INVESTIGATION OF THE TEMPERATURE DISTRIBUTION ON THE TOOL AND WORKPIECE DURING CRYOGENIC MACHINING OF MG ALLOY BY FINITE ELEMENT ANALYSIS

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ABSTRACT

Magnesium (Mg) alloys have always attracted researchers for being a light weight metal and now they have also found that it can also be used in the biomedical implants because of its compatibility with human body environment especially AZ31 Mg alloy. Machining of Mg alloy is a challenge itself because of its low melting point and ignition risks. Cryogenic machining can significantly reduce the temperature during machining. Which not only reduces the risk of ignition but also improved surface integrity of AZ31 Mg alloy. In this paper, a finite element analysis has been done to get the temperature distribution occur during the machining of Mg alloy. We have done the analysis in two different machining condition which were dry and cryogenic machining. The results have been validated from the experiments results and are found to be in good agreement. The temperature distribution at the tool surface and at the machined surface of the work piece were shown in the forms of coloured figures. Temperature distribution at the tool surface has been shown in the form of isothermal lines. In case of cryogenic machining, a notable decrease in the temperature was shown by the results.

Keywords: cryogenic machining, temperature distribution, AZ31 Mg alloy, finite element analysis.

INTRODUCTION

The researchers all around the world working in transportation industry and aerospace applications have been attracted towards magnesium (Mg) alloy 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 behaviour in saline water environment or body fluids. In a case 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. Because of greater corrosive nature of the Mg based implants in the human body environment, it fails within three weeks of the implantation [3-4]. Hence this corrosive nature of the implants which are based on Mg should be controlled. After this it can be used in the bio medical applications especially in lower body implants where there is a need of a good combination of high strength and light weight. Surface Integrity (SI) such as microstructures, grains, crystallographic planes, residual stresses of finished product affects the functional performance as well as corrosive performances of it [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 machining zone that is where actual machining is occurring becomes very high during machining. 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 layer 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. Mg alloy also have ignition risk during machining. Also they are very reactive to most of the cutting fluids and water which eliminates the use of cutting fluids .Hence, controlling temperature during machining of Mg alloy by a novel manufacturing technique with cryogenic liquid i.e. cryogenic machining can be a very handy and safe way for producing Mg alloys with high corrosion resistances. Temperature distribution on the machined surface of workpiece and on the tool have been studies before also. 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.

This paper reports the temperature distribution on the machined surface of the workpiece and on the surface of the tool induced during machining by finite element method. The investigation has been done under two different types of machining condition that is dry and cryogenic machining. Hence, it also reports the influence of the cryogenic machining on the temperature distribution occurred during machining of Mg alloy.

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METHODOLOGY

Materials and parameters

The AZ31 magnesium alloy was used as the working material and uncoated carbide for the tool. Their physical properties are listed below in Table-1[14].

Table-1. Physical properties of workpiece and cutting 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+0.66 6T	5.79
6. Thermal expansion Coefficient (K^{-1})	$2.48\text{x}10^{-5}$	$6.3\text{x}10^{-6}$

Here T is used for temperature in Fahrenheit.

Simulation has been done in two different processing condition of machining that is dry machining and cryogenic machining. Orthogonal turning process has been used for the machining process. For both the processing condition the machining parameters, which have been chosen for the study are listed below in the Table-2.

Table-2. Processing condition and machining parameters.

Parameters	Dry Machining	Cryogenic Machining
1. Cutting speed (m/min)	100	100
2. Depth of cut (mm)	0.2	0.2
3. Feed (m/rev)	0.1	0.1

Finite element model for MG alloy

Finite element method have been widely used for machining processes as it can reduce the need of extensive experiments and help researchers to better understand the metal cutting mechanism through the prediction of information near the cutting tool that cannot be easily measured such as grain size, residual stresses, temperature etc. A finite element analysis has been done for the machining of AZ31 Mg alloy. The results are validated by the experimental results performed by Pu et. al. [15].

FEM model set up

There are software available that can simulate the machining process like ANSYS, LSDYNA, ABAQUS, and Deform 3D. Deform 3D in this regard is the best software available and widely used to simulate the problems relating to the machining process like drilling, milling and turning. Here Deform 3D software was used to simulate the machining process.

Cutting process model

Cutting process in metals consists of sever plastic deformation. In this regards, the Johnson-Cook (J-C) constitutive equation is widely used. The flow stress model which was given by them for the metal is given by Equation. (1).

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

Where, *A, B, C, n* and *m* are material constant which depends on the material property hence vary from material to material. σ is the flow stress of the material. ε is the strain and $\dot{\varepsilon}$ is the strain rate. $\dot{\varepsilon}_0$ is the reference strain rate. *T* is the temperature of the material under consideration. T_m is the melting point of the material. T_{room} is the room temperature which is taken as 20 ^{o}C.

The material constants of AZ31 Mg sheet was tested for a wide range of temperature and strain rates by Hasenpouth [16]. The material constant *A, B, C, n and m* which was found by the Hasenpouth and used here in this research are listed below in the Table-3.

Table-3. Material constant for J-C equation for AZ31Mg [16].

Material Constant for J-C Equation	AZ31 Mg Alloy
A (MPa)	163.45
B(MPa)	321.3
C	0.016
n	0.336
m	1.828

Geometry and boundary conditions

Deform 3D has been used to simulate the cutting process. Turning module of the machining was taken for the study. The workpiece is taken in the form of cylinder having diameter 10 mm and length 10 mm. AZ31 Mg was taken as the work piece material. It was mashed with 38800 elements and 8880 nodes. The workpiece material was taken as elastoplastic in nature. The element geometry was considered as tetrahedral. For better and realistic results the density of elements near the cutting zone was taken much larger than the other part of it. The meshed workpiece with elements can be seen in Figure-1.

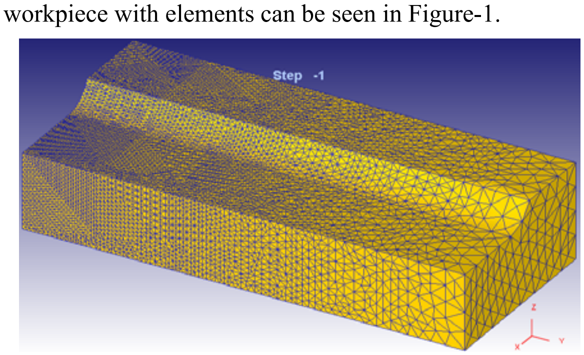

Figure-1. Workpiece meshed with elements.

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The tool was meshed with 21075 elements with 4874 nodes and it was assumed to be rigid but conduct heat. The element geometry was chosen to be tetrahedral. The meshed geometric model for the tool can be seen in Figure-2. Here also, the high density of the elements near the tip of the tool was consider for better results.

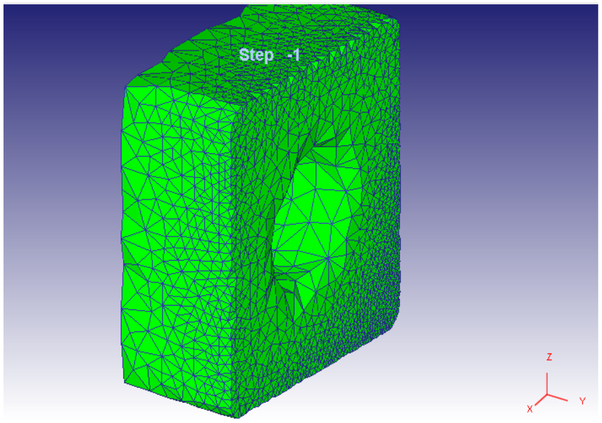


Figure-2. Tool Meshsed with elements.

Bottom face of workpiece is fix and tool can move in Y direction. During dry machining all faces were at 20ºC. For cryogenic machining a special heat convective coefficient (h) was used with tool edge. An iteration method was used to calculate the approximate value of h. The h value was taken according to the cryogenic temperature i.e. -196^{0}C which is the boiling point for the liquid nitrogen at atmospheric pressure.

RESULTS

Maximum temperature at the machined surface

Maximum temperature was predicted by the model for both the machining condition that is for cryogenic as well as for the dry machining. After prediction of the maximum temperature at the machined surface, the values were compared with the experimental values. The experimental values for the same condition was done by the Pu et. al. [15]. According to simulation results, the predicted values for the maximum temperature at the machined surface was found to be 137 ºC during dry machining which is in good agreement with the experimental result which was 125 ºC. Similar scenario was observed for the cryogenic machining also. Experimental value for the maximum temperature at the machined surface during cryogenic was found to be 73 ºC which is also vary comparable to the value predicted by the model here. Figure-3 shows the comparison of the predicted values with the experimental values.

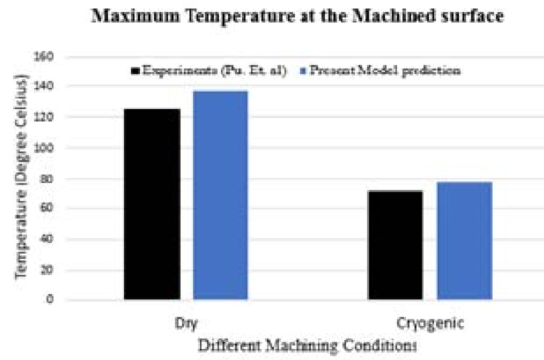
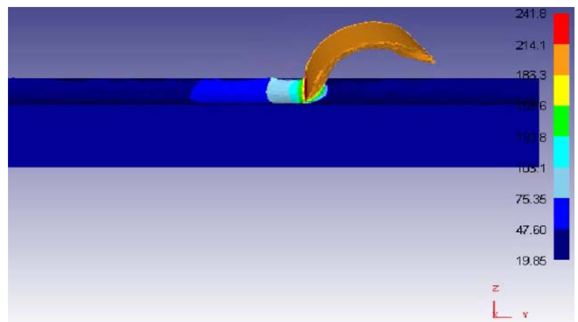
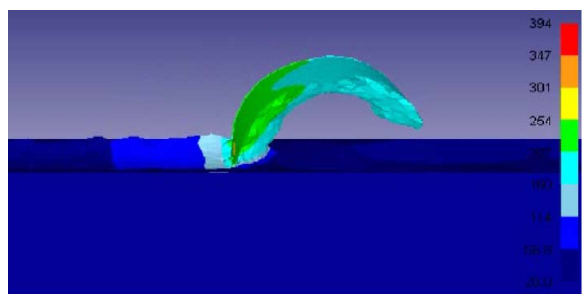


Figure-3. Maximum temperature at the machined surface.



(a)Cryogenic Machining



(b)Dry machining

Figure-4. Temperature distribution in the workpiece and in the chip predicted by the model under different machining condition.

Distribution of the temperature on the workpiece surface and on the chip

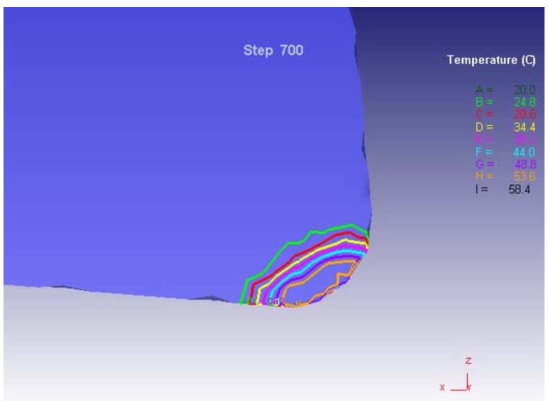
The temperature distribution on the newly form surface that is machined surface and in the chip can be seen in the Figure-4. It clearly shows the effect of cryogenic machining in the form of temperature reduction at the machined surface as well as in the chip.

The temperature gradually drops with increased distance from the start point of the newly formed surface which is quite evident in the Figure-4. 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.

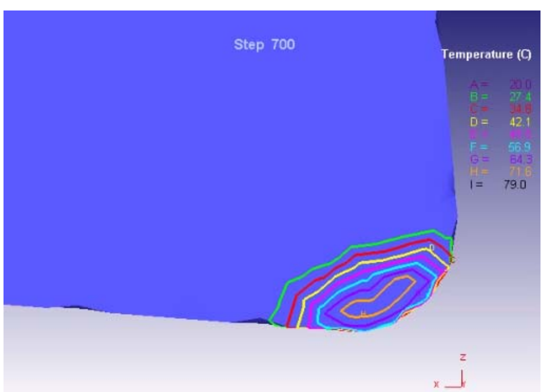
Temperature distribution at the tool surface

Temperature distribution on the tool surface during different machining condition that is dry and cryogenic was predicted in the form of isothermal lines. These isothermal lines are shown in the Figure-5.

The lines have different which indicates to a particular temperature and can be understand easily. 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.



(a) Cryogenic Machining



(b) Dry Machining

Figure-5. Temperature distribution at the surface of the tool in different machining conditions.

CONCLUSIONS

FEM results showed that 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. Around 60% decrease was noticed during cryogenic machining. This decrease due to cryogenic machining will reduce the ignition risk which is always associated with AZ31 Mg alloy. Moreover because of the really low temperature, 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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REFERENCES

[1] Witte F. 2010. The history of biodegradable magnesium implants: A review. Acta Biomaterialia. vol. 6(5). pp. 1680-1692.

[2] Staiger MP, Pietak AM, Huadmai J, Dias G. 2006. Magnesium and its alloys as orthopaedic biomaterials: a review. Biomaterials, vol. 27, pp. 1728–34.

[3] Sankara NTSN, Park S, Lee MH. 2014. Strategies to improve the corrosion resistance of microarc oxidation (MAO) coated magnesium alloy for degradable implants: Prospects and Challenges. Progress in Material Science, vol. 60, pp. 1-71.

[4] Song G, Song S. 2007. A Possible Biodegradable Magnesium Implant Material. Advanced Engineering Materials, vol. 9(4), pp. 298–302.

[5] Villegas J C, Shaw LL, Dai K, Yuan W, Tian J, Liaw PK and Klarstrom DL. 2005. Enhanced fatigue resistance of a nickel-based hastelloy induced by a surface nanocrystallization and hardening process. Philosophical Magazine Letters, vol. 85(8), pp. 427-437.

[6] Wang T. S., Yu J. K. and Dong BF. 2006. Surface nanocrystallization induced by shot peening and its effect on corrosion resistance of 1Cr18Ni9Ti stainless steel. Surface & Coatings Technology, vol. 200(16-17), pp. 4777-4781.

[7] Zhang Y. S.,Han Z, Wang K and Lu K. 2006. Friction and wear behaviours of nanocrystalline surface layer of pure copper. Wear, vol. 260(9-10), pp. 942-948.

[8] Haferkamp H, Boehm R, Holzkamp U, Jaschik C, Kaese V,Niemeyer M, 2001. Alloy development, processing and applications in magnesium lithium alloys. Material Transaction, vol. 42(7), pp. 1160–1166.

[9] Sreejith PS, Ngoi BKA. 2000. Dry machining: machining of the future. Journal of Materials Process Technology. vol. 101, pp. 287–29.

[10] Chan J. S. 2005. Lubrication effect of liquid nitrogen in cryogenic machining friction on the tool chip interface. Journal of Mechanical Science and Technology. vol. 19(4). pp. 936-946.

[11] Wusatowska-Sarnek A., Dubiel B, Czyrska-Filemonowicz A, Bhowal P, Ben Salah N and Klemberg-Sapieha J. 2011. Microstructural Characterization of the White Etching Layer in Nickel-Based Super alloy. Metallurgical and Materials Transactions A. vol. 42, pp. 1-13.

[12] Chandrasekar, S., Y. Guo, C. Saldana and W. D. Compton. 2011. Controlling deformation and microstructure on machined surfaces. Acta Materialia. vol. 59(11). pp. 4538-4547.

[13] Wang, H., Y. Estrin, H. Fu, G. Song and Z. Zuberova. 2007. The effect of pre-processing and grain structure on the bio-corrosion and fatigue resistance of magnesium alloy AZ31. Advanced Engineering Materials, vol. 9(11). pp. 967-972.

[14] Hibbins, S. G. 1998. Investigation of Heat Transfer in DC Casting of Magnesium Alloys. Proceedings of the International Symposium on Light Metals, Calgary, AB, Canada.

[15] Pu Z., Outerio JC., Batista AC., Dillon Jr OW., Puleo DA. and Jawahir IS. 2012. Enhanced surface integrity of AZ31B Mg alloy by cryogenic machining towards improved functional performance of machined components. International Journal of Machine Tools & Manufacture. vol. 56. pp. 17-27.

[16] Hasenpouth, D. 2010. Tensile High Strain Rate Behavior of AZ31B Magnesium Alloy Sheet‖. Master thesis. Department of Mechanical Engineering, University of Waterloo, Waterloo, Ontario, Canada.