The authors

As far as the influence of individual effects of these factors, as well as their interactions, is concerned, results can be discussed from the Pareto-Anova results shown in Table 4. The numerical estimates indicate that the contribution of the speed of cut is the largest (69.2%), and the interaction of the depth of cut is less significant (6.4%).

Table 4.
Pareto-Anova analysis of standardized effects for surface microhardness

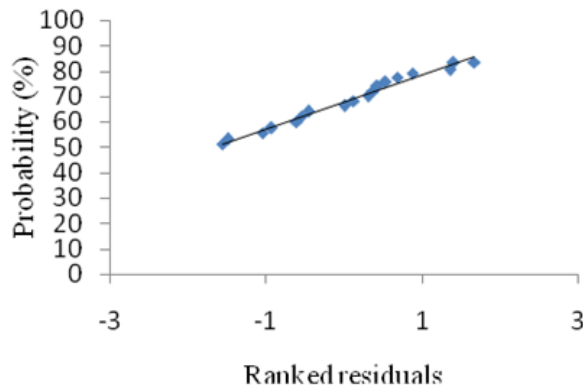| Contributions | Vc | f | d |
|---|---|---|---|
| Simple (%) | 69.2 | 24.4 | 6.4 |
| Cumulative (%) | 69.2 | 93.6 | 100 |

Source: The authors



Figure 5. Probability plot for the mathematical expression (Eq. 1)
Source: The authors

Using the significant regression coefficients, the final model for the prediction of the maximum surface microhardness could be constructed as given in eq. (1):

$$HV = 110.1214 + 0.3610*Vc + 63.5892*f + 3.2589*d \quad (1)$$

$R^2 = 0.9755$
$R^2_{ajust} = 0.9702$
$S = 0.0136$

The $R^2$ and $R^2_{adj}$ values above 95%, indicate that the obtained model fit is on the higher side of the acceptable limit. Finally, the low value for the standard deviation (S), indicates that this expression is adjusted to the experimental values [19].

The plot in Fig. 5 reveals that the residuals follow a straight line and so the errors appear to show that the dependability of the expression is completely proven [15].

## 4. Conclusions

Based on the results obtained by this investigation, the following conclusions may be drawn which are valid for the range investigated.

- The surface microhardness increases when the cutting parameters, depth of cut (*d*), feed rate (*f*) and cutting speed (*Vc*) increase.
- The speed of cut plays an important role and contributes 69.2% on surface hardness to the overall turning parameters. The depth of cut was found to be the least contribution cutting parameter (6.4%).
- The proposed mathematical model can be used to adequately predict the maximum surface microhardness

within the specified limits of the process parameters.

## References

[1] Senussi, G.H., Interaction effect of feed rate and cutting speed in CNC - turning on chip micro - hardness of 304 - austenitic stainless steel. World Academy of Science, Engineering and Technology, [online]. 28, pp. 121-126, 2007. Available at: http://waset.org/publications/4706

[2] Cebron, M., Kosel, F. and Kopac, J., Effect of cutting on surface hardness and residual stresses for 12-Mn austenitic steel, Journal of Achievements in Materials and Manufacturing Engineering, [online]. 55(1), pp. 80-89, 2012. Available at: http://jamme.acmsse.h2.pl/papers_vol55_1/55111.pdf

[3] Krolczyk, G., Nieslony, P. and Legutko, S., Microhardness and surface integrity in turning process of duplex stainless steel (DSS) for different cutting conditions, Journal of Materials Engineering and Performance, 23(3), pp. 859-866, 2014. DOI: 10.1007/s11665-013-0832-4

[4] Che-Haron, C.H. and Jawaid, A., The effect of machining on surface integrity of titanium alloy Ti–6% Al–4% V, Journal of Materials Processing Technology, 166(2), pp. 188-192, 2005. DOI: 10.1016/j.jmatprotec.2004.08.012

[5] Patil, P.M., Kadi, R.V., Dundur, S.T. and Pol, A.S., Effect of cutting parameters on surface quality of AISI 316 austenitic stainless steel in CNC turning, International Research Journal of Engineering and Technology, [online]. 02(04), pp. 1453-1460, 2015. Available at: https://www.irjet.net/volume-2-issue-4

[6] Sadat, A.B., Effect of high cutting speed on surface integrity of AISI, 4340 steel during turning, Materials Science and Technology, 6(4), pp. 371–375, 1990. DOI: 10.1179/026708390790190955

[7] Sasahara, H., The effect on fatigue life of residual stress and surface hardness resulting from different cutting conditions of 0.45%C steel, International Journal of Machine Tools and Manufacture, 45(2), pp. 131-136, 2005. DOI: 10.1016/j.ijmachtools.2004.08.002

[8] Javidi, A., Rieger, U. and Eichlseder, W., The effect of machining on the surface integrity and fatigue life, International Journal of Fatigue, 30(10-11), pp. 2050-2055, 2008. DOI: 10.1016/j.ijfatigue.2008.01.005

[9] Pawade, R.S., Joshi, S.S. and Brahmankar, P.K., Effect of machining parameters and cutting edge geometry on surface integrity of high-speed turned Inconel 718, International Journal of Machine Tools and Manufacture, 48(1), pp. 15-28, 2008. DOI: 10.1016/j.ijmachtools.2007.08.004

[10] Sharman, A.R.C., Hughes, J.I. and Ridgway, K., An analysis of the residual stresses generated in Inconel 718TM when turning, Journal of Materials Processing Technology, 173, pp. 359-367, 2006. DOI:10.1016/j.jmatprotec.2005.12.007

[11] Montgomery, D.C., Design and analysis of experiments, USA, Wiley, 2012.

[12] Suhail, A.H., Ismail, N., Wong, S.V. and Abdul-Jalil, N.A., Optimization of cutting parameters based on surface roughness and assistance of workpiece surface temperature in turning process, American Journal of Engineering and Applied Sciences, 3(1), pp. 102-108, 2010. DOI: 10.3844/ajeassp.2010.102.108

[13] ASTM E3-11, Standard guide for preparation of metallographic specimens, ASTM International, West Conshohocken, PA, 2011, DOI: 10.1520/E0003-11

[14] ASTM E384-11, Standard test method for knoop and vickers hardness of materials, ASTM International, West Conshohocken, PA, 2011, DOI: 10.1520/E0384-11

[15] Montgomery, D.C., Peck, E.A. and Vining, G.G., Introduction to linear regression analysis, USA, Wiley, 2012.

[16] Deepakkumar, P. and Sadaiah, M., Investigations on finish turning of AISI 4340 steel in different cutting environments by CBN insert, International Journal of Engineering Science and Technology, [online]. 3(10), pp. 7690-7706, 2011. Available at: http://www.ijest.info/docs/IJEST11-03-10-114.pdf

[17] Gunnberg, F., Escursell, M. and Jacobson, M., The influence of cutting parameters on residual stresses and surface topography during hard turning of 18MnCr5 case carburised steel, Journal of Materials

Processing Technology, 174, pp. 82-90, 2006. DOI:10.1016/j.jmatprotec.2005.02.262

[18] Ross, P.J., Taguchi techniques for quality engineering, USA, McGraw-Hill Book Company, 1996.

[19] Peña, D., Estadística; modelos y métodos (Statistics; models and methods), Spain, Alianza Editorial S.A., 2001. (in Spanish).

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