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Influence of turning cutting parameters on surface deformation of annealed AISI-1020 steel

Influencia de los parámetros de corte del torneado en deformación superficial del acero AISI-1020 recocido

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KEYWORDS
AISI-1020; feed rate, depth of cut; cutting speed, plastic deformation
AISI-1020; velocidad de avance; profundidad de corte; velocidad de corte; deformación plástica

ABSTRACT: This paper presents a study on the influence of the cutting parameters (depth of cut, feed rate, and cutting speed) of turning with a carbide insert on the plastic deformation induced in annealed AISI-1020 steel. The results showed an increase in the deformation with each cutting parameter, due to the higher forces associated with the machining process and the cutting area. This causes an increase in the energy required for material cutting and, consequently, more cold work on the machined surface. The ANOVA analysis of the results showed that the feed rate had the most significant role in the resulting deformation (86.03%), and the cutting speed contributed less (6.81%). In addition, a mathematical expression for the prediction of deformation based on the evaluated parameters is proposed.

RESUMEN: En este trabajo se presenta el estudio de la influencia de los parámetros de corte (profundidad de corte, velocidad de avance y velocidad de corte) del torneado con inserto de carburo sobre la deformación plástica inducida en el acero AISI-1020 recocido. Los resultados mostraron un aumento en la deformación con cada parámetro de corte debido al incremento tanto de las fuerzas asociadas al proceso de mecanizado como del área de corte, lo cual genera un aumento en la energía requerida para el corte del material, y, en consecuencia, mayor trabajo en frio sobre la superficie maquinada. El análisis ANOVA de los resultados mostró que la velocidad de avance tiene mayor influencia sobre la deformación resultante (86.03%) y la velocidad de corte tuvo una contribución menor (6,81%). Además, se propone una expresión matemática para la predicción de la deformación a partir de los parámetros evaluados.

1. Introduction

To obtain the required geometry, dimensions, tolerances, and surface roughness, mechanical components often need to be machined to achieve their proper function. The quality of the surface after these cutting processes significantly influences the operational characteristics of the parts such as wear, resistance to corrosion, fatigue, among others.

In the turning process, parameters such as cutting speed, feed rate, depth, and tooltip radius are used, which are accompanied by mechanical and thermal effects capable of producing alterations in the surface integrity of the part. The latter represents the relationship that exists between geometric properties such as surface roughness, and physical properties such as microstructural changes, localized plastic deformation, changes in hardness, and residual stress distribution, among others [1].

In most of the investigations, the characterization of the surface integrity after machining has focused on the measurement of the induced plastic deformation for the estimation of residual stresses through X-ray diffraction [2 - 4]. This technique is based on Bragg's law [5] for the determination of the changes in the interplanar distance of a material when it is deformed [6]. This method has the advantage of being a non-destructive test, limited to the possibility of making measurements at depths relative to the wavelength used. Therefore, the removal of atomic layers and subsequent evaluation of each exposed surface is required for greater depths. The results, thus measured, do not correspond to those existing before the removal of the layers, due to the relaxation of the surface. Therefore, these must be corrected by means of various formulas [7].

Other authors have evaluated the residual stresses generated by deformation using the magnetoelastic method [8 - 10]. Based on the Barkhausen effect, it detects changes in micromagnetic domains as a ferromagnetic material is magnetized and demagnetized [11]. This technique has the advantage of being able to be applied quickly in-situ; however, only superficial residual stresses can be detected in ferromagnetic materials, and it is highly sensitive to the microstructure, grain size, and composition of the part. Additionally, the magnetic properties of the material, such as permeability, affect the depth of measurement.

Both methodologies have the disadvantage of losing precision with the increase in cold work and surface hardening of the evaluated material, as well as high cost and difficulties in using the equipment. Therefore, it is proposed to use an economical, simple and fast technique, such as the torsion test, to evaluate and quantify the influence of cutting parameters on the surface plastic deformation generated in the turning process.

2. Literature review

From previous works published by the authors of the present study, it was shown that higher hardness values are generated on the surface of turned samples [12] and that, during the torsion process, higher hardness values are obtained on the surface of the samples [13]. Both increases are attributed to the severe localized plastic deformation in this zone during the shearing process of the material and that shear strains increase with distance from the center of the sample during torsion. Therefore, it can be considered that all the induced plastic deformation occurs on the surface, affecting the torsional strength of the specimens.

To relate the shear yield strength (τ_y) with the tension yield strength (S_y), Equation 1 establishes the relationship using the Tresca yield criterion [14].

$$S_y \cong 2\,\tau_y \qquad (1)$$

The tensile yield strength when the material is cold-worked can be calculated with Hollomon's equation for the material in the annealed state (Equation 2) [15]:

$$S_{yw} = \sigma_o(\varepsilon_w + 0.002)^m \qquad (2)$$

where S_{yw} is the yield strength of the cold-worked material and ε_w is the cold-work strain. The values of the Hollomon coefficients ($\sigma_o y m$), were previously obtained by the authors of the present research [16], leaving Equation 3.

$$S_{yw} = 1012(\varepsilon_w + 0.002)^{0.26} \qquad (3)$$

Finally, with the tension yield strength calculated with Equation 1 for each of the shear yield strength obtained in the torsion tests, it is possible to solve and calculate with Equation 3 the cold work deformation generated by the turning process.

3. Experimental procedure

In all tests, the work material was obtained from AISI-1020 steel bars (0.18 ± 0.01% C, 0.035 ± 0.001% S, and 0.40 ± 0.01% Mn) with a diameter of 31.75 mm and 6 m length, from which 170 mm long cylinders were cut. These were then subjected to annealing heat treatment by heating for 1 hour at 910ºC and slowly cooling inside the furnace.

From the previously annealed AISI-1020 steel samples, all the specimens for torsion tests were manufactured automatically on a numerically controlled (CNC) lathe according to the geometry shown in Figure 1. During the entire cutting process, copious amounts of water-soluble oil were applied as a coolant to avoid microstructural changes [17, 18].

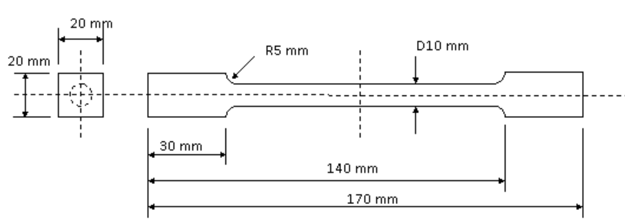


Figure 1 Torsion specimen's dimensions

To manufacture the specimens, coated carbide inserts, code ISO-1832 [19] DCMT11T308MU grade TN 2000, with a tip radius of 0.8 mm were used. A new cutting edge of the insert was used for each specimen, thus guaranteeing the same cutting conditions and the absence of changes in the surface properties of the material due to tool wear [20, 21].

In determining the cutting parameters, three factors were considered for evaluation, and the experiments were designed using the factorial method of variables [22], with three levels of depth of cut (*d*), three levels of feed rate (*f*), and two levels of cutting speed (*Vc*), for 18 combinations in total, with three repetitions each. The limit values shown in Table 1 were selected based on previous investigations with similar steels [23, 24] and lathe constraints.

Table 1 Parameters used in the turning of the samples

***d*, mm**	***f*, mm/rev**	**V_c, m/min**
1	0.05	20
2	0.15	-
3	0.25	70

The torsion tests were carried out in a free-end torsion machine, at a constant strain rate of 2.3×10^{-2} s^{-1} and a rotation speed of 8.6 rpm, according to the ASTM A938-07 standard [25], until reaching the fracture of the specimen. During the entire test, the torque values and the torsion angle of the samples were obtained directly from the equipment. For each combination of cutting parameters, from the torque values, the average shear resistance and the plastic deformation due to cold work were calculated.

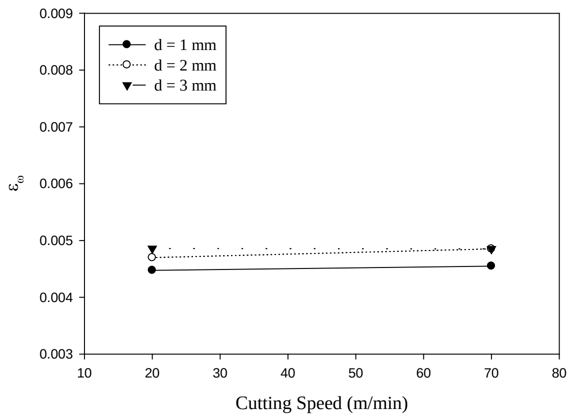
The results obtained from the various tests were treated by statistical analysis of data variance (ANOVA) with Minitab. In the analysis, the effect of the cutting parameters on the plastic deformation induced by the machining process was determined. This analysis was performed with a confidence level of 95%. The level of significance was based on the P-value [26] as follows:

Not significant if $P > 0.10$
Slightly 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 its percentage contribution.

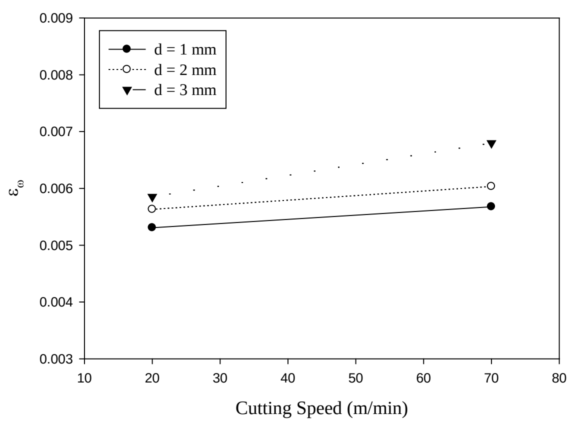
Finally, using multiple linear regression methods [26], a statistical mathematical model was derived for the prediction of the dependent variable evaluated.

4. Results and discussion

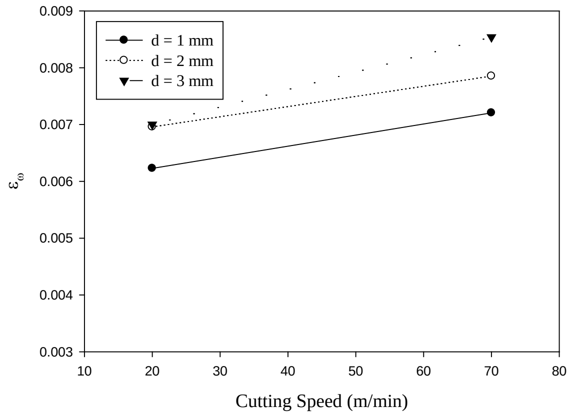
Figure 2 shows how the deformation induced by the turning process increases with the cutting speed. This behavior is consistent with what was previously reported by other investigators [27]. From the results, a minimum and the maximum difference in deformation for fixed feed rate and depth of cut of 2% and 22%, respectively, is obtained.



(a)



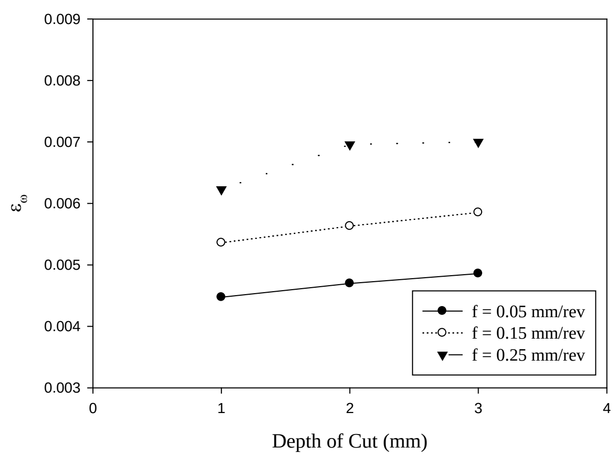
(b)



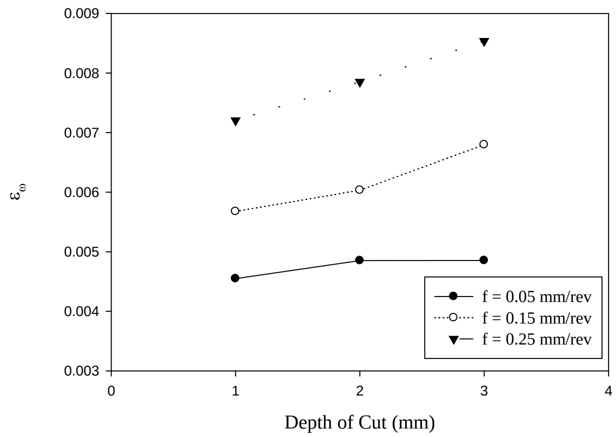
(c)

Figure 2 Strain 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

From Figure 3, it can be seen how the deformation induced by metal cutting increases with the depth of cut for all the conditions evaluated. These results are consistent with those reported by other investigators [28-30]. The experiments show that the deformations for fixed feed rate and cutting speed present a difference in values between 7% and 19%.



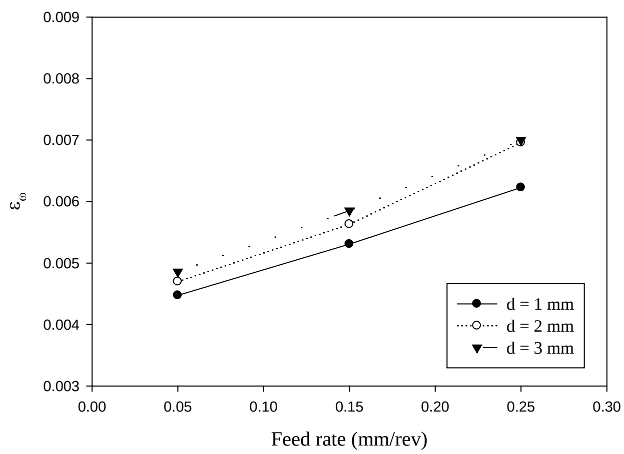
(a)



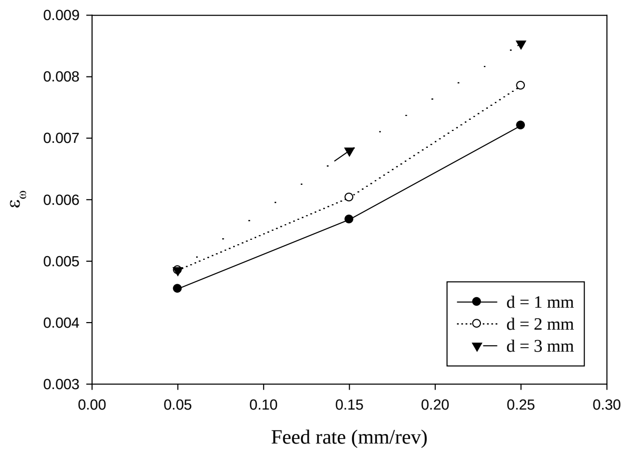
(b)

Figure 3 Strain 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

The effect of feed rate on induced strain is shown in Figure 4, with higher strain values being obtained with increasing feed. This is consistent with what was reported in previous experiments [27, 28, 30]. The significant increase in strain with feed rate is evidenced by the greater slope of the curves, resulting in differences in values of 39% and 76%, for fixed depth of cut and cutting speed.



(a)



(b)

Figure 4 Strain 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

During the turning process, three force components act on the cutting tool [31]. The first in the direction of the feed, the second in the direction of the radial feed of the tool, and the third in the direction of the cutting speed. Therefore, with the results of this work, it was corroborated that any increase in the cutting parameters would result in an increase in the energy required to cut the material, and consequently, greater deformation on the machined surface.

Additionally, the cutting force is influenced by the cutting area, which is proportional to multiplying the feed rate with the depth of cut [32]. Therefore, with this research it was also shown that by increasing either of these two parameters, a surface layer with greater cold work by deformation will be generated.

Table 2 presents the results of the analysis of variance (ANOVA). The significant effect of the cutting parameters on the deformation induced by turning is observed, since the F-values are high (the highest being for the feed rate, 86.93) [33], and in turn, the p-values value are less than 0.05 [26].

Table 2 ANOVA for strain

Source of variance	Degrees of freedom	Sum of squares	Mean squares	F - value	*P*-value
V_c	1	0.0000016	0.0000016	13.76	0.003
f	2	0.0000201	0.00001	86.93	0
d	2	0.0000017	0.0000008	7.24	0.009
Error	12	0.0000014	0.0000001		
Total	**27**				

The estimated individual contribution of each cutting parameter to the induced deformation is shown in Table 3, with the greatest effect attributed to the feed rate (86.03%), followed by the depth of cut (7.16%), and finally the cutting speed (6.81%).

Table 3 Standardized effects for strain

Contribution	*f*	*d*	V_c
Simple (%)	86.03	7.16	6.81
Cumulative (%)	86.03	93.19	100

After performing various mathematical adjustments, it was obtained that the best expression to predict the value of the induced deformation based on the turning cutting parameters of the AISI-1020 annealed steel was Equation 4:

$$\varepsilon_w = 0.0027 + 1.1885 * 10^{-5} Vc + 0.0129f + 0.0004d \qquad (4)$$

S = 0.0003 R^2 = 0.9410 R^2 adjust = 0.9283

The low value of S obtained indicates that the adjustment fits the experimental results, and the high values of R^2 and R^2 adjust show a good correlation between the observed and predicted values by the regression model [26].

Finally, Figure 5 shows the normal probability graph, in which the linear trend is observed, thus demonstrating the dependability of the formulated mathematical expression [26].

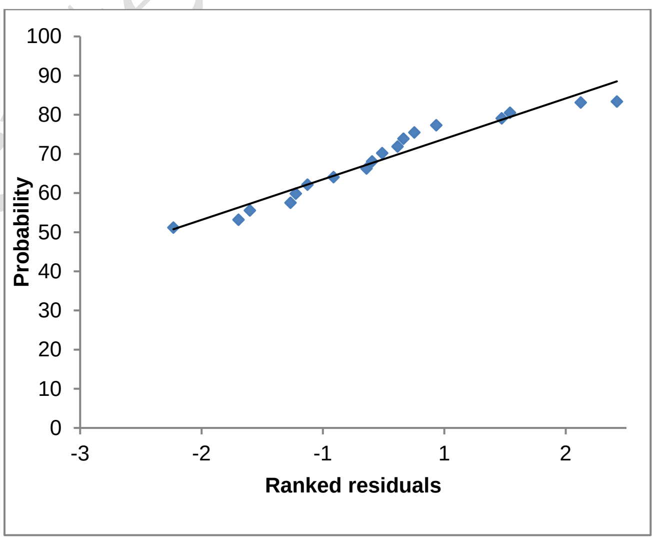


Figure 5 Normal probability plot for the mathematical expression (Equation 4)

5. Conclusions

Based on the results of this work for the conditions evaluated, the following conclusions can be established:

- The shear yield strength obtained by torsion testing allows to calculate, in a relatively simple way, the plastic deformation induced by cold work on the surface of a material after the turning process.

- Plastic deformation induced by turning increases directly with depth of cut (*d*), feed rate (*f*), and cutting speed (*Vc*).

- The feed rate (86.03%) has the greatest individual contribution to the deformation induced by turning, followed by the depth of cut (7.16%) and the cutting speed (6.81%).

- Equation 4 represents the best mathematical expression for the prediction of the induced deformation as a function of the turning cutting parameters.

Declaration of competing interest

We declare that we have no significant competing interests including financial or non-financial, professional, or personal interests interfering with the full and objective presentation of the work described in this manuscript.

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Author contributions

Omar Zurita: Conceived and designed the study, performed the analysis, and wrote the paper. Verónica Carmen Di Graci: Collected the data and performed the analysis. María Capace: Collected the data, performed the statistical analysis, and wrote the paper.

Data availability statement

Data were collected at Universidad Simon Bolivar, using a free-end torsion machine, at a constant strain rate of 2.3×10^{-2} s^{-1} and a rotation speed of 8.6 rpm.

References

[1] J. P. Davim, Surface Integrity in Machining, 1st ed., London, England: Springer-Verlag, 2010.

[2] M. Jacobson, P. Dahlman and F. Gunnberg, "Cutting Speed Influence on Surface Integrity of Hard Turned Bainite Steel", J. Mater. Process. Technol., vol.128, pp. 318-323, 2002.

[3] S. Caruso, D. Umbrello, J.C. Outeiro, L. Filice and F. Micari, "An Experimental Investigation of Residual Stresses in Hard Machining of AISI 52100 Steel", Procedia Eng., vol.19, pp. 67-72, 2011.

[4] V. García, O. Gonzalo and I. Bengoetxea, "Effect of Cutting Parameters in the Surface Residual Stresses Generated by Turning in AISI 4340 Steel", Int. J. Mach. Tools Manuf., vol.61, pp. 48-57, 2012.

[5] M. Fitzpatrick, A. Thomas, P. Holdway, F. Kandil, J. Shackleton and L Suominen, Determination of Residual Stresses by X-Ray Diffraction, NPL, Teddington, UK, 2005.

[6] P. Withers and H. Bhadeshia, "Residual stress. Part 1 – Measurement techniques", Mater. Sci. Technol., vol. 17, no.4, pp. 355-365, 2013.

[7] Z. Kang, J. Li and Z. Wang, "Stress Correction for Removal of Material in X-Ray Stress Determination", J. Test. Eval., vol. 22, pp. 217-221, 1994.

[8] D. Stewart, K. Stevens and A. Kaiser, "Magnetic Barkhausen Noise Analysis of Stress in Steel", Curr. Appl. Phys., vol. 4, no. 2–4, pp. 308-311, 2004.

[9] V. Herrera, C. Cruz, J. Sierra, D. Gutierrez and G. Carro, "Use of X Ray Diffraction and Magnetoelastic Effect for Assessment of Microstructural Parameters and Residual Stresses in Plastically Deformed Steel Bars", Proceedings of the XIII Workshop on Nuclear Physics and VII International Symposium on Nuclear and Related Techniques, Cuba, 2011.

[10] P. Limon, E. Aguilera, H. Plascencia, E. Ledesma, A. Balvantín and J. de la Peña, "Analysis of Residual Stresses in the Roll Hemming Process Using the Barkhausen Magnetic Noise", Acta Univ., vol. 28, no.1, 2018.

[11] D. Buttle, V. Moorthy and B. Shaw, Determination of Residual Stresses by Magnetic Methods, NPL, Teddington, UK, 2006.

[12] O. Zurita, V. Di Graci and M. Capace, "Surface Hardness Prediction Based on Cutting Parameters in Turning of Annealed AISI 1020 Steel" DYNA, vol. 84, no. 203, pp. 31-36, 2017.

[13] V. Di Graci, O. Zurita and M. Capace, “Model for Microhardness Profile Prediction of Annealed AISI 1045 Steel Cylindrical Bars Subjected to Torsion”, Rev. de la Fac. de Ing., Universidad de Antioquia, vol. 89, pp. 68-72, 2018.

[14] G. Dieter, Mechanical Metallurgy, 3rd ed., EE.UU., Mc. Graw – Hill, 2000.

[15] J. Datsko, Material Properties and Manufacturing Processes, New York, EE.UU., John Wiley & Sons, 1991.

[16] G. González, V. Di Graci, O. Zurita and M. Capace, “Axial Stress Prediction of Torsioned Solid and Hollow Cylindrical Bars”, Rev. Tec. Ing. Univ. Zulia, vol. 41, no. 2, pp. 71 – 78, 2018.

[17] S.G. Hussein, “An Experimental Study of the Effects of Coolant Fluid on Surface Roughness in Turning Operation for Brass Alloy”, J. Eng., vol. 20, no. 3, pp. 96- 104, 2014.

[18] D. Deepak and B. Rajendra, “Investigations on the Surface Roughness Produced in Turning of AL6061 (as-cast) by Taguchi Method”, Int. J. Res. Eng. Technol., vol. 4, no. 8, pp. 295-298, 2015.

[19] ISO 1832, "Indexable Inserts for Cutting Tools -- Designation", 2017. [Online]. Available: https://www.iso.org/standard/69202.html. Accessed on: May 2022.

[20] C. Che-Haron and A. Jawaid, “The Effect of Machining on Surface Integrity of Titanium Alloy Ti–6% Al–4% V”, J. Mater. Process. Technol., vol. 166, pp. 188-192, 2005.

[21] A. Sharman, J. Hughes and K. Ridgway, “An Analysis of the Residual Stresses Generated in Inconel 718TM When Turning,” J. Mater. Process. Technol., vol. 173, no. 3, pp.359-367, 2006.

[22] D. Montgomery, Design and Analysis of Experiments, 8th ed.. New York, USA: Wiley, 2012.

[23] 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., vol. 45, pp. 131–136, 2005.

[24] A. Suhail, N. Ismail, S. Wong and N. Abdul, “Optimization of Cutting Parameters Based on Surface Roughness and Assistance of Workpiece Surface Temperature in Turning Process”, Am. J. Eng. Appl. Sci., vol. 3, no. 1, pp. 102-108, 2010.

[25] ASTM A938-07, “Standard Test Method for Torsion Testing of Wire”, ASTM International, West Conshohocken, PA, 2007.

[26] D. Montgomery, E. Peck and G. Vining, Introduction to Linear Regression Analysis, USA: Wiley, 2012.

[27] C. Che-Haron and A. Jawaid, "The Effect of Machining on Surface Integrity of Titanium Alloy Ti–6% Al–4% V", J. Mater. Process. Technol., vol. 166, no. 2, pp. 188–192, 2005.

[28] G. Senussi, "Interaction Effect of Feed Rate and Cutting Speed in CNC - Turning on Chip Micro - Hardness of 304 - Austenitic Stainless Steel", World Acad. Sci. Eng. Technol., vol. 28, pp. 121-126, 2007.

[29] P. Patil, R. Kadi, S. Dundur and A. Pol, "Effect of Cutting Parameters on Surface Quality of AISI 316 Austenitic Stainless Steel in CNC Turning", Int. Res. J. Eng. Tech., vol. 02, no. 04, pp. 1453-1460, 2015.

[30] R. Pawade, S. Joshi and P. Brahmankar, "Effect of Machining Parameters and Cutting Edge Geometry on Surface Integrity of High-speed Turned Inconel 718", Int. J. Mach. Tools Manuf., vol. 48, no. 1, pp. 15–28, 2008.

[31] G. Boothroyd and W. Knight, Fundamentals of Metal Machining and Machine Tools, Marcel Dekker, Inc., New York, USA, 1989.

[32] Z. Cassier, T. Guevara and A. Acosta, "Influencia de las Propiedades Mecánicas del Material Sobre las Fuerzas de Corte en el Mecanizado de Metales", Anal. Ing. Mec. REIM, vol. 3, no. 1, pp. 103-108, 1985.

[33] P. Ross, Taguchi Techniques for Quality Engineering, 2nd ed., McGraw-Hill, New York, USA, 1996.