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Finite element simulation and experimental validation of residual stresses in high speed dry milling of biodegradable magnesium–calcium alloys

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ABSTRACT

Magnesium–calcium (Mg–Ca) alloys have become attractive biodegradable orthopedic biomaterials recently. Residual stresses are proven to be very influential on the degradation rate of an Mg–Ca implant in the human body. Due to the time and cost reasons, development of finite element models to predict residual stress profiles in cutting of Mg–Ca implants is highly desirable. In this study, a finite element simulation model of orthogonal cutting without explicit chip formation has been developed by using the plowing depth approach in order to predict process-induced residual stresses in high speed dry cutting of Mg–Ca0.8 (wt%) alloy using diamond tools. Mechanical properties of Mg–Ca0.8 biomaterial at high strain rates and large strains were determined using the split-Hopkinson pressure bar test. The internal state variable (ISV) plasticity model has been implemented to model the dynamic material behavior under cutting regimes. The residual stress evolution and effects of plowing speed and plowing depth on residual stress profiles are studied. Residual stress measurements were also performed utilizing the X-ray diffraction technique for validation purposes.

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1. Introduction

The in-service performance of machined components substantially depends on *surface integrity*, particularly residual stresses at or near the machined surface [1,2]. Residual stresses directly influence deformation, static and dynamic strength, chemical resistance, electromagnetic, optical, acoustical, and thermal properties of mechanical and electrical components [3]. They are generated by individual or combined effects of mechanical, thermal, and metallurgical impacts in machining processes. Machining process parameters determine the intensity of the mentioned impacts and ultimately the magnitude, penetration depth, profile shape, and type of the induced residual stresses. Therefore, understanding the correlation between process parameters and induced residual stresses is a fundamental step towards realizing the manufacturing for performance concept. However, measuring a residual stress profile using popular X-ray diffraction technique normally takes hours to be accomplished even with the utilization of computerized systems, the slope method for material removal, and position sensitive detectors (PSDs) for capturing diffracted X-rays. In an effort to study process parameter-residual stress correlations more economically and efficiently, researchers have sought to develop predictive models to calculate induced residual stress profiles in machining processes since three decades ago.

Sasahara et al. [4] studied the effect of cutting sequence from roughing to finishing on residual stress and strain, cutting forces, and shear angle using finite element method. They found that tensile residual stress layer made by one pass roughing (250 μm depth of cut) is removed by subsequent fine machining pass (100 μm depth of cut) and compressive stress replaces tensile stress at the surface. Adding two more fine machining passes caused surface layer to become tensile again, shear angle to decrease, and cutting forces to increase. Effects of temperature and strain rate which are important factors in determining residual stresses were neglected.

Liu and Guo [5] investigated the effect of sequential cuts and tool-chip friction on residual stresses in a machined layer. Physical state of the machined layer after first cut, i.e. residual stresses and strains, was applied as initial condition for the second cut. The work hardening caused by the first cut had significant effect on the residual stress distribution in the second cut. Tensile residual stresses from the first cut became more compressive after second cut. Moreover, the work hardening from the first cut caused slight increase in shear angle and decrease in chip thickness. However, no significant change in cutting and thrust forces was observed between the two cuts.

Jacobus et al. [6] developed a plane strain thermoelastoplastic model of metal flow under the flank of the cutting tool to predict the full in-plane biaxial residual stress profiles existing at and

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beneath the newly formed surface. They utilized two coordinate systems to understand the differences in the residual stress profiles in orthogonal and oblique cutting. Inclination angle showed significant effect in the workpiece coordinate frame. However, no significant effect of inclination angle was evident in tool coordinate system. Measured normal stresses were tensile at the surface and dropped down to a compressive state with increasing depth into the material regardless of tool or workpiece coordinate system. The presented thermomechanical rationale indicated that the observed profiles were the result of both thermal and mechanical mechanisms. The thermal mechanism led to the development of tensile residual stresses in the heat affected zone (HAZ) layer and the mechanical mechanism led to tensile plastic deformation below HAZ layer. Compressive plastic strains in HAZ layer result in tensile residual stresses in that layer, and vice versa. Tool edge and normal to tool edge directions turned out to be principal directions for residual stresses in tool coordinate system regardless of inclination angle of the cutting edge with respect to the feed direction. Later, Jacobus et al. [7] extended this model to accommodate for the more complex process geometry associated with turning and the three dimensional nature of thermal conduction in turning. Both prediction and experiment showed that increase in feed and depth of cut lead to increase in workpiece temperatures and, subsequently, to increase in the tensile character of the residual stresses at and near the surface.

Sasahara et al. [8] modeled the face turning operation too. This process is three-dimensional in nature due to involvement of the tool nose. They combined residual stress predictions of the conventional orthogonal cutting model with those of a plane strain indentation model, in which tool nose indents the workpiece, to account for three dimensional nature of the face turning. They used the proposed combined model as a first approximation to evaluate the effects of cutting conditions on surface residual stresses. Both numerical and experimental results showed that nose radius and feed rate significantly affect surface residual stresses while the effect of depth of cut is negligible.

Zong et al. [9] accounted for thermal influence of the diamond tool in their orthogonal turning model. They considered the generated heat from both friction and plastic deformation in their model. Heat transfer was handled through conduction and convection, however, radiation was neglected in their coupled thermal mechanical analysis. They also found that the tool edge geometry is the dominant factor affecting the residual stresses. Outeiro et al. [10] developed a three-dimensional finite element model for turning operation. The difference between prediction and measurement for cutting force was less than 5%, however, the predicted feed and radial forces were significantly different from measured values. They did not use their model to predict residual stresses.

Schulze et al. [11] investigated the influence of the cutting edge radius on residual stresses using an orthogonal model for microcutting. The chip formation process was incorporated into the model by continuous remeshing. Surface residual stresses were overestimated by about 50% for all the investigated cutting edge radii. This nonconformity was partly attributed to short cutting length in the model and its subsequent influence on temperature distribution.

Ee et al. [12] used a remeshing scheme in their orthogonal cutting model to simulate material flow in the vicinity of the rounded cutting edge without the use of a separation criterion. In this model, the viscoplastic material is allowed to deform and flow around the tool tip to form the chip and the machined surface. Applying chip-workpiece separation criterion is a major weakness of FE models developed to calculate residual stresses in the machined surface because it drastically alters the deformation process near the tool tip [5,12]. Strenkowski and Carroll [13] introduced an effective plastic strain based chip separation criterion and found that variation of the threshold for effective plastic strain causes change in the residual stresses. Caruso et al. [14] used a stress based criterion. They defined a bonded contact interface between the chip layer and the workpiece as initial condition. Chip separation achieved when the local stress at specified distance ahead of the tool tip along the chip–workpiece interface reached the specified critical value. The predicted surface residual stresses were smaller than measured values by this model.

Outeiro et al. [15] applied the remeshing technique of Ee et al. [12] to avoid the issues associated with the implementation of chip separation criterion and modeled the orthogonal cutting of 316L steel with 30–100 μm cutting edge radius tools. Addressing the same issues, Özel and Zeren [16] employed the Arbitrary Lagrangian Eulerian (ALE) formulation to allow the workpiece material to flow around the round edge of the cutting tool rather than using a chip separation criterion.

So far, all the numerical studies have included chip formation process and very often the chip is left on the model during the cool down or relaxation phase before extracting residual stress profiles. However, machined surfaces are without chips in practical cases. In order to avoid the possible thermo-mechanical influence of the chip on residual stresses, the overall dimensions of the finite element model should be considered larger to compensate for those effects. On the other hand, very fine mesh around the cutting edge and machined surface is required to provide adequate spatial resolution in order to capture sharp strain, strain rate, temperature, and residual stress gradients. Inconsistency in spatial resolution has caused seemingly contradictory results in numerical/experimental studies of residual stresses in the past [10]. Larger and more refined models translate into more digital storage, computational time, and expensive simulations. Guo et al. [17] proposed a new modeling approach without chip formation based on the concept of plowed depth. This approach avoids the severe element distortion inherent in traditional cutting models with chip formation, does not require a chip separation criterion, and provides enough spatial resolution to capture sharp deformation gradients. Meanwhile, it still reflects the realistic stagnation phenomenon (Section 3) in cutting. This modeling approach is adopted in the present study.

Previous studies have shown that residual stress state after cutting is strongly influenced by material properties [11]. For instance, a higher initial yield strength results in more compressive residual stresses while higher strain hardening leads to more tensile residual stresses at the surface. Therefore, separate studies are needed to investigate the material specific residual stress state after cutting. Magnesium–calcium (Mg–Ca) alloys have emerged as very appealing biomaterials recently particularly for orthopedic applications [18,19]. As compared to currently available orthopedic materials, they do not cause stress shielding, there is no need for second surgeries to excise them since they are both biodegradable and biocompatible, and they have enough mechanical strength to be used in load carrying applications. However, these alloys degrade quickly in body environment and there is a dire need for alternatives to control their degradation rate. Denkena and Lucas [20] were able to decrease this rate by a hundred times using machining to adjust surface integrity particularly residual stresses. In this context, it is critical to develop numerical models which can predict residual stresses under various machining conditions in order to facilitate development of these novel biodegradable materials.

The objective of this study is to predict process-induced residual stress profiles in cutting novel Mg–Ca0.8 biomaterial using FEA method. To meet this objective: (i) an FE model without explicit chip formation is developed; (ii) an internal state variable

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