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Experimental Investigation of the Effect of Cutting Conditions on Tool Wear During Turning of 316L Stainless Steel

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Abstract:
In machining processes, the cutting tool is the most important part of the operation. There is a great need to discuss how to improve the contact conditions around the cutting tool to extend its life, and this improvement can’t be achieved unless there is a good understanding and knowledge of the contact conditions that occur at the tool's cutting edge. The main objective of this work is to add more knowledge for investigating the tool-chip interface during the metal-cutting process and tool wear. This work will look at the chip-tool interface; and examine how tool wear can be evaluated. These aims will be achieved by carrying out practical experimental work during the turning of 316L stainless steel by tungsten carbide cutting inserts at different conditions. The relationship between tool wear and experimental conditions (time, speed, feed, and depth of cut) was adapted into a polynomial response equation of second order for the response. The results are tested statistically using the ANOVA technique. The F-ratio test as a tool of the analysis of variance was used to check the adequacy of the model and to determine whether the final equation is a good fit to the experimental observations. Hence, the regression equation that has been derived is in agreement with the experimental results observed. Based on the work in this study, a couple of points can be concluded: tool wear is influenced by the change in cutting conditions, and low rates of tool wear are recorded at low speeds, low feeds, and short periods.

Keywords: Tool Wear, ANOVA, 316L Stainless Steel, Cutting Conditions, Turning.

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دراسة تجريبية لتأثير ظروف القطع على تآكل الأدوات أثناء الخراطة للفولاذ المقاوم للصدأ L316

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الملخص

في عمليات التصنيع، تعد أداة القطع الجزء الأكثر أهمية في العملية. هناك حاجة كبيرة لمناقشة كيفية تحسين ظروف التلامس حول أداة القطع من أجل إطالة عمرها، ولا يمكن تحقيق هذا التحسين إلا إذا كان هناك فهم ومعرفة جيدة لظروف التلامس التي تحدث عند حافة أداة القطع. الهدف الرئيسي من هذه الدراسة هو إضافة المزيد من المعرفة لفحص واجهة شريحة الأداة أثناء عملية قطع المعادن وتآكل الأداة. سيتناول هذا العمل فحص كيفية تقييم تآكل الأداة. سيتم تحقيق هذه الأهداف من خلال إجراء أعمال تجريبية عملية أثناء تشغيل الفولاذ المقاوم للصدأ L316 بواسطة قطع كربيد التنجستن في ظروف مختلفة. تم تكييف العلاقة بين تآكل الأداة والظروف التجريبية (الوقت والسرعة والتغذية وعمق القطع) في معادلة استجابة متعددة الحدود من الدرجة الثانية للاستجابة. تم اختبار النتائج إحصائيا باستخدام تقنية*ANOVA*. تم استخدام اختبار النسبة F كأداة لتحليل التباين للتحقق من مدى كفاية النموذج وتحديد ما إذا كانت المعادلة النهائية مناسبة للملاحظات التجريبية. ومن ثم فإن معادلة الانحدار التي تم استنتاجها تتفق مع النتائج التجريبية التي لوحظت. استنادا إلى العمل في هذه الدراسة، يمكن استنتاج بضع نقاط: من الواضح أن تآكل الأداة يتأثر بالتغير في ظروف القطع، ويتم تسجيل معدلات منخفضة من تآكل الأداة بسرعات منخفضة، وتغذية منخفضة، وفترات زمنية قصيرة.

الكلمات المفتاحية: تأكل الاقلام، الخراطة، انوفا، ظروف القطع، الفولاذ المقاوم للصدأ 316L.

Introduction

A comprehensive understanding of the chip formation mechanism necessitates an examination of the material behavior at the chip root. It is the region where plastic deformation happens in the deformation zones and separation happens in front of the tool tip. Metal cutting is accompanied by significant plastic deformation and fracture since it has been observed that chip formation is caused by ductile shear failure of the material in front of the cutting edge rather than fracture generated by crack propagation [1]. In order to prolong the life of the cutting tool, it is imperative to talk about ways to improve the contact conditions surrounding it. However, this improvement cannot be made unless the contact conditions at the tool's cutting edge are well understood and known. This work's primary goal is to increase our understanding of the tool-chip interaction during metal cutting and tool wear.

A substance known as a chip rubs and slides across the cutting tool's face during material removal. One of the primary areas of inquiry into the operation of the cutting process is the zone of contact between the chip and the tool face. Feed, depth of cut, and cutting speed are the three primary governing factors in the cutting process. Any variation in the value of these parameters has an impact on the conditions in which the chip and tool face come into contact, which in turn affects the component's quality and tool life. By keeping the contact area at the interface intact, the tool's lifespan may be increased. This contact offers some helpful hints for the quantitative assessment of the cutting process based on real-world experiments that demonstrate how the tool-chip interface's length affects the cutting parameters' effects on chip shape, tool life, and heat generation [2]. The kind of material being cut, the required cutting speed, tool life, and economic concerns are some of the variables that influence the choice of materials for cutting tools. These are some typical materials for cutting tools: high-speed steels, which were made by alloying steel primarily with 5.5% chromium and 18% tungsten. The elements vanadium, molybdenum, and cobalt are also frequently used in alloys.

The tool's lifespan might be extended by maintaining the contact area at the interface. Based on real-world tests showing how the length of the tool-chip interface influences the cutting parameters' impacts on chip form, tool life, and heat generation, this contact provides some useful guidance for the quantitative evaluation of the cutting process [3].

Several factors impact the selection of materials for cutting tools, including the type of material to be cut, the necessary cutting speed, tool life, and financial considerations. High-speed steels, which were created by alloying steel predominantly with 5.5% chromium and 18% tungsten, are some common materials for cutting tools [4]. In alloys, the elements cobalt, molybdenum, and vanadium are also commonly utilized. It needs to be very firmly supported to avoid cracking, though, as it is highly brittle and has a low shock resistance. When cutting at two to three times the speed of cast alloy tools, carbide tools require a substantially smaller feed. A very thin 0.05 to 0.08 mm bonded layer of titanium carbide, aluminum oxide, or titanium nitride to a tungsten carbide substrate can be applied to carbide tools [5]. These coatings lessen the heat produced by adhesion and diffusion as well as the heat generated by the chip passing over the tool. Because of their extreme hardness and brittleness, diamonds are employed as single-point tools for light cuts and high speeds, and they require solid support. They are used for light, high-speed cuts on softer materials where accuracy and surface polish are crucial, or for hard materials that are challenging to cut with other tool materials. Powder metallurgy techniques are used to combine aluminum oxide powder with titanium, magnesium, or chromium oxide additions to create ceramic tools, which are then processed into cutting tool inserts. Hardness and strength at both high and low temperatures, high compressive strength, incompatibility with the metal being cut, resistance to cratering, and low heat conductivity are some of the benefits of ceramic tools. The material of the workpiece, the shape and material of the tool, the cutting parameters (feed, speed, and depth), the process liquid that is utilized, and the cutting machine are only a few of the variables that affect tool wear.

The most crucial factor in determining the machinability of a given material is tool wear. But it's also critical to take machined surface roughness, chip shapes, and cutting forces into account. Tool wear is directly correlated with surface roughness. Numerous working conditions, including softening, brittle fracture, abrupt mechanical load changes or shocks, progressive wear in the working component, etc., can cause a cutting tool to fail during the process. The effluent is forced over the flank surface as the area of contact at the flank grows [6]. There are two distinct areas on the cutting tool that begin to wear after some cutting has been done. A wear zone that extends roughly parallel to the cutting edge will be formed by wear that develops on the tool's flank beneath the cutting edge. A distinct hollow known as a "crater" will also be formed by wear on the tool face, starting at a specific distance from the cutting edge. Wear places a limit on a cutting tool's usable life. Wear control has emerged as a critical requirement for the sophisticated and dependable technologies of the future. Depending on the material chosen and the operating conditions, wear rate varies significantly [4]. The following factors lead to wear or damage to the cutting edge of the tool: abrasion, diffusion, oxidation, and/or heat and/or mechanical load changes; attrition, especially when a built-up edge (BUE) is present [1]. Friction between the tool and the hard particles of the workpiece material is what causes abrasion [7]. The irregular material flow required for attrition is produced by vibration, interrupted cutting, uneven depth of cut, and sliding between the chip and the tool. Rough spots are visible where attrition has worn them down. Seizures zones between the chip and the tool rake face and, sometimes, between the workpiece and the tool flank face, however, might cause diffusion. Diffusion may happen in situations involving high temperatures and pressure, such as when ferrous materials are continuously turned at high cutting speeds, even in cases when the tool exhibits strong chemical stability. Wear can occur in three main areas of the tool due to direct contact with the work material: the face, flank, and nose. When a chip is forming, it passes across the tool's face, which is known as face wear. The principal cutting edge of the cutting tool is placed along the flank, which is also its clearing face [8]. Nose wear is comparable to flank wear and is frequently regarded as such. There are instances in which it warrants consideration of its own.

Experimental Methodology

In this section, the experimental work study of tool wear is presented here in detail. The methodology for presenting the experimentation is shown here. The experimental testing work is being carried out on 316L stainless steel rods specimens. The investigated tool material in this study is tungsten carbide. Nowadays, tungsten carbide inserts are used widely in cutting processes because of their good properties in cutting, such as their ability to resist deformation at high temperatures. This property allow the tungsten carbide inserts to achieve higher metal removal rates compared with HSS tools [9]. In addition, the tungsten carbide tools retain good hardness levels at temperatures of around 1200^{o} C [10]. The results of wear measurements are presented and then based on the processing of the collected data, the investigation of the change in tool wear resulting from the change in cutting conditions is presented and discussed. The target material employed to carry out the tests is 316L stainless steel and its chemical composition (wt. per cent) is shown in Table 1.

Table 1: Chemical Composition of 316L stainless steel [11].

Element	Fe	Cr	Ni	Mo	Mn	Si	C
Content %	balance	16.7	12.4	2.6	1.5	0.7	Max. 0.08

The investigated workpiece specimens are rods in geometry with dimensions of 100 mm diameter and 140 mm length. This length was chosen so that the samples could be securely mounted in the chuck of a lathe with a protruding length of 110 mm, the workpiece was found to be stable, and not subject to static deflection or vibration for any of the investigation parameters chosen in this study. The rig contains the main components of testing; cutting insert and the testing specimen under investigation. The examined tool material, which is the 316L stainless steel mentioned above, is fixed directly on the lathe's chuck where it is rotated according to the spindle speeds of the machine. The cutting holder is mounted by fixed bolts on the tool post of the machine where it can be moved in two axes. One is perpendicular to the face of the workpiece which represent the depth of cut. The movement in this direction is controlled manually. The second direction of movement is parallel to the face of the workpiece. This movement is controlled automatically according to the movement of the lathe mechanism. During this movement the cutting tool, machining of the workpiece take place. The tests take place using a traditional lathe machine of trade mark XYZ 1600 to apply suitable cutting conditions that are designed in this work. The workpiece rotates anticlockwise at speeds which vary according to the investigation conditions. The technique used in this study for designing experiments was introduced by Box and Hunter [12]. A rotatable factorial design of experiments with a central composite of second order 2^k can be used to enhance the reliability of investigation work. In addition, the number of runs of this process is reduced with increased accuracy. It should be noted here, that k is the number of factors involved in the process.

The run of experimental work was made by the use of a particular technique of design of experiments since that traditional experimentation involves considerable effort and time, particularly when a wide range of investigation work is needed. Design of experiments is a very efficient method for developing valuable research while saving time in the process. The technique used in this study for designing experiments was introduced by Box and Hunter.
It helps to the researcher to understand the relationship between the response and parameters and the influence of the different levels on that response, in addition to helping to combine the different levels of parameters for response optimization [13]. The package of design of experiments and analysis of variance used in this study has been used widely in experimentation work [14].

As a rule, the experiment designed to find the optimum conditions of the process is described adequately by a second-order polynomial [15]. For this polynomial, the number N of observations included in the design should not be less than the number of estimated coefficients of the second-order equation for k factors

In the general case, the response tool wear y is defined by the following equation;

$$Y = f(x_1, x_2, \dots\dots, x_k) \qquad (1)$$

where $x_1, x_2, \dots\dots, x_k$ are coded levels of k quantitative variables. Suppose that we have k variables $x_1, x_2, \ldots\ldots, x_k$ and we want to fit them to a polynomial of degree $d = 1$, the simplest response is then given by

$$y = b_0 + b_1 x_1 + b_2 x_2 + \ldots\ldots + b_k x_k$$

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where, b_0 is the free coefficient. According to a 2^k factorial with a central composite-second-order rotatable design [12] the total number N of experiments is calculated by the following equation.

$$N = n_c + n_a + n_o = 2^k + 2k + n_o \qquad (3)$$

where; $n_c = 2^k$, are factorial points or corner points in which all possible combinations of the variables at all levels are used. The group $n_0 = \frac{\lambda n(k+2) - kn}{k}$ are called the center points; $n = n_c + n_a$ and λ is a constant which depends on the number of independent variables. More details about this constant and its values corresponding to a number of variables are given by Box and Hunter [12]. In a dimensionless system, the coordinates of the center point of the design are at zero. In the work where the cutting tests take place the investigated variables are time, speed, feed and depth of cut, so the k is four. The values of the actual and coded variables of the testing conditions are listed in خطأ! لم يتم العثور على مصدر المرجع..

Table 2: Coding of Tool Wear Test Parameters.

Parameters	Symbol	Levels				
		-2	-1	0	1	2
Time (min)	X1	3	6	9	12	15
Speed, (m/min)	X2	100	150	200	250	300
Feed (mm/rev)	X3	0.1	0.2	0.3	0.4	0.5
Depth of cut (mm)	X4	0.3	0.6	0.9	1.2	1.5

The matrix of conditions of experiments using this technique is shown in **خطأ! لم يتم العثور على مصدر المرجع.**.

Table 3: Experimental design matrix in actual and coded form.

Exp. No	Time (min)		Speed, m/min		Feed, mm/rev		Depth of Cut, mm		Results Tool wear
	Coded value	Actual value	Coded value	Actual value	Coded value	Actual value	Coded value	Actual value	µm
1	-1	6	-1	150	-1	0.2	-1	0.6	160
2	+1	12	-1	150	-1	0.2	-1	0.6	240
3	-1	6	+1	250	-1	0.2	-1	0.6	240
4	+1	12	+1	250	-1	0.2	-1	0.6	320
5	-1	6	-1	150	+1	0.4	-1	0.6	200
6	+1	12	-1	150	+1	0.4	-1	0.6	260
7	-1	6	+1	250	+1	0.4	-1	0.6	260
8	+1	12	+1	250	+1	0.4	-1	0.6	330
9	-1	6	-1	150	-1	0.2	+1	0.9	210
10	+1	12	-1	150	-1	0.2	+1	0.9	310
11	-1	6	+1	250	-1	0.2	+1	0.9	280
12	+1	12	+1	250	-1	0.2	+1	0.9	330
13	-1	6	-1	150	+1	0.4	+1	0.9	250
14	+1	12	-1	150	+1	0.4	+1	0.9	320
15	-1	6	+1	250	+1	0.4	+1	0.9	270
16	+1	12	+1	250	+1	0.4	+1	0.9	330
17	-2	3	0	200	0	0.3	0	1.2	60
18	+2	15	0	200	0	0.3	0	1.2	400
19	0	9	-2	100	0	0.3	0	1.2	55
20	0	9	+2	300	0	0.3	0	1.2	440
21	0	9	0	200	-2	0.1	0	1.2	100
22	0	9	0	200	+2	0.5	0	1.2	120
25	0	9	0	200	0	0.3	-2	0.3	140
24	0	9	0	200	0	0.3	+2	1.5	390
25	0	9	0	200	0	0.3	0	1.2	140
26	0	9	0	200	0	0.3	0	1.2	150
27	0	9	0	200	0	0.3	0	1.2	160
28	0	9	0	200	0	0.3	0	1.2	140
29	0	9	0	200	0	0.3	0	1.2	170
30	0	9	0	200	0	0.3	0	1.2	130
31	0	9	0	200	0	0.3	0	1.2	160

The relationship between the tool wear and experimental conditions (cutting time, speed, feed and depth of cut) can be adapted into the following polynomial response equation of second-order for the response y_u .

$$y_u = b_0 + \sum_{i=1}^{k} b_i x_i + \sum_{i=1}^{k} b_{ii} x_i^{\;2} + \sum_{j\geq 1} b_{ij} x_i x_j$$

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where; $x_i(1,2,....,k)$ are coded values for the number of variables, k. b_o is the free coefficient, b_i are the linear coefficients, b_{ii} are the quadratic coefficients, and b_{ij} are the interactions coefficients.

In the case of four variables the equation (4) can be rewritten as follows;

$$\begin{aligned} y_n &= b_0 + b_1x_1 + b_2x_2 + b_3x_3 + b_4x_4 + b_{11}x_1^{\;2} + b_{22}x_2^{\;2} + b_{33}x_3^{\;2} + b_{44}x_{44}^{\;2} \\ &\quad + b_{12}x_1x_2 + b_{13}x_1x_3 + b_{14}x_1x_4 + b_{23}x_2x_3 + b_{24}x_2x_4 + b_{34}x_3x_4 \end{aligned} \tag{5}$$

where; x_1 is the coded value of cutting time, x_2 is the coded value of speed, and x_3 is the coded value of feed and x_4 is the coded value of depth of cut. These variables are coded for convenient identification and for easy calculation.

The regression coefficients b_0, b_1, b_2… etc. in equation (5) can be calculated by the method of least squares using the suitable equations [16]. The values measured during the running of the tests based on the designed matrix are used in the equations mentioned above to find the regression coefficients of the polynomial response equation.

The relationship between the tool wear (response) and the test factors was calculated using the empirical equation mentioned. The results of the experimental work are evaluated and analyzed by the use of the derived adopted response equation in terms of parameters involved in the process. The F-ratio for each term can be determined from the variance analysis. The sum of squares of the Y's is contributed by the first-order term, the second-order terms, lack-of-fit terms and the experimental error.

The wear in the cutting insert appears due to the contact between the tool and the workpiece during the cutting process. To measure the evolution of the wear, an optical microscope NIKON Optiphot 150 is used. The flank wear is being measured. DeltaPix Insight software has the option to calibrate the different magnifications and to create a ruler and a scale to quantify the wear. The measured results are presented in Table 2.

Figure 1: Photo of Optical NIKON microscope.

Results and Discussion

The results shown in table 2 are recorded based on the work which has been carried out to measure the tool wear of tungsten carbide inserts in investigating the tool-chip interface contact during turning 316L stainless steel. A set of matrices of experiments was conducted, with the aim of investigating how this wear is influenced by the change at different cutting times, speeds, feeds and depths of cut.

A matrix of thirty-one tests based on the design of experiments detailed above and adopted in the present study for the tool wear investigations was shown in table 2 with conditions in coded and actual form. The first sixteen experiments represent the corner points, the next eight experiments represent the axial points, and the last seven experiments represent the centre points. 31 tests have been done according to the design of experiments used in this work based on the Box and Hunter technique detailed above [12].

The results are tested statistically using the ANOVA technique described earlier. The analysis of variance was carried out by using the F-ratio test as mentioned. It should be noted that the regression equation fits the experimental data, if the computed F-ratio of both first and second terms are larger than the standard value of the F-ratio. In addition, the computed F-ratio of lack of fit must be smaller than the standard value [16] of the F-ratio. The derived regression equations have a good fit to the experimental results and equation can be derived according to the form mentioned above. Hence, the derived equations fit the experimental results and the equations can be written in the following form. Derivation of this equation is one of the objectives in this work since it is used to show and display the relationship between the experiment conditions and the tool wear.

$$\begin{aligned} Tool\ Wear = {} & 149.6 + 52x_1 + 49x_2 + 7x3 + 33x4 + 11{x_1}^2 + 34{x_2}^2 - 0.5{x_3}^2 + 38.3{x_4}^2 - 3.1x_1x_2 \\ & - 3.1x_1x_3 - 0.6x_1x_4 - 5.6x_2x_3 - 10x_2x_4 - 3x_3x_4 \end{aligned}$$

Figures 2,3 and 4, three-dimensional curves for the effects of various combinations of the input of cutting parameters (time, speed, feed, and depth of cut) on tool wear. The graphs were constructed from the experimental results using response surface methodology (RSM) and the final equation (mathematical model) created above. It can generally be seen from these figures that tool wear increases with an increase in cutting time at any value of speed and feed. The best results obtained is (68 µm) at the lowest time used in this work 3 minutes and speed of 150 m/min.

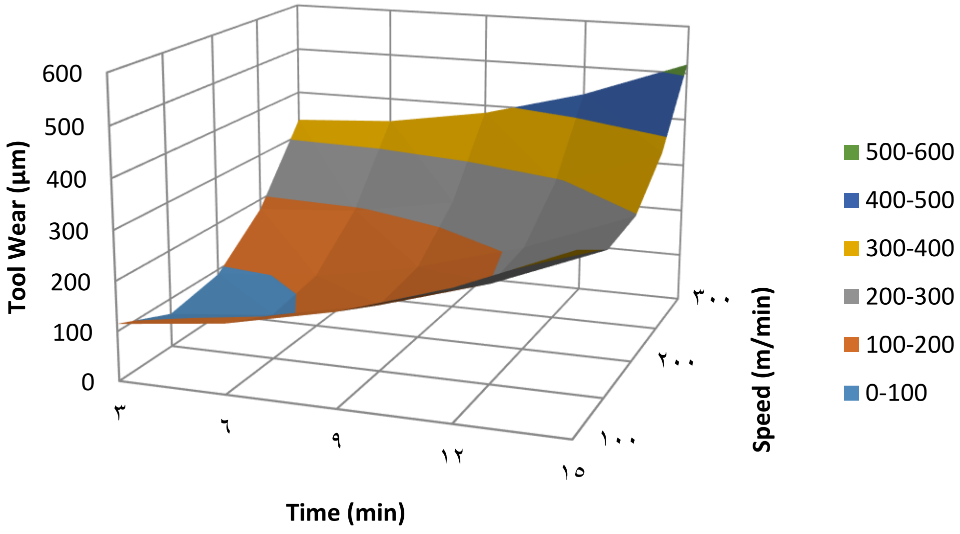

Figure 2: Effect of time and speed on tool wear.

Cutting speed is one of the most significant cutting parameters that affect the tool wear. It can be seen from Figure 2 that for a given feed, tool wear increases as cutting time increases reaching the highest amount of wear (520 µm) which is recorded when speed is highest (300 m/min) and cutting time of 15 minutes.

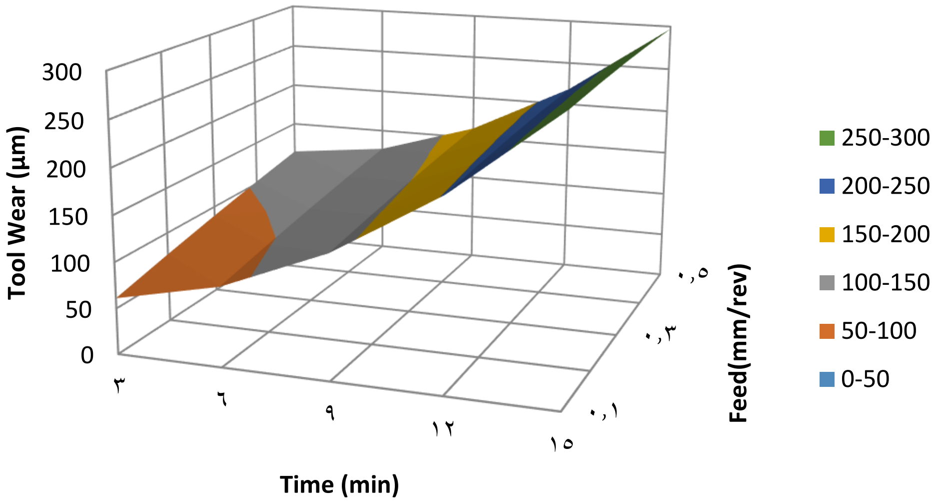

Figure 3: Effect of time and feed on tool wear.

The effect of feed on tool wear can be assessed from Figure 3. The general trend of the results reveals that an increase in feed, within the range used in this study, does not have much effect on tool wear. The highest tool wear value recorded is very close to (300 µm) for all feeds used at a period of cutting time of 15 min. Whereas, the lowest tool wear is 60 µm at a cutting time of 3 minutes and feed of 0.1 mm/rev.

Figures 4 shows the relationship between rime, depth of cut and tool wear at different cutting times. It can be realized that the combination between high depth of cut and long cutting periods results in a considerable increase in tool wear. At cutting time of 3 minutes only 89 µm of wear is recorded at depth of cut 0.9 mm.

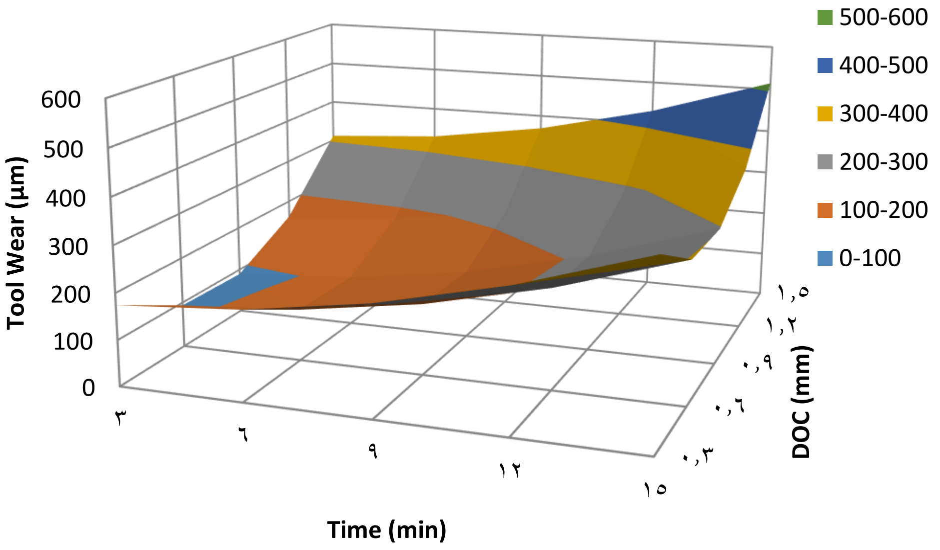

Figure 4: Effect of time and depth of cut on tool wear.

Conclusion

Based on the work on this study couple of points can be concluded and shown as follows:

1. The tool wear is influenced obviously by the change in cutting conditions.
2. Low rates of tool wear are recorded at low speeds, low feeds and short periods of time.
3. Highest amount of tool wear is 520 µm when cutting time is 15 minutes and speed of 300 m/min.
4. The lowest tool wear is 60 µm at cutting time of 3 minutes and feed of 0.1 mm/rev.
5. Design of experiments developed by Box and Hunter can be used in this experimental work to save time and materials and to see the variation under different conditions without losing accuracy of tests.

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