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Examining of Tool Wear in Cryogenic Machining of Cobalt-Based Haynes 25 Superalloy

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***Abstract*—**Haynes 25 alloy (also known as L-605 alloy) is cobalt based super alloy which has widely applications such as aerospace industry, turbine and furnace parts, power generators and heat exchangers and petroleum refining components due to its excellent characteristics. However, the workability of this alloy is more difficult compared to normal steels or even stainless. In present work, an experimental investigation was performed under cryogenic cooling to determine cutting tool wear patterns and obtain optimal cutting parameters in turning of cobalt based superalloy Haynes 25. In experiments, uncoated carbide tool was used and cutting speed (V) and feed rate (f) were considered as test parameters. Tool wear (VBmax) were measured for process performance indicators. Analysis of variance (ANOVA) was performed to determine the importance of machining parameters.

***Keywords*—**Cryogenic machining, difficult-to-cut alloy, tool wear, turning.

I. INTRODUCTION

IN order to achieve the better strength-to-weight ratio, super alloys have been developed, providing higher heat and corrosion resistance compared with conventional alloys. These alloys are extensively used in many applications such as turbine and furnace parts, aerospace, dental, orthopedic, heat-treating and chemical handling equipment, and petroleum refining components in which low thermal conductivity, high strength, wear resistance, heat and corrosion resistance under high working temperature is required [1]. Super alloys are divided into three main groups: nickel (Ni), iron (Fe) and cobalt (Co) based. Due to wear, corrosion, and heat resistance and other properties, Co-based super alloys are employed widely in some fields. These alloys have significant amount of cobalt, nickel, chrome and tungsten. In this group, Stellite, Haynes 188 and Haynes 25 are the most commonly used Co-based super alloys. Co-based Haynes 25 super alloy unites many excellent properties such as: high-temperature strength with good resistance to oxidizing environments up to 980°C for prolonged exposures, and excellent resistance to sulfidation. It has been benefited by aerospace and military industry, commercial gas turbine engines and bearing material for both balls and races [2], [3]. In order to produce different parts in manufacturing industry, turning operation is one of the most common methods for metal cutting. General machinability of super alloy materials with lathe machine is more difficult compared to conventional steels and thus they are often expressed as difficult-to-machine alloy or difficult-to-cut alloy. Some elements such as Co, Ni, Cr and Ti provide such a high strength and corrosion resistance which prevent the machinability of super alloy. One of the major problems is the heat generation at cutting region during machining of difficult-to-cut alloys. The cutting needs more energy and thus high temperature occurs during the deformation process at the tool-chip and tool-workpiece interfaces. The low thermal conductivity of Haynes 25 alloy (about 10 W/m °C) also causes to a substantial increase in temperature at the cutting tool and the material during cutting [1], [4]. Therefore, machining process of the super alloy brings two main problems during metal cutting. The first is a short tool life or rapid tool wear due to the work hardening and attrition properties of the super alloy. The second is poor surface quality of the machined surface due to heat generation and plastic deformation [5]. In order to eliminate these problems and to improve the machining performance of difficult-to-cut alloys, several cooling/lubrication methods such as cryogenic cooling, solid coolants/lubricants, wet cooling (traditional cooling), minimum quantity lubrication, high pressure coolants, compressed air/gases have been used as an alternative to dry-machining [6]. Because cutting fluids improve the tool life and generating better surface quality, productivity increases significantly [7]. Despite these advantages of the cutting fluids, several negative effects including environmental pollution and operator health have been discussed. In addition to these effects, the recycling of cutting fluids is also difficult and expensive [8]. In order to eliminate the all cutting fluids during metal cutting process, cryogenic cooling or high pressure cooling with compressed air can be applied for employee health and environment. There are several studies on the use of cryogenic cooling in machining processes. For example, [9] investigated the effect of cryogenic cooling by using modified tool holder on some quality indicator such as flank wear, tool life and surface roughness in turning of AISI 4340 steel. It was determined that cryogenic cooling form tool inside was more effective than coolant from tool outside. Wang et al. [10] worked experimentally the cryogenic machining application for difficult-to-cut materials. It was seen that cutting insert temperature and tool wear decreased with help of cryogenic cooling by comparison dry machining. Dhananchezian and Kumar [11] carried out an experimental study in order to determine the effect of LN2 as it was delivered to cutting insert surfaces via micro-holes on the tool insert throughout cutting process of the Ti–6Al–4V alloy. It was point out that

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cryogenic machining combine with a modified cutting insert exhibited more better result than wet cooling in terms of quality indicators. Venugopal et al. [12] investigated the effect of cutting conditions such as dry, wet and cryogenic cooling on tool wear in machining of Ti–6Al–4V alloy. An important increase in tool life was achieved under cryogenic cooling compared to other cutting conditions. Umbrello et al. [13] explored the effect of cryogenic and dry machining on the surface integrity. It was found out that cryogenic cooling proved better machining performance. The use of cryogenic cooling exhibited a significant improvement on tool life, surface quality and dimensional accuracy with decreasing temperature at tool-chip-workpiece interface [14]-[16].

According to literature survey, there are very few studies dealing with cryogenic machining. When these studies were examined, it was found out that tool wear was not studied by considering the turning of Co-based super alloy Haynes 25. In the light of the above information, this study aimed the effect of cryogenic machining on tool wear during turning of Co-based super alloy Haynes 25.

II. EXPERIMENTAL SETUP

A. Material, Machine Tool, Cutting Tool and Measurement

Cobalt-based super alloy Haynes 25 (also known as alloy L-605) workpiece material was used during turning tests. The material hardness is 207 HB. The chemical composition of workpiece is presented in Table I.

TABLE I
CHEMICAL COMPOSITION OF MATERIAL

% Weight								
C	Co	Cr	Fe	Ni	P	S	Si	W
0.10	Balance	20.3	1.58	10.20	<0.005	0.0008	0.01	14.7

TABLE II
EXPERIMENTAL PARAMETERS

Item	Description
Cutting speed	30; 45 and 60 m/min
Feed rate	0.08; 0.12 and 0.16 mm/rev
Cutting insert	Uncoated carbide - SNMG 120408
Tool holder	PSBNR 2020K12
Depth of cut	1 mm
Cutting condition	Dry and cryogenic

Turning experiments were conducted on a Falco Fl-8 model (Taiwan) CNC lathe machine with a maximum spindle speed of 4800 rpm and a 15 kW drive motor. The uncoated carbide being type SNMG 12 04 08-QM tool insert and tool holder being type PSBNR 2020K-12 produced by Sandvik were employed as a main tool arrangement with tool geometry as follows: rake angle: 6° which is negative; clearance angle: 0°; major edge cutting angle: 75°; cutting edge inclination angle: -6° and nose radius: 0.8 mm. Photograph of experimental set-up is shown in Fig. 1. One of the most important issues is the rapid tool wear in machining of difficult-to-cut materials. Because tool wear is extremely effective on the machining efficiency and workpiece surface quality. Therefore, tool wear values were measured after it was reached to 10 000 mm^3 metal removal rate (MRR) on workpiece. In this study, maximum flank wear (VBmax) was considered. The insert was removed from the tool-holder and wear was accurately determined through a professional microscope. Further, wear mechanisms occurred on cutting tool were investigated with scanning electron microscopy (SEM).

B. Cutting Condition

Cutting speed (Vc) and feed rate (f)) were taken as cutting parameters. The values of cutting parameters were chosen from the plot experiments and the manufacturer’s handbook suggested for the tested workpiece material. During the machining tests, a constant depth of cut (ap = 1 mm) were used and other cutting parameters and their levels are given in Table II. Tests were conducted under two cutting conditions such as dry cutting, and cryogenic cooling from tool inside with liquid nitrogen (LN$_2$). For cryogenic cooling, liquid nitrogen was directly delivered from liquid nitrogen pressure tank to tool holder at a pressure of 1.5 bars. Three holes were drilled on tool holder. The diameter of the first hole on tool holder was made at 6 mm dimension and it provided a connection between tool holder and liquid nitrogen container with the help of hose and adaptor. Liquid nitrogen accumulated inside of the tool holder has been released towards environment as gas vapor with help of the other two holes by taking the heat from insert. Diameter of the gas exit holes was made at 1.5 mm dimension. Experimental setup for cryogenic cooling is seen in Fig. 1.

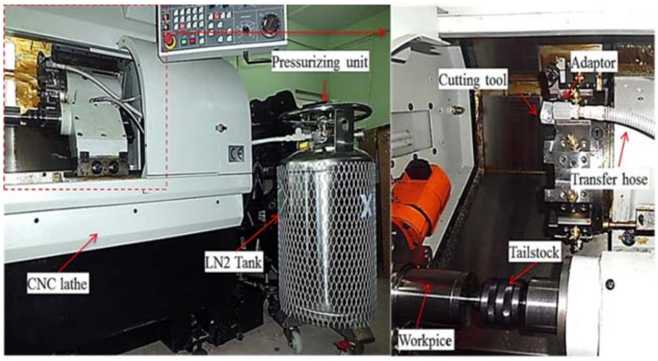


Fig. 1 Experimental setup

III. RESULT AND DISCUSSION

A. Tool Wear

Rapid tool wear is one of the most important problems in machining of difficult-to-cut materials since tool wear is extremely effective on the tool life and surface quality during cutting processes. That is why; tool wear was measured in turning of cobalt-based super alloy Haynes 25. Input parameters were cutting speed and feed rate at different cutting conditions such as cryogenic cooling and dry machining. The results obtained from experiments are shown in Figs. 2 and 3.

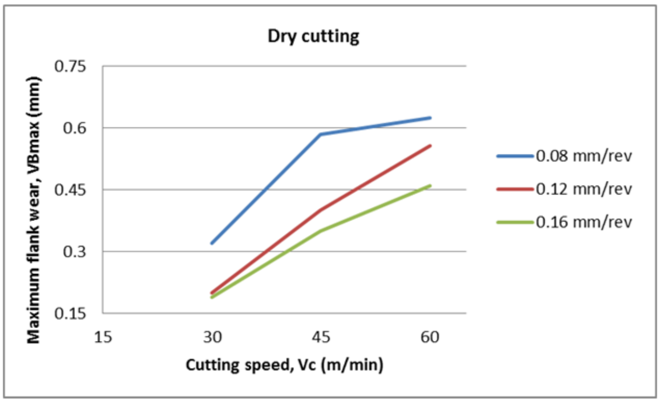


Fig. 2 The effects of cutting parameters on tool wear under dry cutting

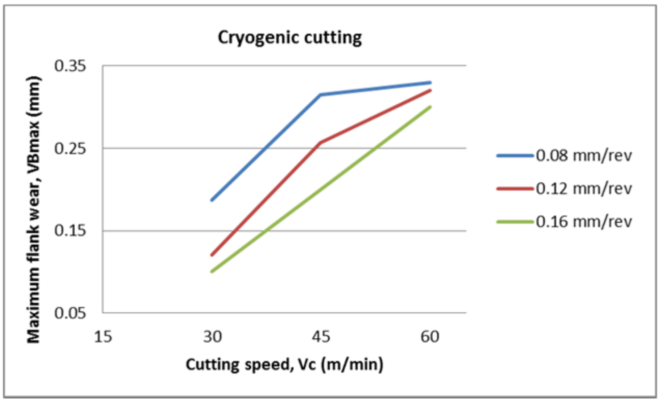


Fig. 3 The effects of cutting parameters on tool wear under cryogenic cutting

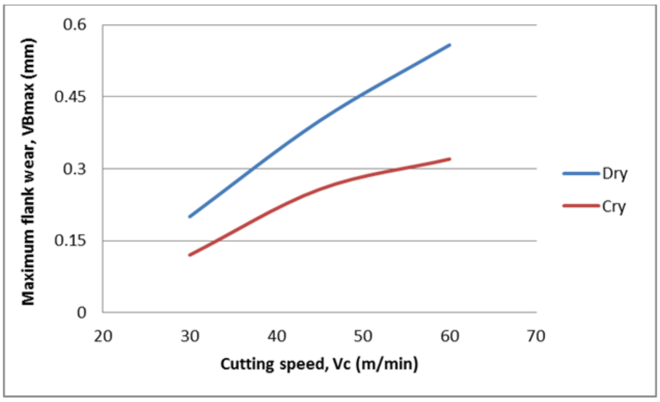
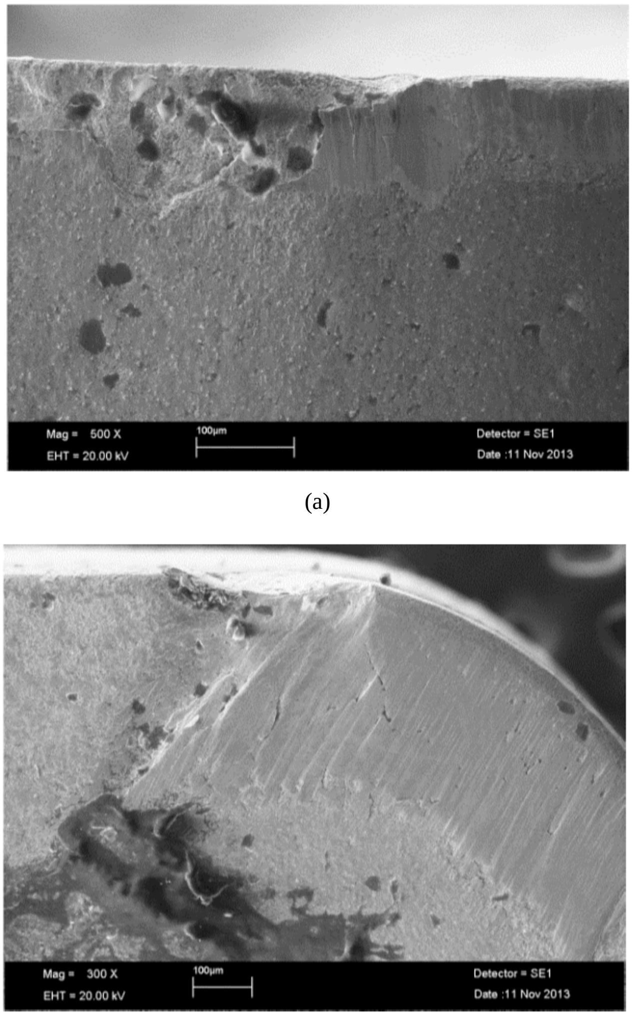


Fig. 4 Comparison of wear results

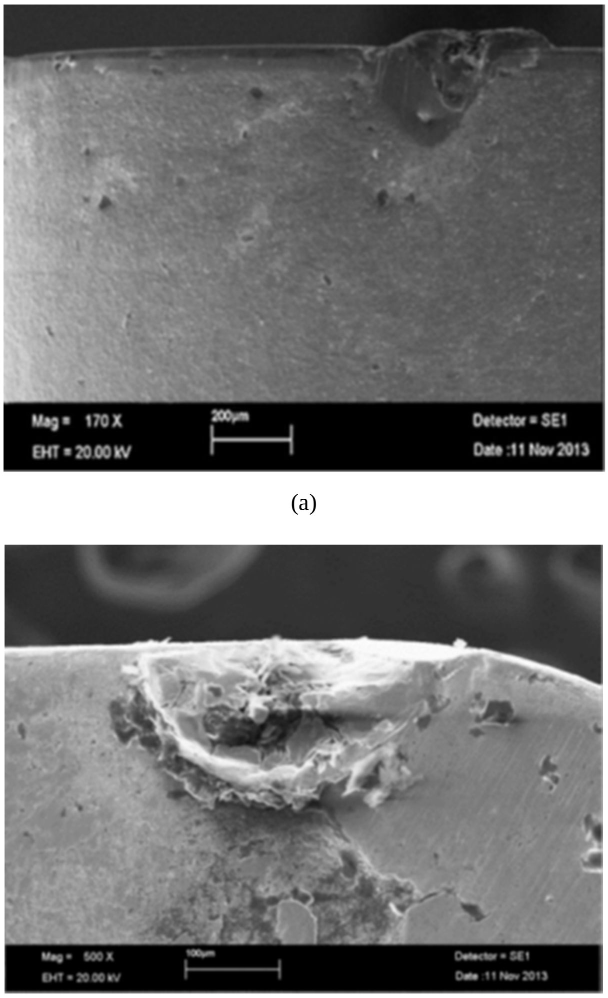
According to Figs. 2 and 3, it was seen that that maximum flank wear (VBmax) values for all feed rates increased with increasing the cutting speed. It was believed an increase in cutting speed leads to an increase in chip volume, friction and temperature, resulting in a reduction in tool strength against wear at cutting zone thereby increasing tool wear. This situation once again verified the previous results in conventional machining processes. Further, for both dry cutting and cryogenic cooling, VBmax decreased with an increase in feed rate under all cutting speeds. In other words, minimum VBmax was obtained at 0.16 mm/rev feed rate. This result was associated with lower contact time at high feed rate between cutting tool and workpiece. When Fig. 4 was examined, cryogenic machining exhibited better result than dry cutting in terms of tool wear. It was point out that economic machining process can be increased with a good analysis of cooling/lubrication methods by decreasing friction and heat production at cutting zone [6]. Further, it is thought to make a significant contribution to a decrease in tool wear by controlling cutting temperature at first shear zone through liquid nitrogen. It can be clearly observed that when cryogenic cooling was used during machining of Co-based Haynes 25, maximum flank wear was approximately 60% lower than tool wear values obtained from dry cutting.



(a)

(b)

Fig. 5 Wear at 30 m/min of cutting speed and 0.12 mm/rev of feed rate under dry (a) Flank face b) Rake face



(a)

(b)

Fig. 6 Wear at 45 m/min of cutting speed and 0.16 mm/rev of feed rate under cryogenic cutting (a) Flank face (b) Rake face

B. Tool Wear Mechanisms

In this section, wear mechanism occurred on cutting tool were evaluated by using SEM images. Due to having nose radius of 0.8 mm and depth of cut of 1 mm, flank wear occurred in nose radius or in the region near the radius of nose radius. Fig. 5 shows the wear mechanism obtained from cutting speed of 30 m/min and feed rate of 0.12 mm/rev cutting parameters under dry cutting. From Fig. 5 (a), it was observed that welded thin material with effecting of adhesive wear mechanism by breaking together cutting tool material caused particle breakage from tool material and further, regular abrasive wear formed in cutting edge surface. This is a typical type of abrasion wear occurring in cutting edge surface and caused by hard particles located in tool material. In Fig. 5, the presence of adhered workpiece material known as Built up Layer (BUL) on cutting flank surface was also seen clearly. When Fig. 5 (b) was examined, chip layer smeared along the tool-chip surface and notch formation was detected. Once welded material with effecting of adhesive wear mechanism was break, adhesion started again and then BUL occurred.

Fig. 6 shows the wear mechanism obtained from cutting speed of 30 m/min and feed rate of 0.12 mm/rev cutting parameters under cryogenic cooling. In Fig. 6 (a), as the overall image of cutting tool is analyzed, the first noticeable was notch wear occurred at the depth of cut boundary. It was seen that cavity generated by notch wear at cutting edge was filled by sticking the workpiece material. As seen in Fig. 6 (b), this adhesion also changed the cutting geometry by exceeding the cutting line of tool. Chip size and geometry welded on cutting line might be prevented the cutting ability of tool edge. Changing the cutting edge geometry caused by welded material has a negative effect on shear and chip flow in both first and second deformation zones. In Fig. 6, the adhesion border of the workpiece material was seen. When welded part reaches to point of hardening, it is break form this border and then it will give more damage to cutter. This situation is an indication that adhesive wear mechanism is quite effective in this region. From Fig. 6, it was observed to be unstable BUL. As a result of diffusion and adhesive wear mechanism, it was shown that tool material particles appeared. Moreover, Fig. 6 indicated BUL, BUE occurred in micro-level, and wears caused from the diffusion and adhesive wear mechanisms.

TABLE III
ANOVA RESULT

Factors	DF	SS	MS	F	P	(%)
Cutting speed	2	0.051084	0.025542	46.84	0.002	82
Feed rate	2	0.009051	0.004525	8.30	0.038	14.5
Error	4	0.002181	0.000545		0	3.5
Total	8	0.062316				100

C. Analysis of Variance (ANOVA)

Analysis of variance (also known ANOVA) is a statistical method that is used to identify the effect of control factors on the experimental results [17]. In this section, the effect of machining parameters such as cutting speed and feed rate on tool wear was evaluated under cryogenic cooling. ANOVA analysis was performed at confidence level by 95% and significance level by 5%.

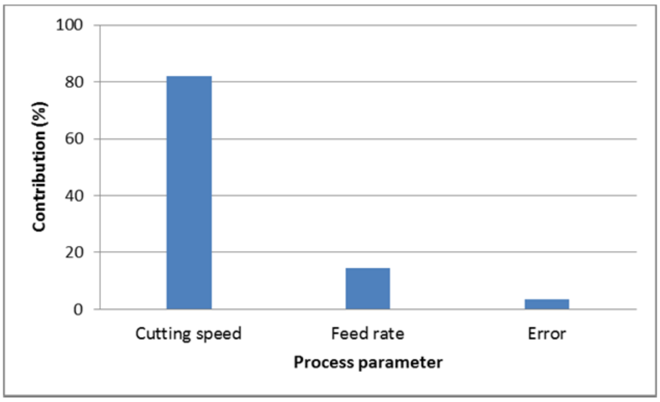


Fig. 7 % Effect of process parameters on tool wear

F value of the control factors in ANOVA analysis indicates the significance of control factors [18], [19]. The percentage contribution of each parameter is shown in the last column of the ANOVA table. ANOVA results are also summarized as

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column chart in Fig. 7. According to Table III, the percent contributions of the factors such as cutting speed and feed rate on tool wear were found to be 82% and 14.5%, respectively and error calculated as 3.5%. Therefore, most effective variable affecting the tool wear under cryogenic cooling was cutting speed by 82%.

IV. Conclusion

The results of this study can be summarized as follows:

- It can be clearly observed that when cryogenic cooling was used during machining of Co-based Haynes 25, maximum flank wear was approximately 60% lower than tool wear values obtained from dry cutting.
- From SEM images, it was observed that adhesive wear mechanism was highly effective as well as abrasive and diffusion wear mechanisms.
- SEM images showed that Built up Layer was highly effective on cutting tool as well as micro-level Built up Edge.
- According to ANOVA analysis, the most effective parameter was cutting speed under cryogenic machining.

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