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Original Article

Effect of dipped cryogenic approach on thrust force, temperature, tool wear and chip formation in drilling of AZ31 magnesium alloy

Ugur Koklu[a,*], *Himmet Coban*[b]

[a] *Department of Mechanical Engineering, Karamanoglu Mehmetbey University, 70100 Karaman, Turkey*
[b] *Natural and Applied Science, Karamanoglu Mehmetbey University, Karaman, Turkey*

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ABSTRACT

Magnesium alloys tend to have inflammable nature and chip self-ignition at high cutting speeds under dry machining condition, although they can be easily machined with good surface quality. In the drilling process, cooling and lubrication have a critical impact as it controls heat generation, tool wear, surface quality, and cutting force. In the present study, drilling tests on AZ31 magnesium alloy were performed with dry and cryogenic conditions at various feed rates and cutting speeds. The effect of dipped cryogenic application during drilling on thrust force, temperature, tool wear, and chip formation were investigated. The results showed that the applied cryogenic drilling method provided less tool wear, smaller chips and reduced amount of adhesions. Drilling tests performed in the cryogenic environment increase the thrust forces by 32 %–39 % compared to dry cutting. Spark and chip ignition were not observed even at high cutting speeds during dry cutting.

1. Introduction

Magnesium alloys attract significant attention in most engineering applications such as electronics, aerospace, automobile, structural and bio-medical industries. Most of the final products used in many engineering applications are manufactured by machining processes [1,2]. It is possible to easily machine, and good surface finish can be achieved. However, under dry cutting condition, inflammable nature of the material may cause self-ignition of fine chip particles at higher cutting speeds. Built-up edge formation in metal cutting, which results in poor surface finish and dimensional accuracy, is caused by low melting point of these alloys and material adhesion on the cutting tool [1]. It is already known that the majority of the work during machining is converted to heat and ends up with a rise in the temperature of tool, workpiece, and chip, which has an important effect on chip formation, cutting tool wear, and machined surface finish. Temperature is always of concern in machining. For the purpose of decreasing the cutting temperature, applying cryogenics as a coolant is the general procedure to eliminate the effect of the temperature, which is known as cryogenic machining [3,4].

Balout et al. [5] investigated the effect of subjecting various metallic materials (magnesium, aluminum and brass) to pre-cooling and preheating on the drilling process. The experimental study was carried out at many different temperature values (15, 10, 5, 0, −20, −30, −40, −50, and −60 °C) and they stated that thrust force and torque decreased with increas-

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* *Corresponding author.*
E-mail: ugurkoklu@kmu.edu.tr (U. Koklu).

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ing material temperature. Kakinuma et al. [6], Mishima et al. [7], and Kakinuma et al. [8] experimentally investigated the micro machinability of frozen polydimethylsiloxane elastic material. The material was machined when the mold was filled with liquid nitrogen. The authors stated that micro channels were milled easily and accurately using this method. In addition, it was emphasized that tests under cryogenic condition yield higher cutting force than room temperature tests. Song et al. [9] investigated the direct mechanical machining of polydimethylsiloxane using cryogenic cooling. The machined surface was analyzed using various machining parameters such as spindle speed and feed rate, and their effects on the cutting temperature were examined. When the cutting temperature rose above the critical value, it was noted that the surface quality of the polydimethylsiloxane was significantly degraded due to increased adhesion and reduced elastic modulus. Dhokia et al. [10] predicted by compensating the shrinkage of midsole foamed polymer and ethylene vinyl acetate which are widely used in the manufacturing of shoe, under cryogenic condition. The authors emphasized that the cryogenic shrinkage factor in the cryogenic processing was less than 1 % of the original CAD model. Dhokia et al. [11], in another study, investigated the machinability of EVA and neoprene elastomer materials under cryogenic conditions. In the experimental study, the glass transition temperature at a specific temperature and elasticity values of the two selected materials were characterized. Koklu and Morkavuk [12] experimentally investigated drilling machinability of carbon fiber-reinforced composite material under cryogenic condition. Drilling tests were carried out using a specially designed thermally isolated mold. The effects of different cutting conditions on thrust force, delamination, tool wear, and surface roughness were investigated. The authors emphasized that the cryogenic method significantly reduced tool wear and improved surface quality; however, it caused to increase the thrust force.

There are many academic papers on the machinability of magnesium alloys in literature. The majority of these studies are focused in the turning process. On the other hand, there are many studies on cryogenic turning of magnesium alloys [1,2,13–21]. But, limited study has been carried out on drilling processes of magnesium alloys under cryogenic condition. Kheireddine et al. [22] examined the influence of cryogenic application on the surface integrity of machined holes in AZ31B Mg alloy. In the experimental study conducted by the authors, thrust force, torque, surface hardness, and grain structure were measured. It was reported that cryogenic application during machining resulted in improved surface hardness of machined holes as compared with machined under dry condition. Kheireddine et al. [23] investigated the effect of using liquid nitrogen in drilling of AZ31b magnesium alloy on the hole surface integrity using a indexable drill. Thrust force, torque, and surface hardness were examined both experimentally and numerically. It was stated that the hardness value was higher in the tests performed under cryogenic condition. Finite element analysis with experimental justification has been discussed. Bhowmick et al. [24] investigated dry and minimum quantity lubrication drilling of AM60 magnesium alloy. Thrust force, torque, cutting temperature, tool life tests, surface topography, chip, microhardness and tool wear were measured. It is emphasized by the authors that uniform torque and thrust force, small and discontinuous chips and smooth hole surface are obtained by drilling the magnesium alloy under MQL condition. Wang et al. [25] studied wear of HSS tools during drilling of magnesium alloy. SEM analysis showed three types of wear mechanisms in HSS tools. These wear types are adhesive wear, abrasive wear and diffusion wear. This wear mechanism map is indicated to be a good reference for selecting suitable drilling parameters for drilling of cast magnesium alloys. Berzosa et al. [26] focused on cutting tool selection in drilling of magnesium workpiece under dry and minimum quantity lubrication environments based on surface roughness. In the experimental study, two different point angles, cutting speeds, feed rates and MQL flow variables were selected. For aeronautical sector, the importance of determining the tool and operation according to the requirement of surface roughness values of 0.8–1.6 μm is emphasized. Gariboldi [27] investigated drilling machinability of a magnesium alloy using PVD coated twist drills. The drills were coated with TiN, CrN and two different ZrN by PVD method. Tool life, tool wear and surface roughness were investigated. Adhesive wear forms, cutting parameters, the presence and type of coating are stated to be related. Karaca and Aksakal [28] studied effect of the TiBN coating on HSS drill in drilling MA8M Mg alloy. The performance of HSS and TiBN coated drill bits were determined by performing tests at various spindle speeds and feeds. Surface roughness, topography and chip formation were investigated. The TiBN-coated drill exhibited poor surface quality. Balamurugan et al. [29] investigated drilling of Mg/SiC composite for defense applications. The effects of machining temperature on chip morphology, tool wear and surface profile were investigated. It has been observed that the most important effect in machining temperature formation is caused by spindle speed and also both abrasive and adhesive wear type occur. Sunil et al. [30] researched influence of aluminum content on drilling characteristics of AZ31 and AZ91 magnesium alloys. Drilling tests were performed using different cutting parameters. Cutting forces and formed chips were analyzed. It is stated that the presence of secondary phase ($Mg_{17}Al_{12}$) has a significant effect on the cutting forces and an increase in cutting speed reduces the resulting cutting force and load fluctuations.

As the literature review shows that in the field of cryogenic machining of magnesium alloys, machinability studies are generally focused on turning process, and there are very few studies on drilling. In the machining under cryogenic condition, it is generally made by spraying the cryogenic liquid into the machining zone through a nozzle. In this study, the magnesium alloy is drilled in a fixture which is completely filled with liquid nitrogen. By using this approach (dipping the workpiece into liquid nitrogen), drilling performance of AZ31 magnesium alloy was experimentally investigated. Two different cutting speeds (40 and 120 m/min) and four different feed rates (0.1, 0.15, 0.2 and 0.25 mm/rev) were chosen as drilling parameters. Also, tool wear tests were performed under both dry and cryogenic conditions at constant 80 m/min cutting speed and 0.08 mm/rev and 0.16 mm/rev feed rates. The results of the experiments demonstrated that cryogenic machining technique proposed in this study can be applied in order to obtain less tool wear and smaller chips.

2. Material and methods

The workpiece used in the experimental study was an AZ31 magnesium alloy plate. The mechanical properties and chemical composition of the AZ31 magnesium alloy are shown in Tables 1 and 2, respectively. The dimensions of the AZ31 magnesium alloy workpiece was 150 × 100 × 10 mm.

In the experimental study, two flute helical PVD (TiAlN) coated drills with a diameter of 4 mm were used as cutting tools (Fig. 1). The point angle of the drill was 140°. A new drill was used for each series of experiments. The first series of experiments were conducted to determine the effect of the cutting parameters on the results. The experiments were carried out in dry and cryogenic conditions at 40 and 120 m/min cutting speeds and 0.1, 0.15, 0.2 and 0.25 mm/rev feed rates. In the second series of the experiments, tool wear tests were per-

Table 1 – Mechanical properties of AZ31 magnesium alloy [31].

Tensile strength (MPa)	Yield strength (MPa)	Elongation %	Hardness HB	Machinability %
290	220	15	73	100

Fig. 1 – Drill used in the experimental study.

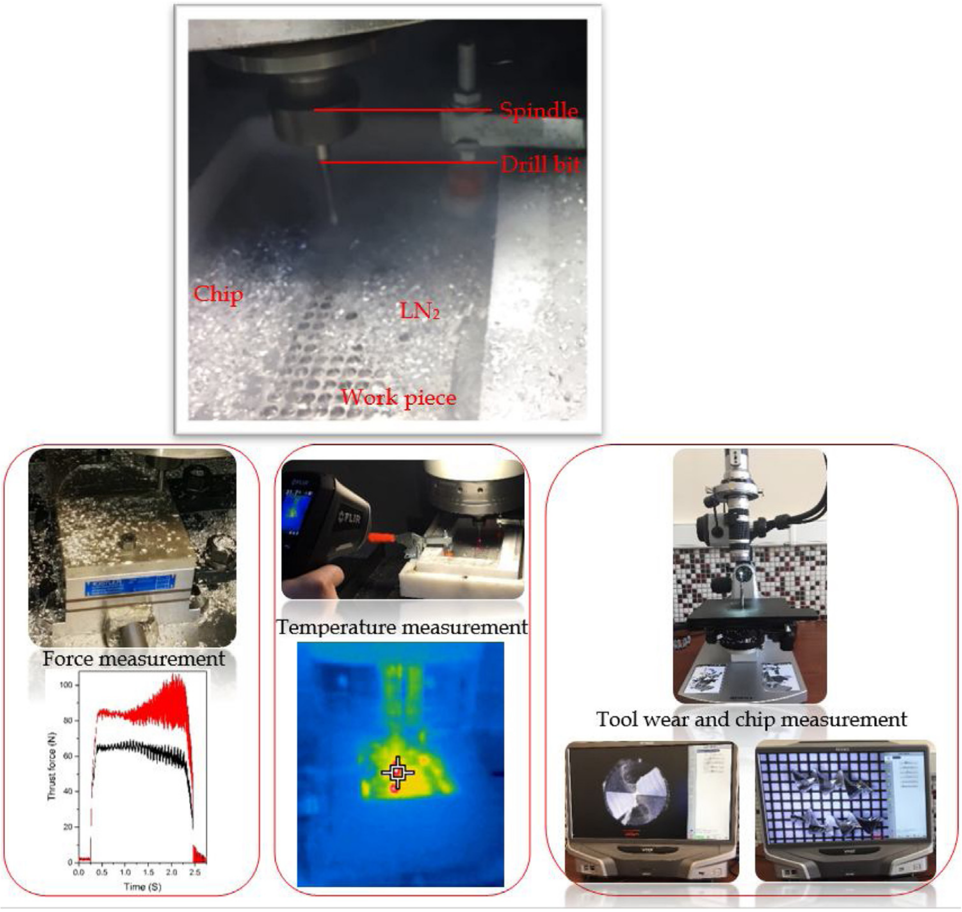

Fig. 2 – Experimental set-up and measuring instruments.

Table 2 – Chemical composition of AZ31 magnesium alloy [31].

Element	Mg	Al	Zn	Mn	Si	Ca	Cu	Fe	Ni
Wt %	96	2.5–3.5	0.6–1.4	≥ 0.2	≤ 0.1	≤ 0.04	≤ 0.05	≤ 0.005	≤ 0.005

formed under both dry and cryogenic conditions at 80 m/min cutting speed and 0.08 mm/rev and 0.16 mm/rev feed rates.

All drilling tests were performed on 3 axis CNC vertical machining center (Quaser MV 154C CNC). At the moment of experiments, thrust forces were measured by a force dynamometer (Kistler 9257B type and data acquisition equipment). Measurement of temperature in machining are very difficult due to closed space, chip obstacles, and the nature of the contact phenomena between tool and chip [32]. Therefore, the thermal camera is positioned to see the cutting process in the best possible way. Temperature measurements were made by a thermal camera (Flir system). Many images were captured with the thermal camera during the drilling process and the maximum temperature obtained from these images was determined. The thermal camera featured object temperature ranges from −25 °C to 380 °C with an accuracy of ± 1.5 % or 1.5 °C, a field of view 50° × 38.6°, IR resolution of 80 × 60 pixels and a thermal sensitivity/NETD of <150 mK. The emissivity value was selected as 0.6 in the experimental study. The wear on the drills were monitored by a digital microscope (Keyence VHX-900 F). The chips formed during experiments were visualized with a digital microscope. The experimental setup and measurement instruments are shown in Fig. 2. A fixture was manufactured to drill the AZ31 magnesium alloy in cryogenic environment without damaging the machine and cutting force measurement devices. The thermal insulator fixture was positioned on the force dynamometer. Polytetrafluoroethylene was employed as a thermal insulation material to avoid the effect of high-level cold cryogenic coolant on the dynamometer. As the cryogenic coolant, liquid nitrogen was employed at −196 °C. More detailed information about the experimental set-up and thermal insulation die can be found in reference [12,33]. Significant improvements in machinability and cutting parameters can be achieved using cryogenic processing [34].

3. Results and discussion

Machinability is the facility or difficulty in machining a material under a certain set of operating conditions that include cutting depth, feed rate and cutting speed. The general criteria commonly adopted for assessing machinability are tool life, power consumption, chip shape, surface finish and component forces during a cutting operation [35,36]. In this study thrust force, temperature, tool wear and chips were considered.

3.1. *Thrust force comparison*

The forces in the X and Y direction during the drilling operation were close to zero. On the other hand, the measurement of thrust force is very important to analyze more effectively the machinability factors of AZ31 magnesium alloy under cryogenic and dry conditions. Each experiment series was made with 3 replicates, and the arithmetic average was taken. Fig. 3 shows a sample chart of the overall thrust force for the experiments carried out at four feed rates (0.1, 0.15, 0.2 and 0.25 mm/rev) and 40 m/min cutting speed. Thrust force increases as the feed rate increases. The effects of dry and cryogenic cutting conditions on the thrust forces occurred at different cutting speeds (40 m/min and 120 m/min) and constant feed rate (0.1 mm/rev) are shown in Fig. 4.

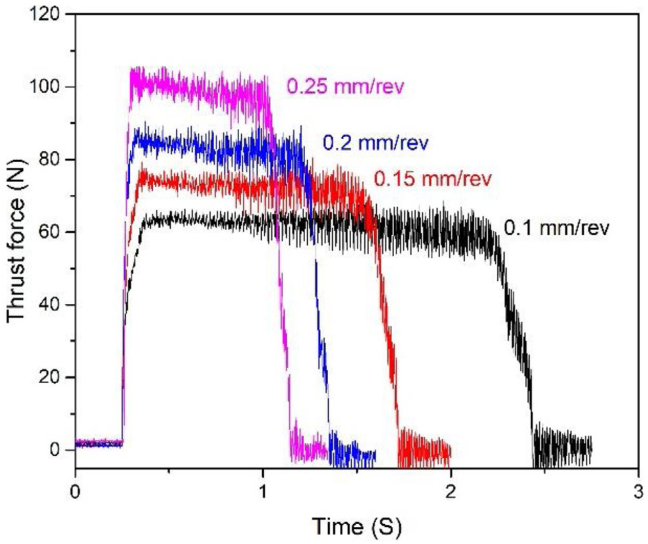

Fig. 3 – The effect of feed rate variation on thrust force.

The thrust force recorded during drilling of the AZ31 magnesium alloy is presented in Fig. 5. Thrust force in dry and cryogenic environment shows decreasing trend when cutting speed is increased. As cutting speed increases, the thrust force decreases by about 16 %–27 %. This behavior can be ascribed to the reduction of the contact area at the drill-Mg alloy interface and the reduction of the specific cutting energy. Furthermore, with an increase in cutting speed, the cutting temperature increased and subsequently reduced the material hardness. Increasing the feed rate in both dry and cryogenic conditions increases (about 34 %–54 %) the thrust force. This phenomenon stemmed from the higher feed rates, which caused an increase in the amount of uncut chip and the energy required for cutting. In addition, drilling tests performed in the cryogenic environment increased the thrust forces by 32 %–39 % compared to dry cutting. In the present study, dipped cryogenic drilling led to higher thrust forces, which was associated with increasing Young modulus and tensile strength of AZ31 magnesium alloy in case exposed to cryogenic environment; and therefore, higher thrust forces are obtained in cryogenic drilling [33]. In previously published studies, it was highlighted that tensile strength, hardness and young modulus of the materials increase as temperature decrease [4,12,37–42].

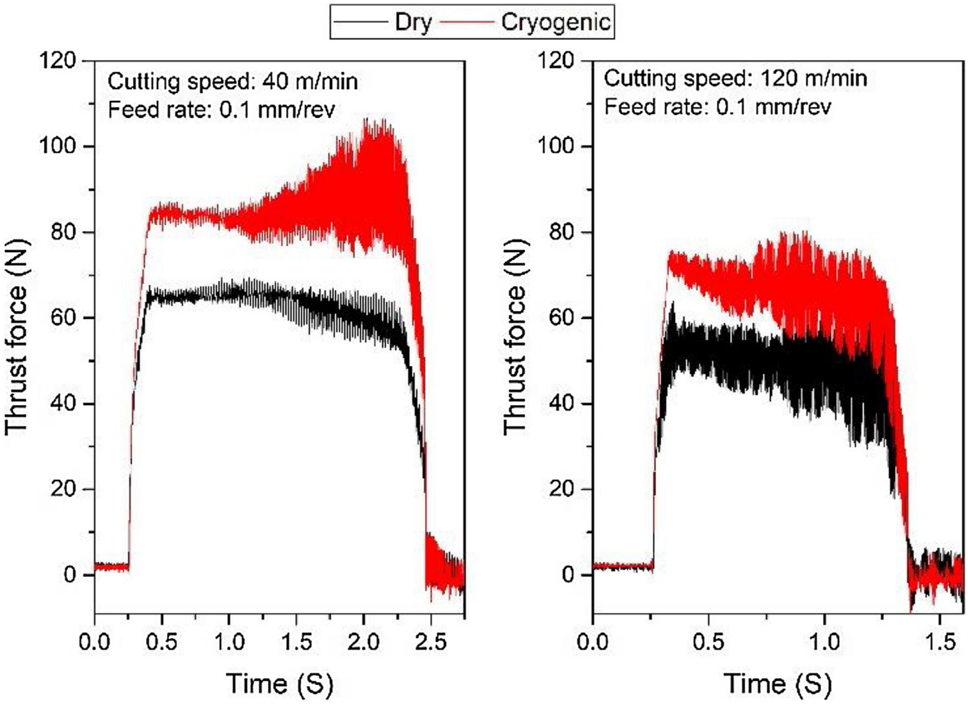

Fig. 4 – Thrust force variations with cutting speed under dry and cryogenic conditions.

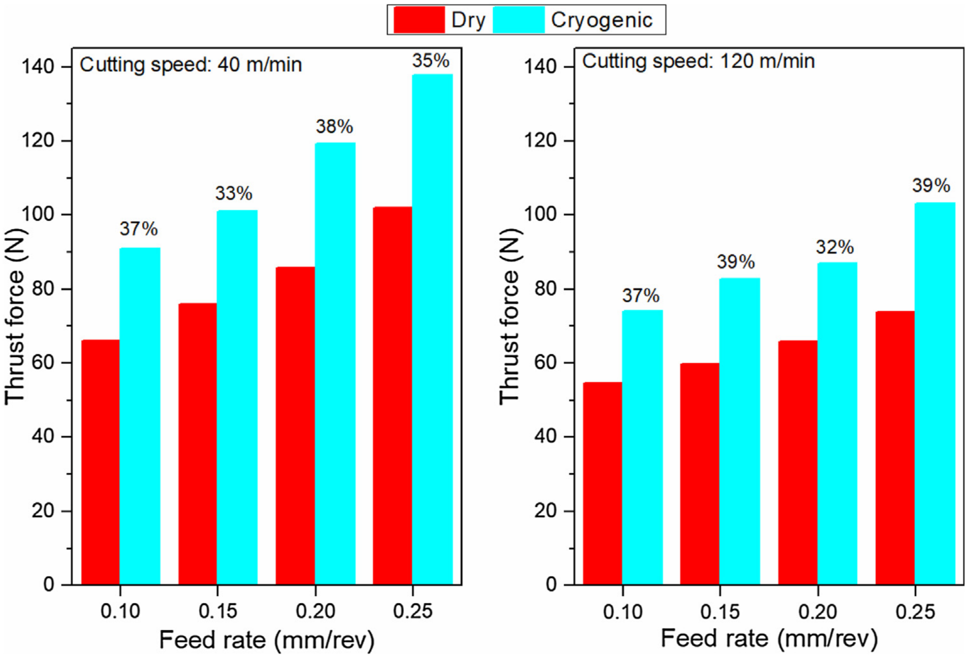

Fig. 5 – Variation of thrust force (a) 40 m/min cutting speed (b) 120 m/min cutting speed.

Tool wear tests were conducted to examine the effect of the subsequent hole number on the thrust force. At different feed rates (0.08 and 0.16 mm/rev) and a constant cutting speed (80 m/min), 360 holes were drilled on the AZ31 magnesium plate under dry and cryogenic conditions. In the tool wear experiments, the thrust force was measured periodically after drilling 20 consecutive holes. The thrust force graph obtained from the tool wear experiments is given in Fig. 6. In both dry and cryogenic conditions, the thrust force tends to increase with increasing number of holes. The fundamental reason for this situation was simply tool wear. In dry drilling condition, lower thrust force was generated than those in the cryogenic condition.

3.2. *Temperature comparison*

Surface temperatures of the cutting tool at the time of drilling were measured by a thermal camera. In the drilling tests per-

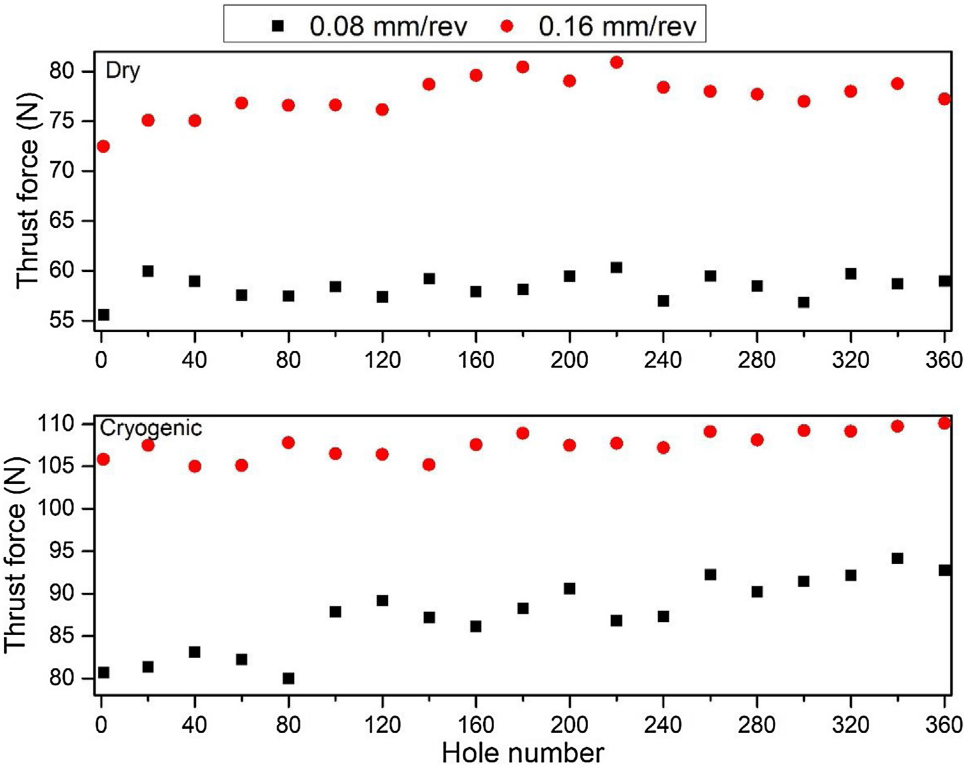

Fig. 6 – Comparison of the thrust force obtained at dry and cryogenic conditions.

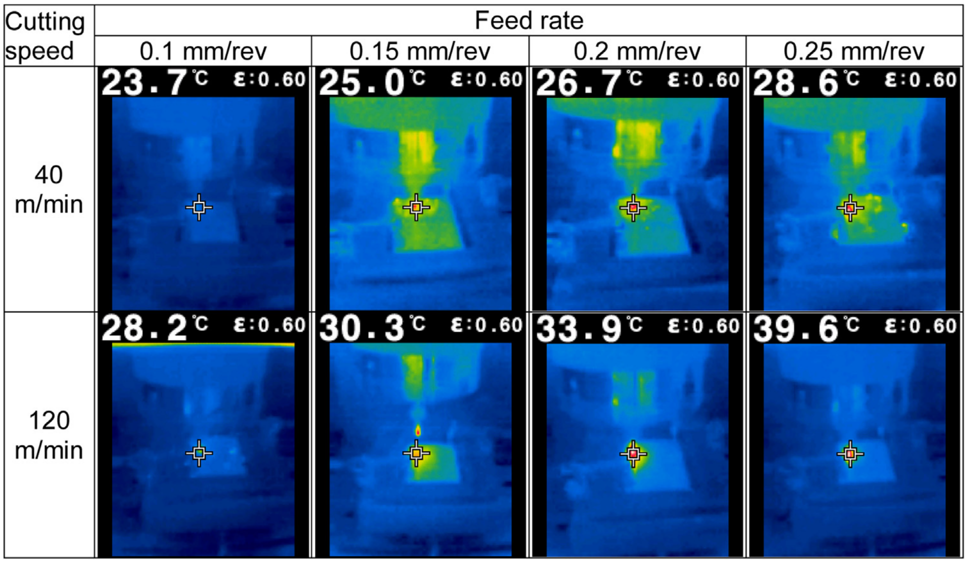

Fig. 7 – Temperatures occurred in dry cutting conditions.

formed under cryogenic condition, the temperature was not measured since liquid nitrogen was supplied continuously therefore the temperatures of tool and workpiece was supposed −196 °C. Temperatures generated at 40 and 120 m/min cutting speeds and different feed rates in dry cutting condition are given in Fig. 7. Temperatures in the drilling process increased linearly with increasing both cutting speed and feed rate. The temperature increased by 20 % with increasing feed rate at low cutting speed, while it increased by 40 % at high cutting speed. Cutting speed has a dominant effect on heat formation. Spark and chip ignition was not observed even at high cutting speeds during dry cutting. This is of vital importance for machining safety.

In the tool wear tests carried out with a constant cutting speed (80 m/min) and two different feed rates (0.08 mm/rev and 0.16 mm/rev) under dry drilling condition, temperatures measured for each 60 holes. Images from the thermal camera are shown in Fig. 8. As can be shown, an increase in the number of holes increases the temperature. At both feed rates, as the number of holes increases, the temperature increases as

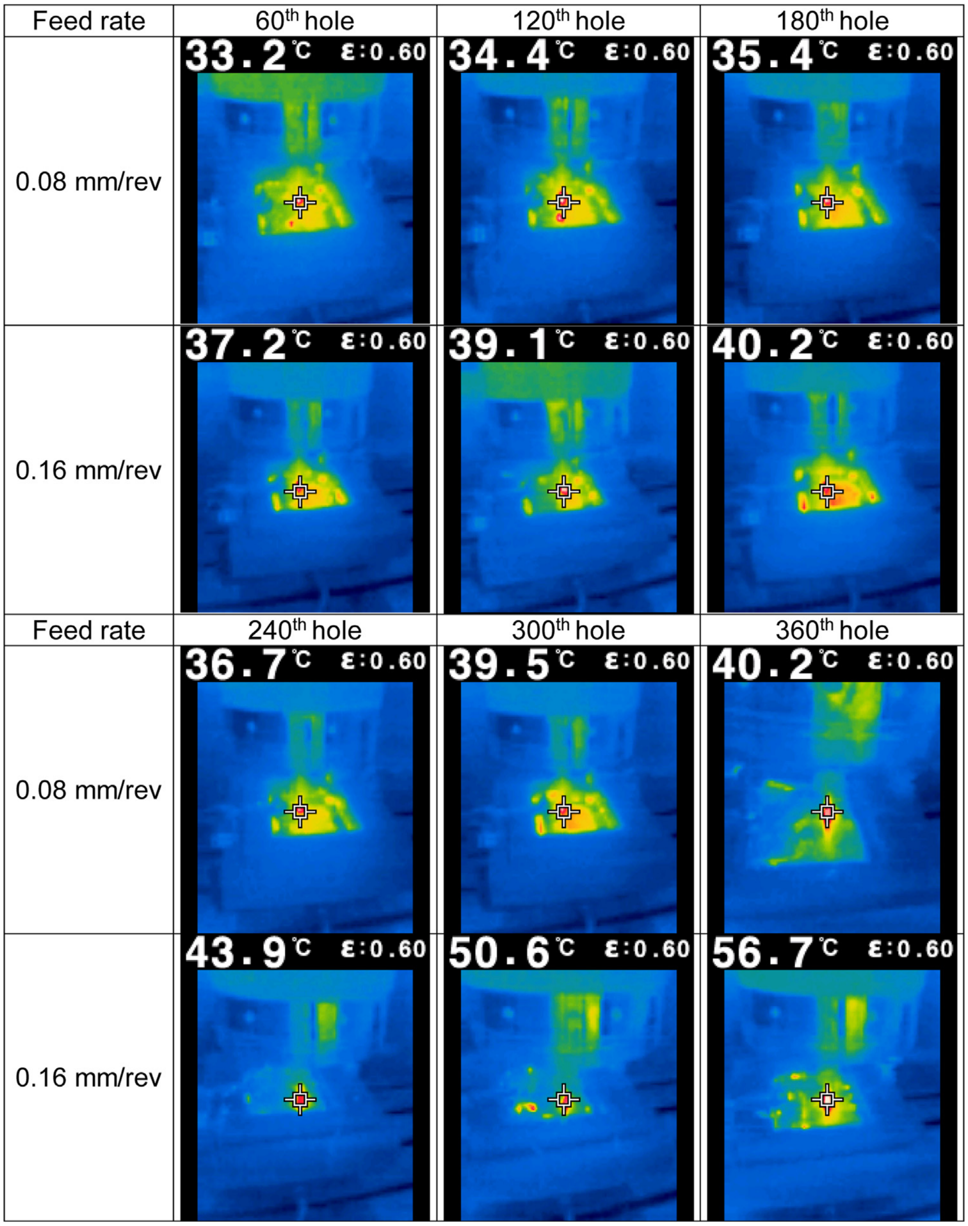

Fig. 8 – Temperature change with number of holes.

well. At 0.08 mm/rev feed rate, the temperature measured as 40.2 °C in the 360th hole, while at the feed rate of 0.16 mm/rev, the temperature was 56.7 °C in the 360th hole.

3.3. *Tool wear*

Because of rapid wear and failure of cutting tool, it is possible to encounter some problems like short life cycle of tool, poor hole quality, low cutting efficacy, and high machining costs [37]. In the tool wear tests performed at dry and cryogenic conditions at a constant 80 m/min cutting speed and 0.08 and 0.16 mm/rev feed rates, the wear on the drill is visualized with a digital microscope. An image was taken from a drill in every 120 holes (Fig. 9). In dry drilling condition, excessive adhesion of AZ31 magnesium alloy on the drill was observed. In tests performed under cryogenic condition, the adhesion is very low, while at high feed rates the adhesion is almost negligible. Tool wear tests conducted under dry condition resulted in greater wear than those in cryogenic condition. In addition, at higher feed rates in both cutting conditions, more wear occurred compared to the tests conducted at low feed rate.

3.4. *Chip morphology*

Chip shape is the most significant factor affecting the smoothness of a metal cutting process. The process will be smooth as long as chips are broken and fragmented into small pieces. However, as the chips get larger, they cannot move well via the flutes of the drill, and this increases torque requirements. Moreover, it may cause the drill bit to break. Yet, many ductile materials do not break but form continuous chips during drilling. In order to show the chip shape depending on cutting

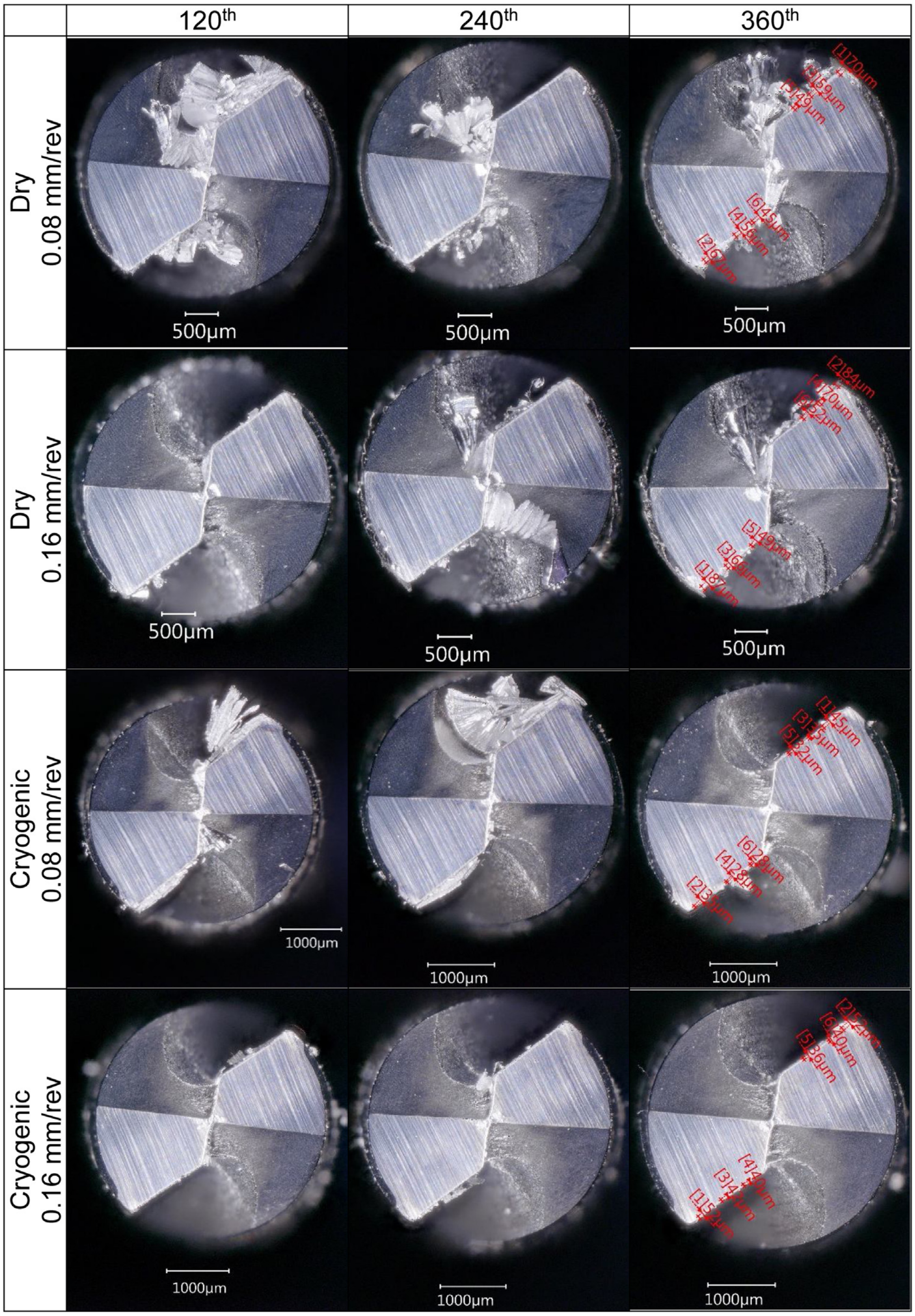

Fig. 9 – Comparison of the tool wear observed at dry and cryogenic cutting process.

parameters (cutting speed and feed rate), number of subsequent holes, dry and cryogenic conditions [43], the chips were collected and visualized in a digital microscope (Keyence VHX-900F) after each experiment. Specimens were represented by digital microscope by selecting samples from the collected chips. Chips formed at 40 and 120 m/min cutting speeds and 0.1, 0.15, 0.2 and 0.25 mm/rev feed rate in dry and cryogenic conditions are given in Fig. 10. Both cutting speed and feed rates have a dominant effect on chip formation. As the cutting speed increases, chips are formed longer in both dry and cryogenic cutting conditions. With increasing feed rate, the chips become shorter in both cutting conditions. The chips formed in cryogenic condition are shorter than those in the dry cutting condition. In the tests carried out under dry cutting condition, with the cutting speed increased from 40 m/min to 120 m/min, more temperature was generated during the cutting process (Fig. 7). In the tests performed at high cutting speed, the increased temperature during cutting caused the chip to emerge in a longer form. The fact that the chips are longer shows that the chips is in ductile form. Previ-

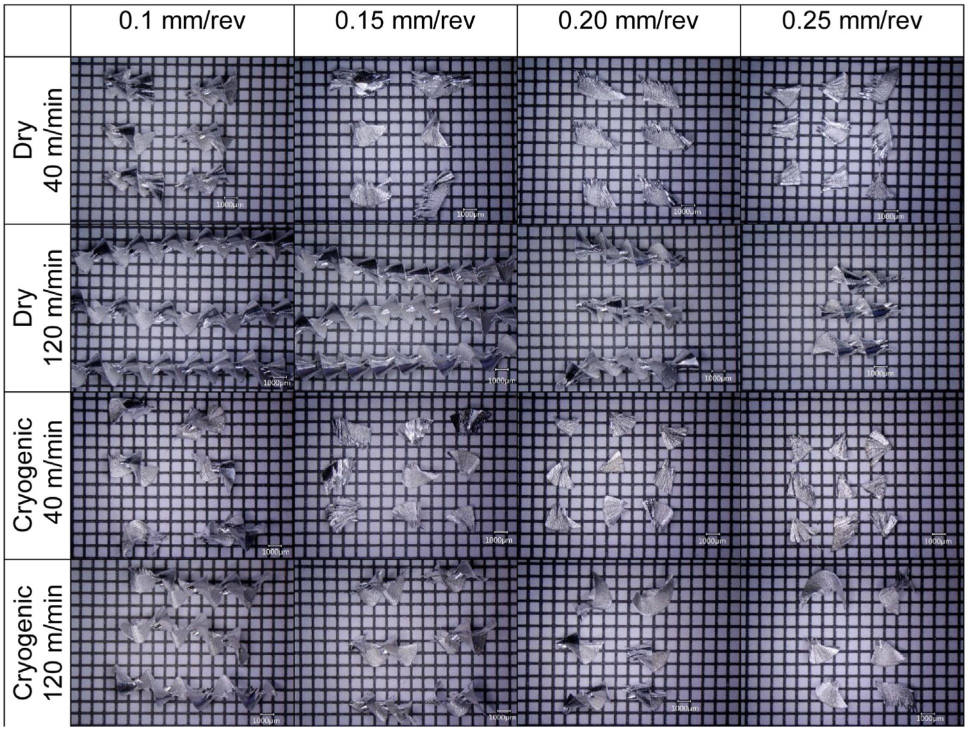

Fig. 10 – Photographs of chips obtained at different drilling conditions.

ously, similar findings are reported in the literature [30,43]. Because the cutting temperature did not greatly increase in the tests performed under cryogenic condition at cutting speed of 120 m/min, the chips were generated in a much shorter form compared to those formed in the dry cutting. Although it is mentioned in the literature that magnesium alloy has a tendency to ignite at higher cutting speed, no such situation has been observed in this study.

360 holes was drilled on AZ31 magnesium plate at a constant cutting speed of 80 m/min and 0.08 and 0.16 mm/rev feed rate. Chips were collected in each 120 holes. This series of experiments were performed under both dry and cryogenic cutting conditions. The chips formed after the experiments are categorized and given in Fig. 11. With an increase in the number of holes, shape of the chips also changes. The chip shape for the first 240 holes in dry cutting condition was in the form of a spiral cone which was more easily removed. After the 240th hole, depending on an increase in the thrust force and wear, the chip thickness decreased as the chip pitch increased, thus ribbon chips were formed. In the tests performed in cryogenic environment, shorter chips are formed because the material becomes brittle. Tool wear was the fundamental reason for the variation of chip shape based on the increase in the number of holes [43]. Under cryogenic condition, a small amount of discoloration was observed in the chips formed at 0.16 mm/rev feed rate for the 360th hole. By performing drilling tests in a cryogenic environment, the material changes from ductile mode to brittle mode. Brittle material becomes more rigid and harder. Much more power is needed to drill the harder material. In Section 3.1 it was mentioned that tests carried out under cryogenic condition generated more thrust force than under dry cutting. More plastic deformation occurred during drilling of the hardened material under the cryogenic process. This high plastic deformation was reflected in the form of the chip.

4. Conclusion

The effect of dipped cryogenic approach and dry condition on thrust force, temperature, tool wear and chip formation in drilling of AZ31 magnesium alloy was investigated.

- In the tests performed under both dry and cryogenic conditions, the thrust force decreases (about 16 %–27 %) with increasing cutting speed; and the thrust force increases (about 34 %–54 %) with an increase of the feed rate. Drilling tests performed in the cryogenic environment increase the thrust forces by 32 %–39 % compared to dry cutting. In tests performed under dry and cryogenic conditions, in addition, the thrust force tends to increase with increasing number of holes.
- Temperatures in the drilling proses increased linearly with increasing both cutting speed and feed rate. Cutting speed has a dominant effect on heat formation. Spark and chip ignition were not observed even at high cutting speeds during dry cutting. An increase in the number of holes increases the temperature.
- In dry drilling condition, the AZ31 magnesium alloy is in an excessive amount of adhesions to the drill. In tests performed under cryogenic condition, the adhesion is very low, while at high feed rates it is almost negligible. Tool wear tests conducted under dry condition resulted in greater tool

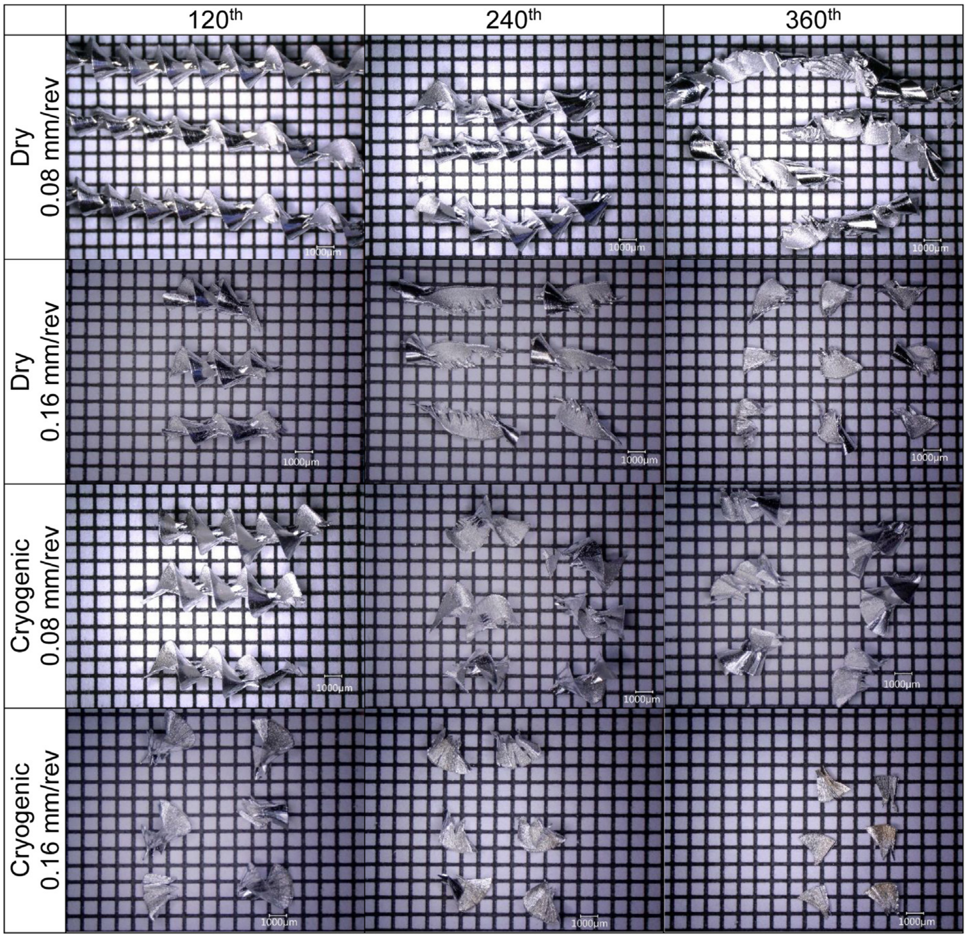

Fig. 11 – Chip change with number of holes.

wear. In addition, at higher feed rates in both cutting conditions, more wear occurred.

- It is observed that the cutting speed is dominant on the chip formation and the chips formed in cryogenic condition are shorter than the chips formed in dry cutting condition.

Conflict of interest

The authors declare no conflict of interest.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.jmrt.2020.01.038.

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