Experimental Investigation and Mathematical Modeling of Composite Ceramic Cutting Tools with Alumina Base in the Machining Process of PH-hardened Austenitic-ferritic (Duplex) Stainless Steel

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Abstract: The tool life of a cutting tool is an important critical factor in evaluating its performance. The amount of tool abrasion seriously affects the dimensions and surface quality of the working piece so that one of the main factors determining the tool life of a tool is the degree of wear. For this purpose, an abrasion standard is defined for each particular tool above which the tool is no longer applicable. In this paper, studies are concentrated on the machining of PH-hardened Austenitic-ferritic (Duplex) stainless steel (330HRC) to analyze the effect of tool wear on the tool life of the ceramic cutting tool with Alumina base (aluminium oxide). The abrasion tool parameters like flank wear, crater wear, and notch wear have been addressed. To develop the mathematical models for the parameters studied in tool wear, the experimental results are applied in a multi-regression analysis (MRA) and the results obtained by these models are studied and analyzed by analysis of variance (ANOVA).

Keywords: Ceramic Cutting Tool, Tool life, Regression Analysis, Stainless Steel, Tool Wear

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1 INTRODUCTION

Alumina based composite ceramic cutting tools are extensively used for machining hard materials. Among these, different kinds of cast iron with a wide range of hardness, various types of non-alloy carbon steels, alloy steels with a hardness number of 34HRC to 66HRC, stainless steels and also high-temperature alloys having a good chemical stability and hardness are good examples [1].

Aluminum oxide based ceramic cutting tools are divided into three main groups referred to as non-alloyed alumina ceramic cutting tools, mixed alumina ceramic cutting tools and ceramic cutting tools reinforced with whisker. The structure and the most important features of each of these groups are described as follows:

1- Non-alloyed alumina ceramic cutting tools: If zirconium oxide is added to the aluminum oxide base, the obtained cutting tool is called a non-alloyed alumina ceramic cutting tool. By adding zirconium to the alumina base, the fracture toughness of the composite ceramic is highly increased [2].

2- Mixed alumina ceramic cutting tools: If non-oxide particles such as titanium carbide (TiC) or titanium nitride (TiN) is added to the aluminium oxide base, the cutting tool will be a mixed alumina ceramic cutting tool. Adding TiC or TiN significantly increases the tool hardness and thermal conduction capability [3].

3- Ceramic cutting tools reinforced with whisker: If whiskers like silicon carbide (SiC) is added to the aluminum oxide base, the ceramic tool thus obtained is a ceramic cutting tool reinforced with whisker. By reinforcing the oxide aluminum base with silicon carbide (SiC) whisker, the resulting composition will have a high fracture toughness and improved strength [3].

In this paper, in addition to considering ceramic cutting tools with aluminum base regarding flank wear, other parameters like crater and notch wear of these tools are investigated specially in the cutting operation of hard and tough materials.

Xiao observed that for machining hardened steels, ceramic alumina cutting tools toughened by zirconium oxide (zirconia) and ceramic alumina cutting tools combined with titanium carbide are more useful because of their high flank wear resistance [4]. Mikus and Brandt reported that in ceramic alumina cutting tools, crater wear influences the efficiency of these tools. They also concluded that by using these tools in the machining processes of different steels, crater wear depends on superficial plastic deformation of the tool [5].

Although the most important parameter in determining the tool life of alumina-based ceramic cutting tools is the flank wear, some other kinds of abrasion may affect the tool life of tools. As a result, in order to effectively use these tools, the influence of different types of abrasion on their tool life has to be considered and analyzed. For this reason, the abrasion of alumina-based ceramic cutting tools in the machining process of PH-hardened Austenitic-ferritic (Duplex) stainless steels is addressed in detail.

2 ANALYSIS OF THE TOOL WEAR

In the current research work, four different alumina-based ceramic cutting tools are used and listed as follows:

1- Alumina-based ceramic cutting tools reinforced with zirconia (tool A)

2- Alumina-based ceramic cutting tools mixed with titanium carbide or nitride along with zirconia (tool B)

3- Alumina-based ceramic cutting tools mixed with titanium carbide or nitride without zirconia (tool C)

4- Alumina-based ceramic cutting tools reinforced with silicon carbide whisker (tool D)

The complete details of these tools including chemical structure, insert specification, density, Vickers hardness number, transversal fracture strength, Young's module, fracture toughness, thermal conductivity and thermal expansion coefficient along with their units are listed in table 1.

In all the analysis performed with the above tools, PH-hardened Austenitic-ferritic (Duplex) stainless steel, SS 410 grade, is used as the material undergoing thermal operation and its hardness has reached 330 HRC.

There is a minimum of 11.5% chromium in the chemical structure of this type of steel, which can be hardened as a non-alloy carbon steel in the heat treatment process. They are used in high-power thermal plants, nuclear energy machines and other exhausting environments because of their appropriate thermal properties and high-creep fracture strength.

Table 1 Tool's specifications

Details of Tool properties	Unit	Tool A	Tool B	Tool C	Tool D
Composition		Al_2O_3(96.5%) ZrO_2(3.5%)	Al_2O_3(70%), Ti[C,N] & ZrO_2(30%)	Al_2O_3(70%), TiN(22.5%), TiC(7.5%)	Al_2O_3(80%), SiC_w(20%)
Insert specification		CNGN120708-T	CNGN120708-T	CNGN120408T01020	CNGN120408T 01020
Density	g/cm^3	4.02	4.25	4.26	3.74
Vickers hardness	HV	1730	1930	1800	2000
Transverse rupture strength	MPa	700	620	550	900
Young's Modulus	GPa	380	400	400	390
Fracture toughness	$MPa^{1/2}$	4.5	4.5	4.0	8.0
Thermal conductivity	W/mK	16	20	24	18
Coefficient of thermal expansion	$K^{-1}\times10^{-6}$	8	8	8.6	6

The exact alloy structure of PH-hardened Austenitic-ferritic (Duplex) stainless steel, grade SS410 used in cutting operation analyses, includes 11.5 to 13.5 % chromium (Cr), 0.09 to 0.15 % carbon (C), 1% silicon (Si), manganese (Mn) and nickel (Ni) along with a small amount of phosphor (P) and sulphur (S). Cutting operation experiments are carried out using highly precision turning under the following conditions:

1- Cutting tools: In each of the experiments, four tools (A, B, C and D) have been used.

2- Cutting velocity: Each of the experiments is done based on four different cutting velocities of 120, 170, 220 and 270 m/min.

3- Feed rate: All the experiments have been performed with a constant feed rate of 0.12 mm/rev.

4- Depth of cut: The depth of cut is constant and equals 0.5 mm.

5- Cutting fluid: No cutting fluid has been used in the experiments.

After performing each experiment, all three abrasive parameters, flank, crater and notch wear of the tool are measured by tool room microscope and micro stylus to which the index gage is connected. The surface roughness is also measured by roughness tester. The results obtained from these three parameters are used to expand wear mathematical models.

2.1. Flank wear of the tool

The flank wear phenomenon occurring on the lateral side of the tool is often assigned to the wearing of the tool and workpiece on their common surface. Generally, this wear takes place with two different mechanisms: Abrasive wear and Adhesive wear. Each of these mechanisms produced at high temperatures during the cutting operation affects the property of constitutive tool and workpiece. In the flank wear of the tool, abrasive wear mechanism is more important and usually determined in two states:

1- By creating notches and lumps in the direction of the tool slip versus newly machined surface of the workpiece

2- With chip slip versus the tool rake face tool

The severity of abrasion in abrasive wear mechanism can be significantly increased when the workpiece material includes hard particles or when there is some debris on the common surface of the workpiece or tool. Fig. 1 shows the flank wear region of alumina ceramic tool reinforced with whisker of silicon-carbide (tool D) during chip operation of PH-hardened Austenitic-ferritic (Duplex) stainless steel. Grooves and bumps produced by abrasive wear mechanism, on the lateral surface of the tool, can be seen.

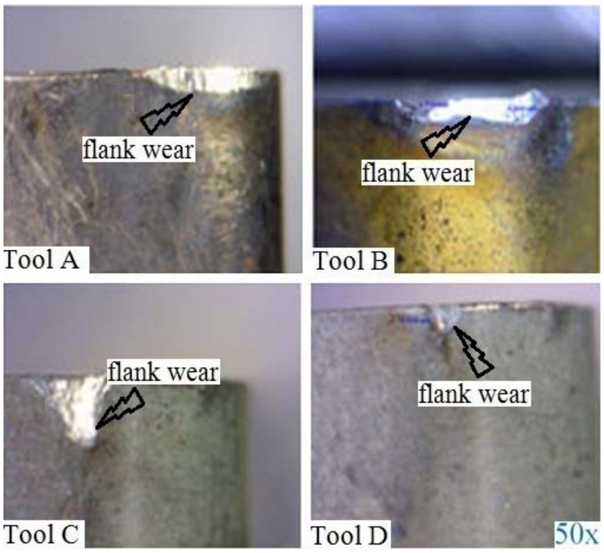

Fig. 1 Flank wear region of alumina ceramic tools A, B, C, D

2.2. Crater wear of the tool

Crater wear occurs on the rake face tool and influences the geometry of the tool-chip common surface. The most important factors affecting the amount of this phenomenon are:

1) The temperature on the common surface of tool-chip
2) Tendency to create a chemical composition within the substances of the cutting tool and the workpiece Abrasion in the crater wear occurs through different mechanisms. In ceramic tools, diffusion of particles in the workpiece is the main mechanism. The process of creating crater wear comprises chemical interactions of the materials of the chip and ceramic tools that can be seen on the common surface of the chip-tool. Because of the tendency to create a tribochemical composition in the materials of the workpiece and the cutting tool, chemical wear takes place. This process becomes active at the high temperatures generated by the cutting operation [6]. Different experiments show that this type of wear becomes more evident at high cutting velocities and when the temperature on the common surface of the chip-tool is high causing a high tendency towards developing a chemical composition within the substances of the workpiece and the cutting tool.

Fig. 2 indicates the crater wear region on the surface of the alumina ceramic tools A and D during the cutting operation of the PH-hardened Austenitic-ferritic (Duplex) stainless steel.

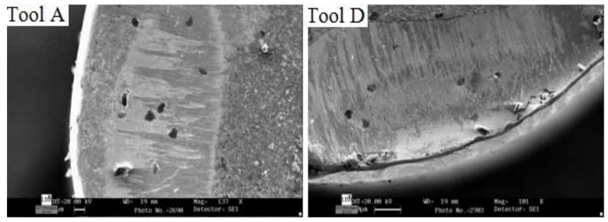

Fig. 2 Crater wear region on the surface of the alumina ceramic tools A and D

2.3. Notch wear of the tool

Notch wear phenomenon is produced by the friction of the machined surface with the cutting tool on the boundary where the chip is no longer in contact with the tool. After the cutting operation, a thin hardened layer may be created on the surface of the workpiece. Since this layer is hard and wear can help produce and enhance notch wear.

Fig. 3 illustrates the notch wear region of the ceramic cutting tools A, B, C, D during the cutting operation of the PH-hardened Austenitic-ferritic (Duplex) stainless steel.

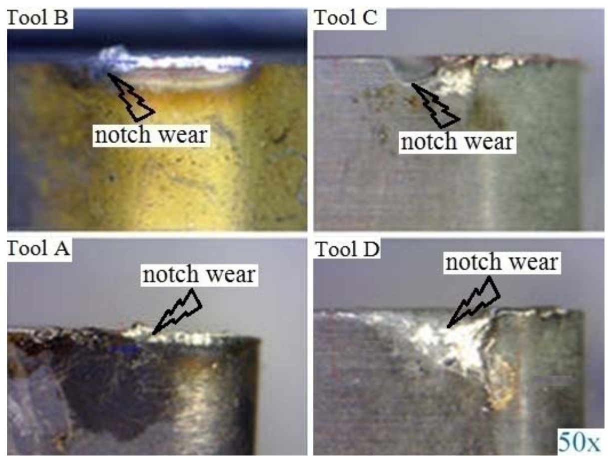

Fig. 3 Notch wear region of the ceramic cutting tools A, B, C, D

Abrasion in the notch wear phenomenon takes place with different mechanisms, the most important of which are abrasive wear and adhesive wear. In the abrasive wear mechanism, single particles or some small masses or aggregates of the surfaces or edge of the tool are cut out by the bottom side of the chip whereas in the adhesive wear, these single particles or small masses stick to the workpiece and will be carried out. On the common surface of the tool and the workpiece, the connection between the different phases of the ceramic is weaker than the connection between the different phases of the workpiece material and this can increase the adhesion intensity. It is necessary to say that notch wear is mostly seen in ceramic cutting tools with lower toughness [6].

An effective and important parameter in the formation of the notch wear mechanism is the type of chip produced during cutting operation. For example, the chips can extensively scratch the cutting tool and create the notch wear phenomenon through the abrasion wear mechanism.

A type of chip extensively seen during machining of PH-hardened Austenitic-ferritic (Duplex) stainless steel is the saw toothy chip. Fig. 4 shows a picture of this type of chip taken by an optical micrographer.

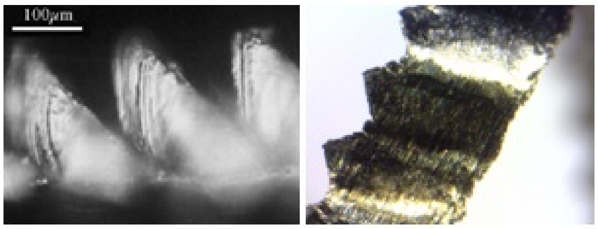

Fig. 4 Saw toothy chip taken by an optical micrographer

3 ANALYSIS OF THE TOOL LIFE OF THE TOOL

The wear phenomenon of cutting tools is a gradual process where the factors affecting their abrasion rate are: material of the workpiece and the tool, the geometry of the tool, amount and type of the cutting fluid, parameters of the process and the characteristics of the applied cutting tool.

It is obvious that the most important criterion for determining tool life is tool wear. There is a completely inverse relation between these two parameters. In addition to gradual abrasion of the tool, other factors affect tool life such as the fracture of the tool, excessive chipping and surface roughness which all have an inverse relation with tool life.

In this paper the tool rejection criterion in the roughing operation is used for measuring tool life. The values and conditions of this criterion according to ISO 3685 are described as follows:

1- Average flank wear > o.4 mm

2- Maximum flank wear > 0.7 mm

3- Maximum crater wear > 0.14 mm

4- Notch wear > 1 mm

5- Surface roughness > 0.6 mm

6- Over-abundant chopping (exfoliate) or the catastrophic fracture of the cutting edge

In all experiments performed in this research work, this research work, no over-abundant chopping or catastrophic fracture of the cutting edge was seen during the cutting operation of the workpiece by the tool. Therefore, in all cutting conditions, surface roughness values measured by the roughness tester and the maximum flank wear have been used for rejection of tool criterion. However to evaluate the tool life of alumina based ceramic cutting tool, in the cutting operation of the PH-hardened Austenitic-ferritic (Duplex) stainless steel, grade SS410, some other standard parameters have been used which are average flank, crater and notch wear. Then, the wear data results, obtained from a large number of cutting operations have been used to create and develop tool wear mathematical models. The desired mathematical models will be considered and analyzed using multi regression analysis (MRA) and analysis of variance (ANOVA).

3.1. Tool wear models

Multi-regression analysis (MRA) is extensively used in various types of statistical analyses. The main purpose of this analysis is to obtain information considering the dependant–independent variable relations.

Lin et al studied the machining of the composite materials and compared MRA with a neural network analysis to investigate the various types of cutting operations [7].

Dabade et al in their study of the cutting operation using an insert of milling powder used a multi-regression analysis to measure effective parameters on the surface roughness [8].

Jain et al simulated the machining process with abrasive particles and analyzed the effects of machining parameters on the separation rate of the materials and the surface [9].

Table 2 Constant values for the flank wear

Tool	a_1	b_1	c_1	R^2	R^2 adj
Tool A	0.00423	0.4652	0.7314	0.995964	0.994928
Tool B	0.00412	0.5133	0.6918	0.993324	0.988742
Tool C	0.00399	0.4879	0.7045	0.992142	0.998943
Tool D	0.00591	0.4901	0.5748	0.996179	0.985349

Table 3 Constant values for the crater wear

Tool	a_2	b_2	c_2	R^2	R^2 adj
Tool A	0.0014	0.6917	0.8614	0.999213	0.989635
Tool B	0.0017	0.3951	0.6123	0.998701	0.998214
Tool C	0.0032	0.4012	0.7900	0.998621	0.997956
Tool D	0.0021	0.7239	0.4321	0.997132	0.996058

Table 4 Constant values for the notch wear

Tool	a_3	b_3	c_3	R^2	R^2 adj
Tool A	0.0019	0.8957	0.7953	0.997302	0.995312
Tool B	0.0021	0.7359	0.7939	0.995012	0.991964
Tool C	0.0014	0.8564	0.8016	0.996132	0.981698
Tool D	0.0017	0.8124	0.8319	0.992934	0.991123

Applied mathematical models used in this paper, analysing experimental results of the machining tests are divided into three categories; flank wear, crater wear and notch wear models; developed according to the Taylor tool life equation [6]. The values of constant parameters in the mathematical relations of the mentioned models were obtained through multi-regression analysis performed, also through the results of experimental abrasion data obtained during cutting operations carried out at different machining intervals and cutting velocities. Applied wearing models are described as follows.

1- Flank wear model VB = a1Vb1tc1 (1)

2- Crater wear model KT = a2 Vb2 tc2 (2)

3- Notch wear model VB = a3 Vb3tc3 (3)

In these relations, VB, KT and VN state the flank, crater and notch wear respectively. "V" is the cutting velocity in meters per minute (m/min) and "t" the time of machining in minutes (min). The coefficients and powers are the constant values previously mentioned.

Tables 2, 3 and 4 present the constant values and R^2 and R^2adj variance analysis indexed respectively for flank wear, crater wear and notch wear individually for tools A, B, C and D.

4 RESULTS

In this paper, the effect of each tool wear phenomenon, on its relative tool life has been investigated at different cutting velocities and the resultant graphs, depicted separately for tools A, B, C and D.

The maximum allowable machining time for flank, crater and notch wear has been calculated according to the tool rejection criterion for the cutting velocity of all alumina based ceramic cutting tools. The profiles of Fig. 5 show the maximum allowable machining time for the cutting velocity for three wear phenomena for each of the applied tools.

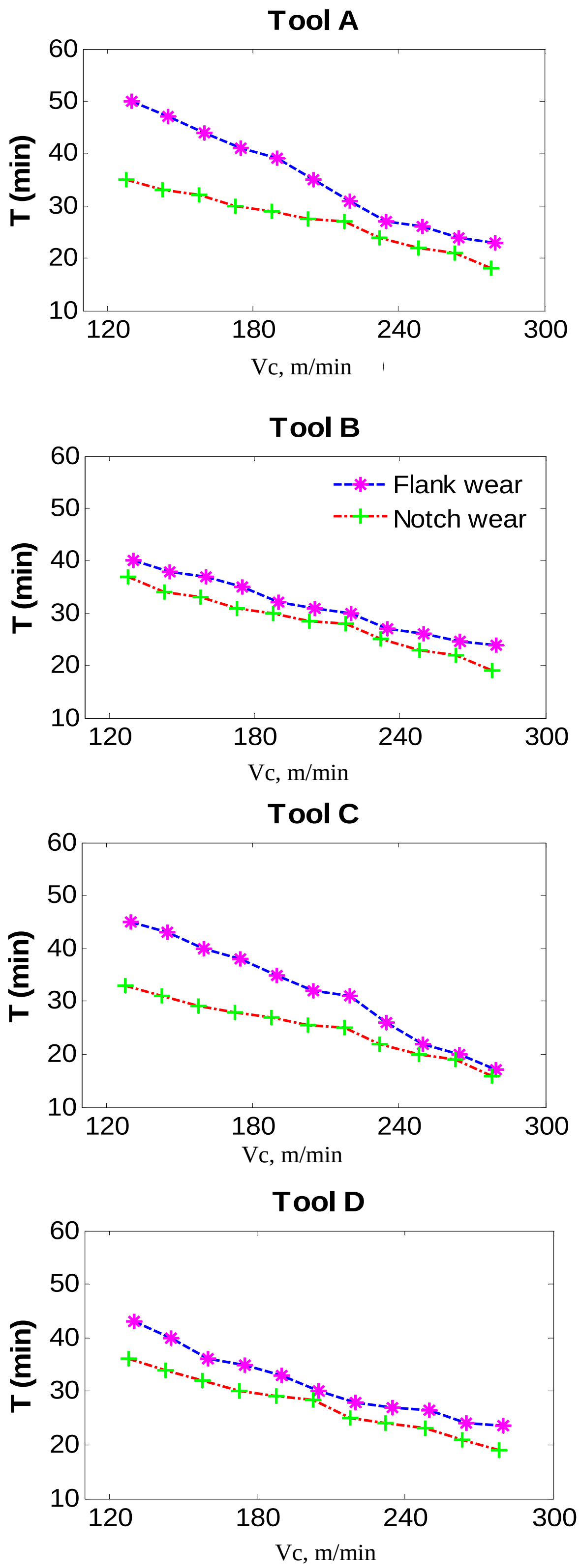

Fig. 5 Maximum allowable machining time vs. the cutting speed

Generally, it can be concluded from Fig. 5-d that at low speeds the tool life of alumina-based ceramic cutting tools is influenced more severely by the flank wear phenomenon whereas at high speeds, the effect of crater and notch wear are more pronounced.

The results of the experimental tests, the analysis of applied mathematical models and the profiles obtained can be summarized as follows:

1- The tool life of the alumina-based ceramic cutting tools reinforced with zirconia (tool A) at low speeds is mostly affected by the flank wear and this effect is intensely decreased at higher speeds (Fig. 5-a). The effect of notch wear on the tool life of this tool is considerable at speeds above 220 m/min.

2- Similarly, the tool life of the alumina-based ceramic cutting tools mixed with titanium carbide or nitride (tools B and C) at low speeds is influenced by the flank wear such that this effect decreases with increased cutting velocity but this declination is milder compared to tool A.. The effect of the notch wear on the tool life of tools A and B respectively, is considerable at speed values higher than 260 m/min and 230 m/min.

3- An important result obtained by precise consideration of the profiles related to tools A, B and C is that at any arbitrary cutting velocity, the tool life is not influenced by the crater wear phenomenon.

4- Flank wear has a considerable more effect on alumina-based ceramic cutting tools reinforced with silicon carbide whisker (tool D), at lower speeds.

Whereas at speeds above 200 m/min, the determinant is with the crater wear phenomenon. The tendency of silicon carbide to combine with iron can explain this effect of the crater wear. As depicted in the profile related to tool D, its tool life is almost unaffected by notch wear. According to the presented standard definitions, if the applied tool reaches any one of the tool rejection criterions, it is said that tool failure has occurred.

In this paper, the tool life of the alumina-based ceramic cutting tool is defined as the time in which the tool reaches one of the wear tool criterions during machining operation of the tool at a certain cutting velocity.

The profiles of Fig. 6 indicates the tool life of the ceramic cutting tool with an alumina base in the machining process of PH-hardened Austenitic-ferritic (Duplex) stainless steel, grade SS410, at different cutting velocities. It must be noted that in these profiles, the maximum allowable time of the chip operation for different wear tool criterions has been used as the tool life of each tool.

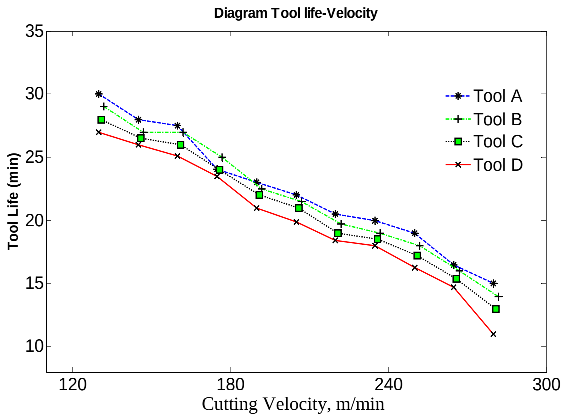

Fig. 6 The tool life of the ceramic cutting tool at different cutting speeds

Fig. 6 depicts the profiles of four kinds of alumina based ceramic cutting tools, namely:

1- Alumina-based ceramic cutting tools with titanium carbide or nitride along with zirconia (tool B). This tool has the longest tool life among of other tools used.

The reason for this long tool life is its ability to maintain hardness at high temperatures.

2- Alumina-based ceramic cutting tools with titanium carbide or nitride without zirconia (tool C)

3- Alumina-based ceramic cutting tools reinforced with zirconia (tool A)

4- Alumina-based ceramic cutting tools reinforced with silicon carbide whisker (tool D). This tool has the shortest tool life among other tools used.

In addition to the above experiments, in order to have a more precise comparison of the findings from the tool life of the tool and their careful confirmation, some other supplementary experiments have been independently carried out on the AISI 4340 steel with a hardness number of 45HRC. It has been concluded from these experiments that:

In the machining process of the AISI 4340 steel, the crater and notch wear phenomenon also has no effect at low speed cutting velocities whereas at speeds higher than 270 m/min, these phenomena are seen and will play a substantial role in determining the tool life of ceramic cutting tools with alumina base.

5 CONCLUSION

In this research work, the study of the effective parameter on the tool wear using ceramic cutting tools with an alumina base in the machining process of PH-hardened Austenitic-ferritic (Duplex) stainless steel (330 HRC) has been performed and the influence of different types of wear phenomenon has been observed and analyzed.

The information obtained from the experiments performed on the tool wear was used to develop governing tool life mathematical models. These models were used to analyze the effects of the wear phenomenon on tool life.

Experimental results and mathematical models lead to the following conclusions:

1- At low cutting velocities, the most effective wear phenomenon on the tool life of the tool is the flank wear phenomena.

2- At average cutting velocities above 200 m/min, the effective phenomena are crater and notch wear phenomenon.

3- Alumina-based ceramic cutting tools with titanium carbide or nitride (tools B and C), in the machining process of the PH-hardened Austenitic-ferritic (Duplex) stainless steels have a longer tool life than other types of tools used.

4- The effective factors on the tool life of the cutting tools A, B and C are different from the factors effective on the tool life of the cutting tool D. Tools A, B and C at low cutting velocities are affected by the flank wear and at a high cutting velocity affected by the notch wear phenomenon whereas the tool life of the cutting tool D at low cutting velocities is affected by the flank wear and at a high cutting velocity by the crater wear phenomenon.

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