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Finite Element Simulation of Residual Stresses in Cryogenic Machining of *AZ31B Mg* Alloy

Z. Pu[a], D. Umbrello[b]*, O.W. Dillon Jr.[a], I.S. Jawahir[a]

[a]*University of Kentucky, Institute for Sustainable Manufacturing (ISM), Lexington, KY 40506, USA*
[b]*University of Calabria, Department of Mechanical, Energy and Management Engineering, 87036 Rende (CS), Italy*
* Corresponding author. Tel.: +39-0984-494820; fax: +39-0984-494673. *E-mail address*: d.umbrello@unical.it.

Abstract

Magnesium alloys are lightweight materials primarily used in transportation industry, and are also emerging as a potential material for biodegradable fixation implants. However, unsatisfactory corrosion resistance largely limits the application of these materials. Residual stresses were reported to have significant influence on corrosion resistance of *Mg* alloys. In this study, a finite element model was developed to simulate the residual stresses in cryogenic machining of *AZ31B Mg* alloy. After calibration using experimental data, numerical simulations were conducted to study the influence of cutting edge radius and cooling method (dry vs. cryogenic) on residual stresses. The model can be used to establish proper cutting conditions to induce compressive residual stresses to enhance the corrosion resistance of *Mg* alloys.

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1. Introduction

Magnesium alloys are lightweight materials with increasing applications in transportation industry, and are also emerging as a potential material for biodegradable fixation implants [1]. These alloys can be safely absorbed by human body after the fractured bone heals itself [1]. However, unsatisfactory corrosion resistance limits the application of these materials to a large extent. Surface integrity induced by manufacturing processes has been found to have significant influences on the corrosion resistance of *Mg* alloys [2]. Residual stress is one of the most critical influencing factors on the performance of components made from materials. The high compressive residual stress generated in the subsurface via a deep rolling process was claimed to reduce the corrosion rate of a biphasic magnesium-calcium alloy by a factor of approximately 100 [3]. Compressive residual stresses induced by cryogenic machining [2], cryogenic burnishing [4] and laser shock peening [5] were also claimed to improve the corrosion resistance of magnesium alloys.

Due to their remarkable influence on corrosion resistance, residual stresses generated in the machined workpieces need to be controlled. In addition to experimental studies, there is a great need for developing predictive models to simulate the distribution of residual stresses on machined surface and sub-surface so that proper machining conditions can be selected. Finite element (FE) modeling has been used successfully to predict residual stresses induced by machining [6, 7]. However, there are limited studies on simulating residual stresses in machining magnesium alloys. The influence of cryogenic cooling on residual stress distribution has not been simulated by researchers. It is the aim of this paper to stress these issues. The influence of cutting edge radius will also be simulated.

2. Experimental Work

2.1. Experimental procedure

In order to calibrate and validate the FE model, orthogonal machining tests were conducted on *AZ31B*

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Mg alloy under both dry and cryogenic conditions. The composition of the workpiece material is shown in Table 1. The initial hardness is 52.3 HV. The details of the experimental study were reported elsewhere [2]. The machining tests were conducted on a Mazak Quick Turn-10 Turning Center using uncoated carbide tools with TNMG 432 geometry. For cryogenic machining, an Air Products ICEFLY® system was used to spray liquid nitrogen to the machined surface from the clearance side of the cutting tool as shown in Figure 1. Forces and temperatures were recorded during the machining tests. The machining conditions tested are shown in Table 2.

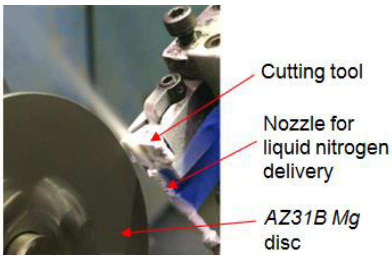

Fig. 1. Experimental setup for cryogenic machining [2].

Table 1. Nominal composition of *AZ31B* magnesium alloy (wt. %)

Al	*Zn*	*Mn*	*Mg*
2.5 - 3.5	0.7 - 1.3	0.2 – 1.0	balance

Table 2. Experiment matrix (V = 100 m/min; f = 0.1 mm/rev) [2].

Test	**Cooling Method**	**Cutting Edge Radius (μm)**
1	Dry	30
2	Cryogenic	30
3	Dry	70
4	Cryogenic	70

2.2. Residual stresses

The experimental residual stress state in machined *AZ31B Mg* samples was analyzed by X-ray diffraction technique using the $\sin^2\psi$ method [8]. The equipment used was a PROTO machine (model iXRD).The parameters used in the X-ray analysis are shown in Table 3. To determine the in-depth residual stress profiles, successive layers of material were removed by electropolishing to avoid the modification of machining-induced stresses. It is noted that in the present study, the total penetration depth of the X-ray beam for *Mg* is about 25 μm. Since the strength of the X-ray beam decreases exponentially with the distance from the surface, it is estimated that the measurement for the nominal depth is an average value of a layer about 15 μm thick below the surface.

Table 3. X-ray diffraction parameters for residual stress measurement of *AZ31B Mg* alloy

Radiation	Mn-Kα
Voltage and current	20kV, 4 mA
Collimator diameter (mm)	5
X-ray elastic constants (MPa^{-1})	(½)S_2 = 29.32 × 10^{-6}, S_1 = -6.59× 10^{-6}
Bragg angle 2θ (°)	151.06 (hkl) = (203)
Number of ψ angles	30

3. FE Analysis

3.1. FE Model

The proposed numerical procedure developed in this paper employs a FE based thermo-mechanical model formulation of the orthogonal hard turning process. In particular, 2D plane-strain simulation was carried out using SFTC Deform 2D®, and it was based on the following assumptions:

- rigid cutting tool (divided into 3500 elements);
- isotropic hardening for workpiece material, modelled as elastic-plastic and divided into 8500 elements;
- high mesh density was defined on the workpiece. In particular, the elements located around the cutting edge, along the machined surface and, for about 1 mm, below it were fifty times as dense as the other ones (average element edge length ≈ 5-6 μm);
- non–isothermal elastic-visco-plastic material governed by incremental theory of plasticity and Von Mises yield condition. A modified Johnson-Cook [9] flow stress rule [10, 11] was implemented in the FE code as material constitutive law:

$$\sigma = \left[200 + 400 \cdot \varepsilon^{0.337}\right] \cdot \left[1 + 0.016 \cdot \ln\left(\dot{\varepsilon} + A\right)\right] \cdot \left[1 - \left(\frac{T - T_{room}}{618 - T_{room}}\right)^{1.829}\right]$$

$$A = 0.0001 + e^{(-100\dot{\varepsilon})} \qquad (1)$$

  The detailed procedure and the explanation for the calibration of above equation can be found in [10];
- Cockroft and Latham's fracture criterion was used to predict the effect of the stress on the chip segmentation during cutting. A modified material flow stress model incorporating "flow softening" effects was successfully used in Ti–6Al–4V to simulate chip serration [12]. It is noted that the authors prefer to use the modified flow stress approach. However, due to the limitation of the existing material testing data on *AZ31B Mg* alloy, it is not possible at this time to develop a modified material constitutive model incorporating flow softening effects and this will be the focus of future research. The critical damage value, $D_{critical}$, was set equal to 35 MPa, as found by a FE calibration in a prevoius work [10]. More details on the changes of $D_{critical}$ during a chip segmentation cycle were