EVALUATION OF TOOL WEAR AND MACHINED SURFACE INTEGRITY WHEN DRILLING ALUMINIUM ALLOY 7075 UNDER COLD AIR AND DRY CONDITIONS

BY

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ABSTRACT

Application of aluminium alloy 7075 (Al7075) in automotive components is in demand due to its high strength-to-weight ratio. For assembly purposes, drilling operations need to be performed on the components for joining using mechanical fasteners. Drilling in dry condition is typically conducted in industry to avoid environmental pollution caused by the usage and disposal of cutting fluid. However, dry drilling is challenging as it often results in high tool wear rates and poor machined surface finish. Using cold air in drilling operations is seen as an alternative to achieve a hygienic and clean process. This study investigates the tool wear mechanisms and machined surface integrity of Al7075 under dry and cold air (10°C) conditions. Drilling experiments were conducted using tungsten carbide cutting tools at cutting speeds of 82 - 163 m/min and feed rates of 0.01 - 0.1 mm/rev. The least tool wear was found to occur when drilling with the lowest cutting speed of 82 m/min and the highest feed rate of 0.1 mm/rev, which is 0.06 mm after 140 holes in dry condition, compared to 0.18 mm when using cold air. Whereas, the highest tool wear occurred when drilling with the highest cutting speed of 163 m/min at all feed rates in which the tool broke after only 10 holes in both dry and cold air conditions. The tool failure in dry drilling of Al7075 was found to be due to adhesive wear mechanisms as a result of chip adhesion on the cutting edges that led to cutting edge chipping. Whereas, drilling with cold air resulted in more fracture and edge chipping compared to dry drilling due to work hardening. Nevertheless, the application of cold air during drilling Al7075 at cutting speeds of 82 – 123 m/min and feed rates of 0.05 – 0.1 mm/rev particularly when the wear is minimum (hole 10) was found to improve the surface roughness (S_a) by 14% - 52% than dry drilling. This is due to less material adhesion on the machined surfaces when using cold air which caused 22 ºC lower temperature than dry drilling. As for burr height, the usage of cold air in drilling at cutting speeds of 82 – 123 m/min and feed rate of 0.1 mm/rev resulted in 38% - 68% lower burr height than dry drilling at the 10^{th} holes. As more holes were drilled (hole 80), the use of cold air in drilling Al7075 still resulted in 78% lower burr than dry drilling at the cutting speed of 123 m/min and feed rate of 0.1 mm/rev. This study shows the usage of cold air when drilling Al7075 was not favourable to reduce tool wear, however, it can be beneficial in improving the quality of machined surface in terms of surface roughness and burr formation.

Keywords: aluminium alloy 7075; drilling; cold air; tool wear; surface roughness; burr

خلاصة البحث

يشتد الطلب على استعمال سبائك الألومنيوم 7075(A17075) في مكونات السيارات؛ وذلك لأنها تمتلك القدر العالي من نسبة القوة–إلى–الوزن. ويتطلب تركيب هذه المادة إجراءَ عمليات الحفر على المكونات للتوصيل مستعينًا بالمثبتات الميكانيكية. إن إجراء الحفر في الصناعة عادة ما يتم في حالة جافة لتجنب التلوث البيئي الناتج عن استخدام سوائل القطع والتخلص منها. وعلى الرغم من ذلك، يعاني الحفر الجاف من بعض المشكلات لأنه غالبًا ما يؤدي إلى معدلات تآكل عالية للأداة وضعف السطح المشكَّل في نهاية العملية. وينظر إلى استعمال الهواء البارد في عمليات الحفر على أنه بديل لتحقيق عمليات صحية ونظيفة. ويهدف البحث الحالي إلى دراسة آليات تآكل الأداة وسلامة السطح المشكَّل لـ A17075 تحت ظروف الهواء الجاف والبارد (10 درجة مئوية). وأجريت تجارب الحفر باستخدام أدوات القطع (المسمى بـ:كربيد التنغستين / tungsten carbide) بسرعات قطع 82–163 متر (م) / دقيقة ومعدلات تغذية تتراوح من 0.01 إلى 0.1 ميليمتر (مم) / دورة (rev) . وأشارت الدراسة إلى أقل تآكل للأداة عند الحفر بأقل سرعة قطع تبلغ 82 م / دقيقة وأعلى معدل تغذية يبلغ 0.1 مم / دورة، وهو بنسبة 0.06 مم بعد 140 ثقبًا في حالة الجفاف، مقارنة بـ 0.18 مم عند استخدام الهواء البارد. وبالمقابل، كشفت هذه الدراسة عن حدوث أعلى تآكل للأداة عند الحفر بأعلى سرعة قطع تبلغ 163 م / دقيقة في جميع معدلات التغذية التي انكسرت فيها الأداة بعد 10 ثقوب فقط في كل من ظروف الهواء الجاف والبارد. كما تلاحظ الدراسة فشل الأداة في الحفر الجاف لـ A17075؛ وذلك عائد إلى آليات التآكل اللاصقة نتيجة التصاق الرقاقة، والذي أدى إلى تشقق الحافات لأداة القطع، في حين أن الحفر بالهواء البارد أدى إلى مزيد من التصدع وتشقق الأداة مقارنة بالحفر الجاف بسبب تصليد المواد المقطوعة. ومع ذلك، فإن استخدام الهواء البارد أثناء عملية حفر A17075 بسرعات قطع تبلغ 82 – 123 م / دقيقة ومعدلات تغذية تتراوح ما بين 0.05 إلى 0.1 مم / دورة خاصة عندما يكون التآكل ضئيلًا (الثقب العاشر / 10) قد ساعد على تحسين خشونة السطح (S_a) بنسبة 14٪ – 52٪ مقارنة بالحفر الجاف. ويعود ذلك إلى قلة التصاق المواد على الأسطح المشكَّلة عند استخدام الهواء البارد، الأمر الذي أدى إلى انخفاض درجة الحرارة بمقدار 22 درجة مئوية إذا ما قُورِن بعملية الحفر الجاف. وبالنسبة لارتفاع الحوافي/burr (وهي عبارة عن حواف بارزة من المادة تظل متصلة بقطعة معدنية بعد عملية الحفر)، فإن استخدام الهواء البارد في الحفر بسرعات قطع تبلغ 82 – 123 م / دقيقة ومعدل تغذية يبلغ 0.1 مم / دورة يسبب في الانخفاض لارتفاع الحوافي بنسبة 38٪ – 68٪ من الحفر الجاف في الفتحات العاشرة. وبعد حفر المزيد من الثقوب حيث وصل إلى (الثقب الثمانين / 80)، فما زال استخدام الهواء البارد في حفر A17075 يؤدي إلى حدوث حواف أقل بنسبة 78 ٪ مقارنة بالحفر الجاف بسرعة قطع تصل إلى 123 م / دقيقة ومعدل تغذية يصل إلى 0.1 مم / دورة. وتوصلت هذه الدراسة إلى أن استخدام الهواء البارد عند حفر A17075 لم يكن ملائمًا للتخفيف من تآكل الأدوات، لكن بإمكانه أن يكون مفيدًا في تحسين جودة السطح المشكَّل من حيث خشونة السطح وتشكيل الحوافي البارزة.

الكلمات المفتاحية: سبائك الألومنيوم 7075؛ حفر؛ هواء بارد؛ تآكل أداة؛ خشونة سطح؛ حافة بارزة.

APPROVAL PAGE

I certify that I have supervised and read this study and that in my opinion, it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a thesis for the degree of Master of Science in Engineering.

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DECLARATION

I hereby declare that this thesis is the result of my own investigations, except where otherwise stated. I also declare that it has not been previously or concurrently submitted as a whole for any other degrees at IIUM or other institutions.

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LIST OF ABBREVIATIONS

Al7075	aluminium alloy 7075
BUE	built-up edge
CO_2	carbon dioxide
GHG	greenhouse gas
HSS	high speed-steel
MRR	material removal rate
PCD	polycrystalline diamond
RPM	revolution per minute
SEM	scanning electron microscopy
SCT	shallow cryogenic treatment

LIST OF SYMBOLS

π	a mathematical constant = 3.142…
Al	aluminium
Cr	chromium
Cu	copper
D	diameter of drill (mm)
Fe	ferum
f_r	feed per revolution (mm/rev)
Mg	magnesium
Mn	manganese
n	spindle speed (rpm)
R_a	average roughness of line profile (µm)
S_a	average roughness of the whole surface (µm)
Si	silicon
V_c	cutting speed (m/min)
V_f	feed per minute (mm/min)
Zn	zinc

CHAPTER ONE

INTRODUCTION

1.1 BACKGROUND OF THE STUDY

Aluminium is the most abundant element that is widely available in Earth's crust comprising 8% of the Earth's stable surface weight (Krishnan *et al*. 2019). Aluminium is generally used in the industry due to its light weight. As a comparison, the density of aluminium (2700 kg/m^3) is three times lower than mild steel (7850 kg/m^3). In addition, aluminium also has good fabricability criteria that make it useful to a range of applications in industry. However, the pure aluminium is low in yield strength (7-11 MPa) which limits its usage for high performance application. This issue can be overcome by alloying aluminium with other elements such as zinc, copper, and magnesium (Estrada-Ruiz, Flores-Campos, Herrera-Ramírez, & Martínez-Sánchez 2016). Aluminium alloy 7075 (Al7075) was introduced for improving the strength properties which makes it an alternative to other heavier metals such as steel. This can be shown by the general characteristics of wrought aluminium 7xxx series alloys where these alloys have greater combinations of strength, corrosion resistance, and fracture toughness compared to the copper (Santos *et al.*, 2016).

In automotive, aerospace, and manufacturing industry Al7075 is mainly used for structural components (Polak *et al.*, 2017) where drilling operation is typically performed and crucial for assembling of the parts. However, drilling aluminium alloy is challenging due to its ductility at high cutting temperature which leads to material adhesion on cutting edges, accelerated tool wear, and poor drilled hole quality. Water and oil-based cutting fluid has been used to improve the drilling performance in industry. Despite that, managing and disposal of the fluid is an issue as it could lead to environmental pollution, health issues, and increase cost. In this research, dry drilling and usage of cold air during drilling operation which is clean and environmentally compatible is proposed as an alternative to conventional water and oil-based cutting fluid. This study aims to investigate the drilling performance of Al7075 in dry and cold air conditions on the wear of carbide tools and machined surface integrity in terms of surface roughness and burr formation.

1.2 STATEMENT OF THE PROBLEM

Aluminium alloy is the most economical and attractive metallic materials that has been used in various manufacturing industries such as automotive, aerospace, and construction of machines. Aluminium alloys are generally soft and ductile, therefore, it adheres easily to the cutting edges during drilling operation. The built-up edge forms on the cutting lips during drilling the alloy at low cutting speed causing the tool to be less effective in removing the chip, consequently lead to material adhesion and built-up. Therefore, industry has been using higher cutting speed in drilling Al7075, however, at higher cutting speed, cutting temperature increases. This had resulted in rapid tool wear which shorten the tool life, hence, increasing the operational cost. Thus, cutting fluid or lubricant has been used by industry as solutions to dissipate the heat generated hence minimizing edge buildup during the drilling operation of aluminium alloy 6061 (Asok and Chockalingam , 2016).

However, there are some concerns with the usage and disposal of cutting fluid. It would eventually be accumulated with bacteria, harmful to the operators and its disposal could lead to environmental pollution. If the cutting fluid is overexposed to the operators, the possibility to get various kind of disease such as respiratory disease and skin disease is high (Schwarz *et al.,* 2015). In addition, the cutting fluid cannot be simply disposed into the river or any streams, thus a proper waste disposal management system need to be considered which could also increase the operational cost. Therefore, to achieve a hygienic and clean drilling operation of Al7075, this research proposes to use cold air (10°C) as an alternative in drilling Al7075, however, there is limited research in the effectiveness of cold air on the tool wear mechanism. Therefore, this research investigates the effect of cold air in drilling Al7075 on the wear of carbide drill compared to dry drilling.

Furthermore, in drilling operation, machined surface integrity is a crucial aspect in production of holes for assembly part as it represents the product integrity and function. However, when drilling aluminium alloy, material adhesion at the tool-workpiece interface tend to occur due to the ductility properties and higher cutting temperature. This had resulted in presence of scratches, feed mark, and smeared at the surface of the drilled holes which led to product quality deterioration (Goindi & Sarkar, 2017). These problems usually occurred when drilling operation was conducted at the combination of higher cutting speed and feed rate which resulted in higher cutting temperature and plastic deformation that can affect the machined surface integrity negatively. Thus, this research investigates the application of cold air in reducing the cutting temperature when drilling, hence, improving the machined surface integrity of Al7075. In summary, the problems that occurred when drilling aluminium alloy can be encountered with the proper selections of cooling conditions and cutting parameters which are cutting speed and feed rate

1.3 RESEARCH OBJECTIVES

The performance of cold air during drilling Al7075 is investigated in comparison to dry drilling. The drilling operation was conducted using tungsten carbide drills at cutting speed of 82, 123, 163 m/min and feed rates of 0.01, 0.05, 0.10 mm/rev. This was achieved by the following objectives:

1. To investigate the effect of cutting parameters and drilling conditions (dry and cold air) on tool wear of carbide drills in drilling Al7075.
2. To investigate the wear mechanisms of carbide drills with respect to dry and cold air cooling conditions.
3. To investigate the machined surface integrity of Al7075 in terms of surface roughness and burr formation produced by drilling with cold air and dry conditions at different cutting parameters.

1.4 RESEARCH SCOPE

The main purpose of this research is to investigate the potential of cold air as a coolant during drilling Al7075 using uncoated tungsten carbide drill bits. The source of cold air was generated from the vortex tube system where the specifications as stated in Chapter 3. Selection of cutting speeds and feed rates were made based on the materials of cutting tool, workpiece and machine conditions. This research studies the tool wear and its mechanisms also the machine surface integrity in aspect of surface roughness and burr formation. Furthermore, the cutting temperature, Al7075 hardness and chip morphology were inspected as the supportive evidences for tool wear and machined surface integrity.

1.5 SIGNIFICANCE OF THE STUDY

The application of Al7075 in automotive industry has been evolving due to their high strength-to-weight ratio, high corrosion resistance and high fatigue strength. However, the ductility of aluminum alloy is a major challenge when drilling operations are required to be performed since the material tends to adhere at the cutting tool edge. When material adhesion occurs on cutting edges, this can lead to built-up edge which accelerated the tool wear, hence, results in shorter tool life and poor drilled hole quality. The key factor in this crucial manufacturing process of parts assembly is the higher heat generated between the tool and workpiece interface. Therefore, there is a need to investigate the use and effect of cold air as a coolant on tool wear and machined surfaced integrity in drilling Al7075.

1.6 THESIS OUTLINE

This thesis outline as stated below:

I. Chapter 1: Introduction

   Background of this research was discussed where the current industrial practice and the challenges also the significance of this research to industry was stated.

II. Chapter 2: Literature Review

   Discussion on previous studies on drilling of aluminium alloys with various grade and the typical cutting tool materials used in achieving lower tool wear and better surface finish. The cooling conditions and cutting parameters had been reviewed in ensuring the research gap.

III. Chapter 3: Research Methodology

This chapter represents the workflow of this study where the specifications for each component such as the workpiece, cutting tool and machine tool used were discussed. Moreover, all the related experimental setup and procedures were demonstrated precisely.

IV. Chapter 4: Results and Discussions

Findings of this research was particularly analyzed and discussed in term of tool wear and machined surface integrity (surface roughness and burr formation).

V. Conclusions

The benefit on application of cold air in aspects of tool wear and machined surface integrity during drilling Al7075 was summarized.

CHAPTER TWO

LITERATURE REVIEW

2.1 ALUMINIUM AND ITS ALLOY

Aluminium is silvery white metals that exist abundantly in comprise about 8.1% in the Earth's crust. This metal coexist with others minerals such as bauxite and cryolite which means aluminium is rarely found in nature by itself. Hence, aluminium is obtained through a process known as Hall-Héroult where the pure aluminium is extracted electrolytically by dissolving aluminium oxide in molten cryolite (Royal Society of Chemistry, 2017). Even though aluminium is the most economical metal resources but the nature of aluminium that is soft and malleable has restricted its capabilities to be used extensively in various ranges of products and industries. Therefore, the pure aluminium has been alloy with various metal elements for improving the mechanical properties respectively and these alloys have their own designation system centred to the principal alloying elements as shown in Table 2-1.

Table 2.1 Aluminium Alloys Series (MatWeb Material Property Data, n.d.)

Series	Major Alloying Element
1xxx	Commercially pure aluminium (99% aluminium with small amounts of silicon and iron)
2xxx	Copper
3xxx	Manganese
4xxx	Silicon
5xxx	Magnesium
6xxx	Magnesium & Silicone
7xxx	Zinc

Aluminium alloys are widely used in various manufacturing industries such as automotive, aerospace, home appliances, electrical conductors and processing equipment for chemical and food industry. This is due to the low density, highly corrosion resistant properties and cost-effective. In this study, the main focus is on the application of aluminium alloys in automotive industry where it can be said that it is one of the industries that contributed to a large scale of greenhouse gas (GHG) emission. Babatundea, K.A., Saida, F.F., and Nora (2019) reported that 14% of carbon dioxide (CO_2) has been emitted from manufacturing and automotive industries. The CO_2 emission is dangerous since it can be trapped in the earth ozone layer which cause increases of atmosphere temperature and consequently, be the source of global warming and climate changes. As Malaysia is currently moving towards sustainable development, there is a need to reduce the GHG emissions which lead to an increasing demand to reduce the weight of automobiles. Generally, mild steel is the most widely used metal in the automobile industry due to its superior strength (295 – 2400 MPa). However, due to it higher density of 7600 kg/m^3, this heavy metal contributes significantly towards GHG emissions as it needs higher consumption of fuel.

Reducing the weight of automobiles is important as it leads to an improvement in fuel consumption efficiency, consequently reducing the automobile fuel cost and carbon dioxide emission. Serrenho, Norman, & Allwood (2017) reported that reducing vehicle mass by substituting mild steel to aluminium alloy would result in 21% reduction of carbon dioxide emission by 2050. Thus, using aluminium alloys specifically Al7075 as alternative to heavier alloys such as mild steel for automotive components is beneficial economically and environmentally. The advantageous of Al7075 centred at the higher strength properties with lower density value. In automobiles construction, Al7075 is normally used for making the vehicles frames, door panels and some external parts of engine block (Kelly, Sullivan, Burnham, & Elgowainy, 2015). Then, drilling operations are needed to be conducted on the components in order to assemble them by mechanical means.

2.1.1 Composition and Properties

Aluminium alloy is a high strength-to-weight ratio alloy that is made up of a mixture of aluminium with other alloying metals or non-metals such as copper, magnesium, silicon, tin, and zinc as demonstrated in Table 2-2 (JR Davis , 2013). The aluminium alloy has great durability and corrosion resistance which make it versatile and economical to the industries. In addition, aluminium alloy has no toxic reaction and come with good electrical and thermal conductivity. Tensile strength of commercial pure aluminium increase significantly by alloying aluminium with other metals via cold working or heat treatment process (Lee & Mishra, 2017).

Table 2.2 Composition of common aluminium alloys used in the automotive industry (MatWeb Material Property Data, n.d.)

Series		**Composition**								
1100	Chemical element	**Si+Fe**	Cu	Mn	Al					
	Weight %	0.95	0.2	0.05	99					
2011	Chemical element	**Cu**	Fe	Pb	Bi	Si	Zn	Al		
	Weight %	6.0	0.7	0.6	0.6	0.4	0.3	94.6		
2014	Chemical element	**Cu**	Si	Mn	Mg	Fe	Zn	Ti	Cr	Al
	Weight %	5.0	1.2	1.2	0.8	0.7	0.25	0.15	0.1	95
2024	Chemical element	**Si+Fe**	Cu	Zn	Mn	Mg	V	Ti	Al	
	Weight %	0.7	0.1	0.1	0.05	0.05	0.05	0.03	99.3	
5005	Chemical element	**Mg**	Fe	Si	Zn	Mn	Cu	Cr	Al	
	Weight %	1.1	0.7	0.3	0.25	0.2	0.2	0.1	97	
5052	Chemical element	**Mg**	Fe	Cr	Si	Mn	Cu	Zn	Al	
	Weight %	2.8	0.4	0.35	0.25	0.1	0.1	0.1	97	
6061	Chemical element	**Mg**	**Si**	Fe	Cu	Cr	Zn	Ti	Mg	Al
	Weight %	1.2	0.8	0.7	0.4	0.35	0.25	0.15	0.15	98.6
6063	Chemical element	**Mg**	**Si**	Fe	Cu	Cr	Zn	Ti	Mn	Al
	Weight %	0.9	0.6	0.35	0.1	0.1	0.1	0.1	0.1	97.5
7075	Chemical element	**Zn**	Mg	Cu	Fe	Si	Mn	Ti	Cr	Al
	Weight %	6.1	2.9	2.0	0.5	0.4	0.3	0.2	0.28	91.4