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An FEM Analysis with Experimental Validation to Study the Hardness of In-Process Cryogenically Cooled Drilled Holes in Mg AZ31b

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Abstract

The goal of a number of many recent studies is to assess the potential of cryogenic cooling in improving the sustainability of manufacturing processes. One prime interest is the enhancement of surface integrity properties of newly machined surfaces. In this paper, we study the effect of liquid nitrogen cryogenic cooling on the surface integrity of drilled holes in magnesium AZ31b using an indexable drill. Utilized are both experimental techniques and numerical (FEM) simulations. Specifically, liquid nitrogen at cryogenic temperatures was pumped through the drill's built-in through spindle coolant holes. HV micro-hardness measurements were performed on the newly machined holes surfaces. Furthermore, the process was modelled in FEM via an appropriate convective cooling approximation superimposed on the drilling process. Outputs of the numerical model such as strains, strain rates, and temperatures were used to predict the grain size at the surface of the holes and, consequently, hardness. Hardness values (determined from both experiments and FEM analyses) with different feed rates for dry drilled holes were compared against those from cryogenically cooled holes with the latter being found to have higher hardness values when compared to non-cooled ones.

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Keywords: Cryogenic; Drilling; AZ31; FEM; Vicker Hardness

1. Introduction

The significant advantages of cryogenic cooling during machining processes in reducing tool wear and, consequently, reducing production cost have been well established (e.g., [1]). Another effect of cryogenic cooling machined products is corrosion performance enhancement of [2]. More recently, researches started to study the enhanced surface integrity parameters that cryogenic cooling leaves on newly machined surface.

One of main enhancements is surface microstructural refinements. Such grain refinements were proved to occur in different fabrication processes such as burnishing [3]. It is believed that these microstructural developments take place just below the surface and bulk material is reached within a short depth below the surface. The depth of the microstructural refinements can be optimized by altering the process parameters (spindle speed, feed …) [4]. Moreover, A fine grained featureless layer on the surface similar to "white layer" on machined steels, was formed due to recrystallization occurring on the machined surface of Magnesium alloy under cryogenic conditions [5].

Another surface integrity parameter is surface roughness. In [6], the authors proved that the application of cryogenic cooling in turning process lead to better reduction in surface roughness and dimensional deviation compared to dry machining.

Hardness is another important surface integrity parameter studied in literature. Similarly to other properties, hardness varies with the depth from machine product surface. After machining, hardness at the surface is significantly increased from that of the bulk material. This hardness increase is about 15% higher in cryogenic conditions [7]. Other surface integrity parameters induced by cryogenic cooling application mentioned in [7] are: large intensity of basal plane on the machined

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surface and 10 times larger compressive areas in residual stress profiles.

Moreover, there is ample evidence in the literature [8] supporting the idea that refined grain structure at the surface and thus enhanced surface properties leads to a better product functional performance, product life and product sustainability. Furthermore, surface hardness was related in [9] to microstructure and grain size refinement and was classified as a salient integrity parameter associated with surface integrity. In turn, surface hardness was correlated to such product life-determining properties as fatigue and wear resistance. Therefore, in this work surface hardness was chosen as a base parameter for product surface integrity qualification.

Magnesium alloys are light weight alloys used heavily in many aerospace and automotive applications mainly because of its well-known high strength to weight to ratio. The effect of cryogenic cooling on surface integrity properties during machining of Magnesium alloys, specifically Mg AZ31b, is studied before. The main operations investigated on AZ31b in literature were turning (e.g., [7]) and burnishing (e.g., [5]). Regarding cryogenic drilling, it was studied along with turning and grinding in [10] but the material was Ti alloys and not magnesium. In [10] it was proven that superior quality surfaces and more precise holes can be developed in holes drilled. In this paper the material used is Mg Az31b and the operation is drilling under both dry and cryogenically cooled conditions.

Most approaches followed in literature were experimental ones and very few were numerical ones. The evolution of relatively low cost numerical simulation compared to experimental setups along with accurate results in the last decade encouraged the simulation of machining processes. A fair number of studies succeeded in simulating drilling process. However, the modelling drilling with cryogenic cooling to study the surface integrity properties is not yet investigated to our knowledge.

Marusich et. al. [11] developed a thermo-coupled FEM model for drilling (using *AdvantEdge*), an experimental validation was performed and good results were achieved. Mieszczak and Lis [12] presented an ABAQUS drilling FEM model that focused on calculating the temperature profile during common drilling operations. Gardner and Dornfeld [13] simulated the drilling process using the FEM software DEFORM and showed that it is possible to capture most of the process parameters associated with drilling. In [14], Pu succeeded in studying the surface integrity of in turning processes using 2D Deform model. In this study the commercial software DEFORM 3D was chosen as the FEM software because of its capabilities in capturing microstructural changes in thermo-mechanical models.

In this work, the authors study the effect of in-process cryogenic cooling along with other processing parameters on the surface hardness of drilled holes in magnesium AZ31b. An experimentally validated 3D FEM model for cryogenic drilling was developed using DEFORM software. Hardness was calculated numerically and measured experimentally. Different feed rates for dry and cooled drilling cases were analysed.

2. Experimental

2.1. Cutting setup

The tool used was KENNAMETAL indexable drill (25mm diameter) with thru-spindle holes for cooling purposes with inserts. The drill tool body part number is DFT0984R2SSF100. The inserts were carbide coated inserts (part number DFT05T308-LD, a Drill Fix™ DFT™ and insert grade KC7225). The construction of the insert is shown in Figure 1 [15]. Table 1 lists the values of the salient geometric features of the insert.

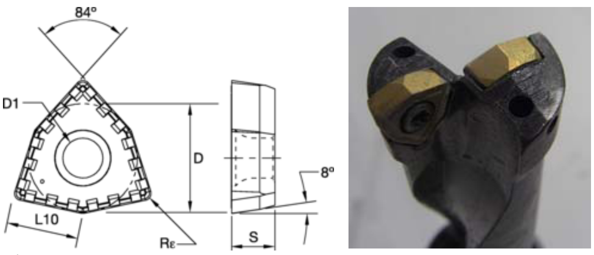


Figure 1. Insert DFT05T308-LD Geometry [15] (left); inserts attached to the tool holder where can also be seen two through-the-tool-coolant-holes (right).

Table 1. The values of the insert's salient dimensions [15]

Dimension	L10	D	D1	S	Rε
Value (mm)	5,29	8,00	3,40	3,75	0,80

In the experiment, the tool was held fixed while the work was rotating being held in the spindle of a Haas VF2 vertical machining center. This arrangement was required to facilitate the cooling fluid to work as conceived. The drilled holes were 10mm in depth. This inverted setup is reminiscent of that used by Hamade and Jawahir in [16]. The downward thrust force was measured using a KISTLER fixed plate dynamometer placed underneath the work.

2.2. Liquid Nitrogen cryogenic cooling setup

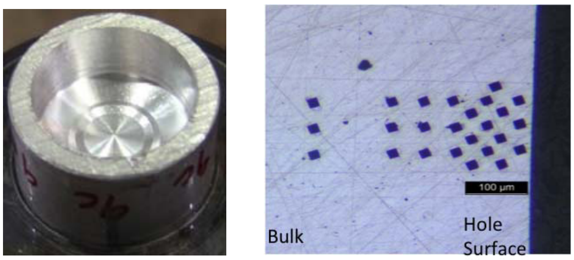
In the setup used (Figure 2), cryogenic liquid Nitrogen was stored in a tank at pressure of 100 psi (689 475 pa). The flow meter allows some control of flow with two settings: low and high. Only low setting was used in this study giving a mass flow rate of approximately 10 g /sec of Nitrogen. Figure 3 shows the cryogenically cooled drilling setup in action. The setup is inverted where the tool is on the bottom, the workpiece on the top and rotates being attached to the spindle. Liquid nitrogen was channelled from the tank to the through-the-tool-coolant-holes and from there to the work where the freezing action takes place prior after which drilling commences.

Fig. 2. Liquid Nitrogen cryogenic cooling setup with the storage tank can be seen at the bottom of picture

Figure 3. Photograph showing the cryogenically cooled indexable drill engaged with Mg work.

2.3. Hardness measurements

HV micro-hardness tests were performed using a Vickers setup (Sun-Tec Corporation, Novi, Michigan) on the drilled holes as shown in Figure 4 where a typical drilled hole is shown in (a). A typical micrograph of Vickers hardness indentation marks is shown in (b). The hardness was measured at three locations in lines at different distances away from the hole inner surface starting from as close as 30 μm from the surface and reaching a few hundred μm into the bulk material.



(a) (b)

Fig 4. (a) Example of a drilled hole; (b) Micrograph of Vickers hardness indentation marks (hole surface is to the right side and bulk material is to the left).

3. FEM Model

3.1. Parts and Meshes

All The different parts of the model shown in Figure 5 are the tool, the inserts, and the work-piece. The tool and inserts were modelled as one rigid (un-deformable) body while the workpiece was modelled as a visco-plastic body.

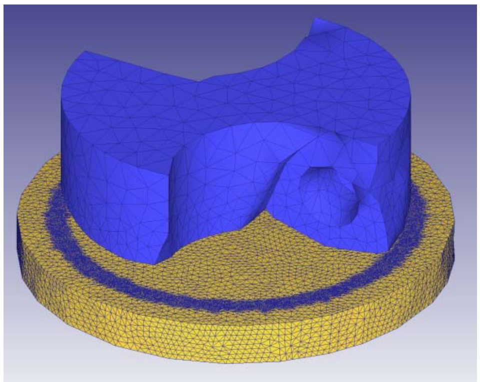


Fig. 5. The meshed tool and the work piece from DEFORM™.

The tool and insert geometry should be imported as FEM input exactly as per Fig 1 and Table 1 because small misrepresentations in the geometry may lead to significant deviations in estimated results. Therefore, the 3D CAD model of the tool and insert were supplied by the vendor (KENNAMETAL) and are displayed in Figure 4. Only a portion of the tool holder was used in the model (10 mm thick at the lower tip holding the inserts). The AZ31b work was modeled as a cylinder 30mm diameter and 3mm in depth. The different parts of the model shown in Figure 1 are the tool, the inserts, and the work-piece. The tool and inserts were modelled as one rigid (un-deformable) body while the workpiece was modelled as a visco-plastic body.

The tool and insert geometry should be drawn exactly because any difference may lead to erroneous results and geometric misrepresentation. Therefore, the

3D CAD drawings of the tool and the insert were requested from the supplier (KENNAMETAL). However, not all the tool was used in the model but rather only a cut of 10 mm of the lower tip was imported to the FEM solver because the rest is not of interest. The AZ31b work used was a cylinder 30mm diameter and 3mm in depth.

3.2. Material Modeling

The material used for the tool was steel AISI 1075, while the insert material was carbide (15% cobalt). As for the workpiece, a new material was created with the properties of Magnesium AZ31b. The mechanical and thermal characteristics of Mg AZ31 are adopted from [10-12] and are as listed in Table 2. The material model for Mg AZ31 is adopted from [13,14] Flow stress is related to strain and temperature according to the following equation:

$$\dot{\bar{\varepsilon}} = A\left[\sinh\left(\alpha\bar{\sigma}\right)\right]^{n}\exp\left[-\Delta H/\left(RT\right)\right] \quad (1)$$

Table 2: Material properties of AZ31b used in the model

Property	Value
Elastic Modulus [17]	44830 MPa
Poisson's ratio [17]	0.35
Coefficient of thermal expansion [17]	$2.65\text{x}10^{-5}$
Thermal conductivity [18]	96 N/(s K)
Heat capacity [18]	2.43 N/(mm^2 C)
Emissivity [18]	0.12
Material constant A [19]	27.5 s^{-1}
Material constant α [19]	0.052 MPa^{-1}
Activation energy ΔH [19]	130 kJ/mol
Material constant n [19]	1.8
Universal gas constant R [19]	8.314 J/(kg K)

3.3. Friction and Boundary Conditions

The boundary conditions defined were a fixed boundary on the outer surface of the work and a heat transfer condition for all the surfaces with the environment.

The shear friction factor at the contact interface between the tool and the work is an important parameter to define and it is directly dependent on the temperature. By performing sensitivity analysis with experimental validation a friction factor of 0.5 was used. A constant thermal heat transfer coefficient equal to 40 N/sec/mm/C was defined also at the interface. A time step of 0.0006 was used in the simulation.

3.4. Cryogenic Cooling

In experimental setup, cryogenic liquid nitrogen was applied from the two thru-the-spindle-cooling holes found in the tool. In FEM, the effect of this cryogenic cooling on the work was modelled by using a uniform, rapid heat transfer with a convective heat coefficient according to

$$\dot{q}_c = h_c(T - T_{\min}) \quad (2)$$

Where the heat flux is related to
h_c convective heat transfer coefficient
T current temperature
T_{min} minimum coolant temperature

The assigned values for h_c were 2 N/(mm.s.C) as per [19] and -170°C for T_{min} which is found to be a representative temperature for the cryogenic effect at the surface.

3.5. Grain size and hardness estimates

In order to numerically predict the hardness of the drilled holes, the average grain size (d) was calculated using

$$\ln d = 9 - 0.27\ln Z \quad (3)$$

Where Z is the Zener-Hollomon parameter and the constant values in the equation for AZ31 were obtained from the literature [20]. The Zener-Hollomon parameter is related to temperature and strain rate by

$$Z = \dot{\varepsilon}e^{\frac{Q}{RT}} \quad (4)$$

with Q being the activation energy and R the universal gas constant as per Table 1. Then the hardness is retrieved from the grain size as per Equation 5 which was derived from experimental measurements in [21].

$$Hv = 40 + 72d^{-0.5} \quad (5)$$

4. Results

4.1. FEM Model Validation

To validate the results of the FEM model, the simulated downward thrust forces against drilling are compared against experimentally measured forces. The average force after tool engagement was calculated and plotted. One can observe from Figure 5 that the experimental force measurements and FE simulation results are in a good agreement. Similarly, the experimental average torque was calculated and compared against torque determined from the FEM and good agreement was reached. The comparison was conducted also for both cryogenic and dry case as shown in Figure 5. Moreover, if we compared the thrust forces of in dry drilling, Figure 6, to the cryogenically cooled one we observe a small reduction in the cutting forces due to the friction reduction effect caused by the liquid nitrogen. This fact helps in reducing production costs.

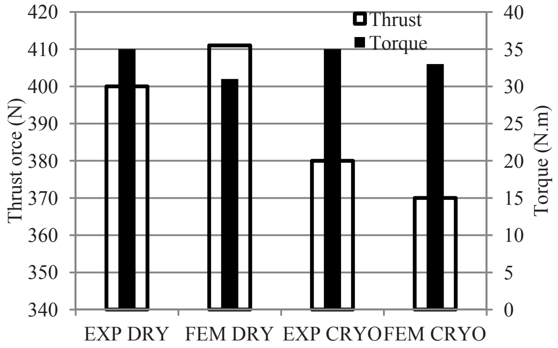


Fig 6. FEM-Simulated and experimental forces and torques for dry and cryogenic (all cases at RPM=512; f=0.2 mm/rev)

4.2. Test Matrix

In order to study the effect of both feed rate and cooling, different case studies were designed (as listed in Table 3). A constant rotational speed of 512 RPM was used in all cases.

Table 3. Test matrix of Experimental and FEM runs

Feed (mm/rev)	Cases	Analyses
0.05	Cryo/Dry	EXP
0.1	Cryo/Dry	FEM/EXP
0.2	Cryo/Dry	FEM/EXP

4.3. Effect of Cryogenic Cooling and Feed On Surface Hardness

Figure 7 is a plot of the experimentally measured micro-hardness, in Vickers (HV), for three values of feed: 0.05, 0.1, and 0.2 mm/rev (all at 512 RPM). From figure, it can be seen how drilling, in general, and cryogenically cooled drilling in particular would induce higher hardness (HV) values as compared with bulk hardness values (measured to be about, or just under, 60 HV). Moreover, one can see how the in-process cryogenically cooled holes have higher hardness values as compared with dry drilled holes in all cases. The hardness values plotted in Figure 7 are the average values of three hardness measurements taken as close as 30 micrometers away from the hole surface (as described in Section 2.3 above).

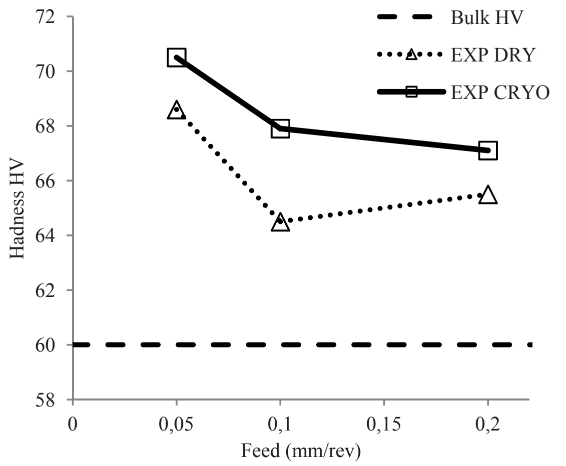


Fig 7. Experimental surface hardness (HV) for 3 values of feed: 0.05, 0.1, and 0.2 mm/rev (RPM=512)

Figure 8 is a plot of experimental and FEM predicted surface hardness (HV) for different feeds (RPM=512). From the figure, the FEM hardness results for cryogenically cooled cases are generally in good agreement with experimental measurements. This is true regarding the effect of feed (hardness decrease with feed increase) and effect of cryogenic cooling (surface hardness values of cooled holes are higher than non-cooled one). Differences of up to 10 HV are observed between experimental measurements and FEM predictions for cryogenic drilled holed (typically larger values in FEM simulations).

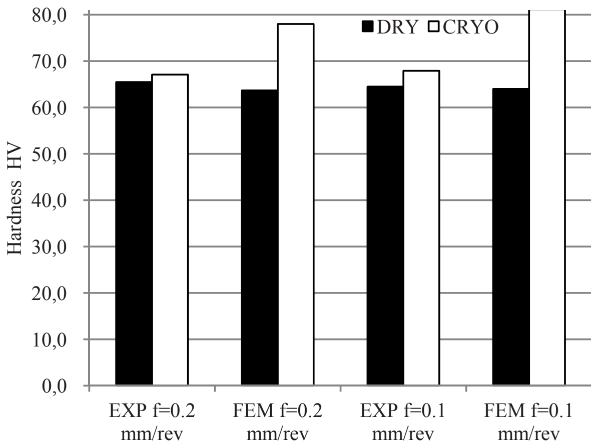


Fig 8. Experimental and FEM-Simulated surface hardness (HV) for 2 values of feed: 0.1 and 0.2 mm/rev (RPM=512)

5. Summary

A combined experimental and numerical (FEM) study was performed to study the surface hardness of in-process cryogenic (liquid nitrogen) cooling while drilling in Mg AZ31b. Micro-hardness (Vickers) measurements were made experimentally at the surface of the drilled holes for 3 feed values: 0.05, 0.1, and 0.2 mm/rev (all at 512 RPM). An FEM model was also developed the results of which compare reasonably well with the experimentally measured hardness values. Such values showed appreciable increase in surface hardness for cryogenically cooled holes compared with those drilled in the dry condition (with both dry and cryogenically cooled hole surfaces being appreciably harder than that of bulk Mg).

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