THERMAL ANALYSIS OF CRYOGENIC MACHINING OF MG ALLOY USING FEM

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ABSTRACT

Being a novel material by having high strength to weight ratio, magnesium (Mg) alloys have attracted researchers working on variety of applications such as, automobile parts, aerospace and most recently in biomedical implants. Surface Integrity (SI) of any manufactured products has a significant effect on its functional performances, as well as corrosion resistance. It has been noticed that, the temperature is the most vital factor that influences all SI factors. The present study is to understand the temperature distribution occur in the Mg alloy which is machined under different operating condition i.e., dry and cryogenic machining. A finite element model (FEM) is used for the analysis. The investigation shows that, the distributions of temperature in the work piece, chip and tool is in the form of isothermal lines. It also shows that highest temperature reached on the machined surface is significantly reduced under the cryogenic condition. Results have found to be in good agreement with the experimental results.

Keywords: cryogenic machining, finite element analysis, magnesium alloy.

INTRODUCTION

Magnesium (*Mg*) alloys have attracted researchers all around the world working in transportation industry and aerospace applications due to its light weight [1]. Recently Mg alloys have found new applications in biomedical sector. They have emerged as novel biodegradable materials which can be used in biomedical implants [2]. However, their applications are seriously restricted in biomedical implants due to their unsatisfactory corrosive behavior in saline water environment or body fluids. In a study, it has been seen that it is required for an implant to hold its strength for at least 12 weeks so that fractured bone can have sufficient time for healing. But Mg based implants fails within 3 weeks of implantation because of high corrosion rates occurred in human body environment [3-4]. Therefore controlling the corrosion rate of Mg alloy in human body environment is a very important factor for using it in biomedical implants.

Surface integrity (*SI*) factors such as grain refinement, microstructural changes, residual stresses and crystallographic planes is found to have an impact on the corrosion rate of the machined products [5-7]. Temperature is one of most important factor which influences all types of SI factors on the machined surface. There have been various literature published which shows how temperature can be the actual factor which can control all the types of SI [8-10]. As machining involves severe plastic deformation and friction, temperature at the point of contact of tool and work piece becomes very high. This increase in temperature modifies the *SI* at the machined surface such as grain growth, microstructural morphology etc. It has been observed that due to increase in temperature the white layer on the machined surface become very thin [11-13]. This white usually consists of very fine grain which were formed due to sever plastic deformation occurred during machining process. But as during machining temperature also rises and because of that grain growth will take place which indeed the cause of reduction of thickness of the white layer. This white layer on the machined surface also acts like a barrier to corrosion rate. Hence, controlling *SI* by a novel manufacturing technique with cryogenic liquid i.e. cryogenic machining can be a very handy and efficient way for producing Mg alloys with high corrosion resistances.

Studies have been done before on the temperature distribution on the machined surface and tool during machining. However there is lack of literature which discuss about the thermal fields during the different machining process i.e. dry and cryogenic machining.

Therefore a systematic study of temperature distribution on the machined surface, subsurface and tool is still required for the better understanding of the subject. The current paper aims to investigate the thermal effect of cryogenic machining on the machined surface of the Mg alloys by developing a numerical method using finite element modelling (FEM) techniques to predict temperature distribution on the machined surface, chip and tool surface induced during machining under different processing conditions.

Finite element model (FEM) for Mg alloy

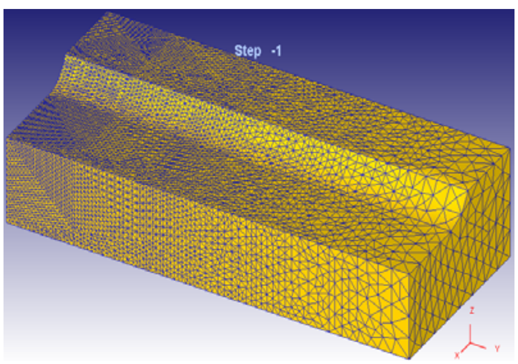
Finite element modelling (FEM) has been used widely in machining to reduce the need for extensive experiments and help researchers to better understand the metal cutting mechanism though the prediction of information near the cutting tool that cannot be easily measured, such as strain, strain-rate and temperature. A FE study for machining of AZ31 Mg alloy was developed and calibrated using the experimental data.

Finite model set up

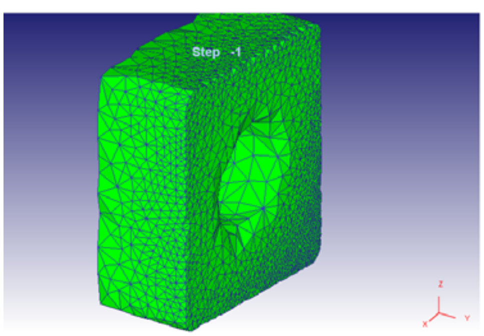
The commercial FEM software DEFORM-3D, a Lagrangian implicit code, was used to simulate the orthogonal cutting process of AZ31 Mg alloy. The workpiece was meshed with 38841 elements and 8889 nodes. The element geometry was choosed to be tetrahedral in the case of workpiece. The element density around the cutting edge, along the machined surface and in the machined chip was set to be much larger than at the other location as shown in Figure-1(a). The work piece material was assumed to be elastoplastic.

The tool was meshed with 21075 elements with 4874 nodes and it was assumed to be rigid but conduct heat. The element geometry was choosed to be tetrahedral. The meshed geometric model for the tool can be seen in Figure-1(b). For thermal analysis, the temperatures at the bottom and left sides of the workpiece as well as the top and right sides of the cutting tool were set to equal to the room temperature, Troom, which was 20 °*C*.

The top and right sides of the workpiece as well as the left and bottom sides of the cutting tool were allowed to exchange heat with the environment; the convection coefficient was taken as 20 *W/(m2K)*, which was the default value for free air convection in DEFORM 3D (normally in the range of 5-25 *W/(m2K)*). The local convection coefficient for the heat exchange can be adjusted to simulate the cryogenic cooling effects.



(a)



(b)

Figure-1. Geometry meshed with FEM (a) Workpiece and (b) Tool.

Material properties

In The physical and thermal properties of AZ31 Mg alloy used in the FE model are listed in Table-1 (Hibbins) [14]. The default values for the uncoated carbide tool (15% cobalt content) in DEFORM were used and also listed in the Table-1.

Table-1. Physical and thermal material properties of AZ31Mg alloy and carbide tool.

Properties	AZ31 Mg Alloy	Cutting Tool
1. Melting Temperature (*K*)	891	5198
2. Young's Modulus (*GPa*)	45	600
3. Possion's Ratio	0.35	0.23
4. Thermal Conductivity (*W/(mK)*)	77+0.096T	82.24
5. Specific Heat Capacity (*J/(kgK)*)	1000+0.666T	5.79
6. Thermal expansion Coefficient (K^{-1})	2.48x10-5	6.3x10-6

Flow stress model

The Johnson–Cook constitutive equation was implemented in the FEM based software that is DEFORM 3D to model the material behavior of AZ31B Mg alloy during machining. Equation 1 shows the Johnson-Cook constitutive equation.

$$\sigma = (A + B.\varepsilon^n)[1 + C.\ln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)][1 - (\frac{T - T_{room}}{T - T_{room}})^m] \quad (1)$$

where σ is the equivalent flow stress; ε is the equivalent plastic strain; $\dot{\varepsilon}$ is the equivalent plastic strain-rate (s^{-1}); $\dot{\varepsilon}_0$ is the reference equivalent plastic strain-rate (s^{-1}); T is the temperature of the work material; T_m is the melting temperature of the work material and T_{room} is the room temperature (20 ºC). Coefficient A is the yield strength (*MPa*); B is the hardening modulus (*MPa*); C is the strain-rate sensitivity coefficient; n is the hardening coefficient and m the thermal softening exponent.

Hasenpouth performed a wide range of mechanical tests of AZ31B Mg sheet where the strain-rates varied from 0.003 s^{-1} to 1500 s^{-1} and the temperature from room temperature to 250 ºC [15]. The average of the two directional values was used as the start values for the Johnson-Cook constants in the FE model.

Friction model

The influence of different tool-chip friction models on FEM results was investigated by *Filice et al.* and it was found that as long as the friction coefficient was well calibrated, both cutting forces and chip morphology could be well predicted independent of which friction model was used [16].

In this study, a simple constant shear friction model is applied

$$\tau = \mu.\tau_o \quad (2)$$

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where τ is the frictional stress between the tool and the chip and work material, τ_o is the shear flow stress of the work material and μ is a friction coefficient.

RESULTS

Maximum temperature at the machined surface

Here we have used it for thermal analysis of magnesium during dry and cryogenic machining. Figure-2 shows the maximum temperature reached at the machined surface during different machining condition that is dry and cryogenic machining. It has been found that maximum temperature on the machined surface during dry machining was predicted to be 137 *ºC* which is in good agreement with the experimental results given by *Pu. et al.* i.e. 125 *ºC* [17].

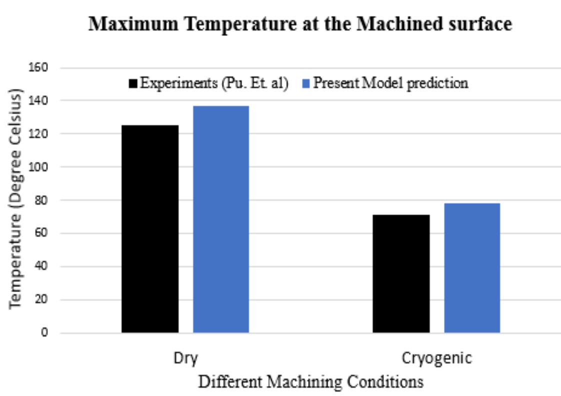
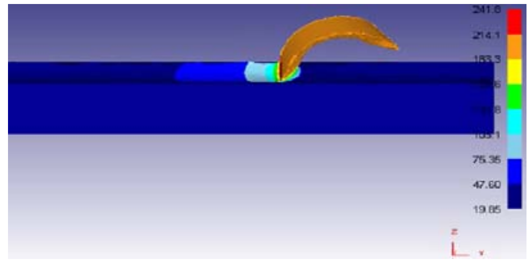


Figure-2. Maximum temperature reached at the machined surface.

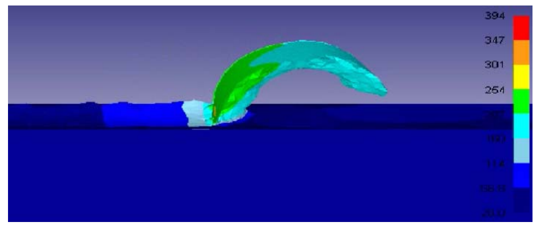
Similarly in the case of cryogenic machining, the maximum temperature at the machined surface predicted by this model is very similar to the results found by *Pu. et al.* experimentally which is shown in Figure-2 [17].

Temperature distribution in the workpiece and chip during different machining process

The temperature distribution in the chip and the newly formed surface on the workpiece during dry and cryogenic condition can be seen in the Figure-3. The temperature gradually drops with increased distance from the start point of the newly formed surface which is quite evident in the Figure-3. In case of dry machining the maximum temperature at the newly formed surface was found to be 137°*C*, which is about 8% higher than the experimental value. While during cryogenic machining the maximum temperature at the machined surface was predicted to be 78°*C* in comparison with 71°*C* which was experimentally determined.

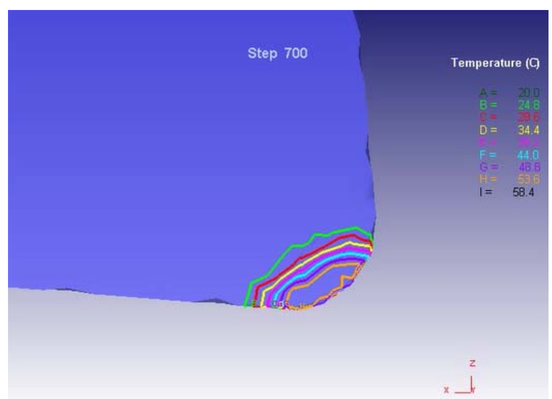


(a) Cryogenic Machining

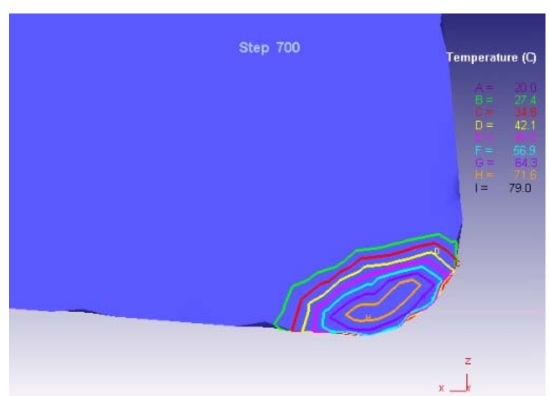


(b) Dry Machining

Figure-3. Temperature distribution in the workpiece and in the chip predicted by the model under different machining condition.



(a) Cryogenic Machining



(b) Dry Machining

Figure-4. Temperature distribution at the surface of the tool in different machining conditions.

Temperature distribution on the tool during different machining process

Figure-4 shows the temperature distribution on the tool surface during machining of Mg alloy. In Figure-4 different temperature zones can be seen by different colored lines. Their respective temperature are shown in the table on the right side of the figure. It is quite clear from the picture that the area near to the tip of the tool has the highest temperature. The highest temperature reached during the dry machining at the surface of the tool is also decreased in the case of cryogenic machining.

CONCLUSIONS

By using this novel technique of using cryogenic medium during machining operation, it is possible to get desirable amount of surface integrity. Finite element method can be a very powerful, reliable and precise method to study the subsurface properties of the machined material such as temperature distribution during machining in different machining condition i.e. dry and cryogenic.

Cryogenic machining can decrease the temperature of the machined surface as well as of the tool which helps in producing good surface finish and integrity. Moreover because of the really low temperature, the adhesion of chips over tool surface will not occur which will increase tool life and machinability of Mg alloy and thus improves economy of production.

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