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Diagnosis of involutometric issues in flat rolling of external helical gears through the use of finite-element models

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Abstract

High-volume production of precision external-involute helical gears using flat-rolling is impeded by a number of quality issues. Experimental resolution of these issues is expensive and time consuming. The present study utilizes finite-element models (FEM) to diagnose three of these quality issues and to explore possible solutions. Two- and three-dimensional (2D and 3D) ABAQUS models were developed for a specific gear-manufacturing process and resulting geometries were not satisfactory. Subsequently, 3D DEFORM simulations were developed for the same process. Numerically predicted geometries were benchmarked against actual results obtained through designed experiments. Finite-element modeling and experimental results were correlated and the models were validated. Possible solutions were simulated and analyzed through additional modeling. Results obtained from the initial pass of the 3D models have been promising although progress has been limited by the excessive computational time needed. Frequency of re-meshing, high number of elements due to fine mesh, and changing re-mesh criteria contribute to the computational difficulties.

Keywords: Involute gears; Flat rolling; Finite-element modeling

1. Introduction

Planetary gear sets are at the heart of most automatic transmissions. A gear set, typically, consists of one sun gear, one ring gear, and several pinion or planet gears [1]. The tooth geometry of all these gears is classified as helical involute. Furthermore, these gears must meet very tight dimensional tolerances. Overwhelming majority of sun and pinion gears are machined from blanks through hobbing followed by a finishing operation. These operations are technically demanding, and they produce large quantities of metal chips as waste. Consequently, there is industry interest in net-shape forming of gears. Danno and Tanaka [2] reported developmental work on hot rolling of precision helical gears at Toyota research laboratories. Smith [3] reported that Ford motor company had successfully implemented hob and roll as a viable high volume production technique at its automatic transmission plants. He went on to say that this was an intermediate step towards full roll-forming of gears. However, a recent industry survey has revealed that the goal of full-form rolling has not been achieved yet [4].

In recent years, research has been conducted using finite-element models (FEM) to analyze a number of metal forming processes [5]. However, few researchers have developed models to simulate roll-forming processes. Koenig and Munzinger [6] performed FEM simulations of gear forging and obtained information about material distribution during the forming process. He used a variable friction coefficient and a rate-dependent flow stress model. He did not remesh his model, and the mesh density was much lower than densities that would be used today, since computers were much slower in 1992. Martin [7,8] used MARC computer code to study thread rolling residual stresses. Domblesky and Feng [9] has done extensive research on flat rolling of threads using commercially

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available DEFORM code. His research facilitated a number of improvements to the software which directly benefited the present work.

The present paper uses FEM to analyze and diagnose the gear flat-rolling process and focuses on some of the quality problems confronting this process. Specifically, this paper explores possible solutions for three quality problems (Fig. 1):

1. *Rabbit ears*: Excessive metal on the major diameter of the gears. Egan [10] and Egan et al. [11] reported that this problem could be partially solved by reversing the direction of the dies. No additional data was published regarding their work. The present study endeavors to verify the results through FEM simulation.
2. *Asymmetrical flanks*: Dissimilar metal flow on drive and coast sides. This problem was also resolved partially by reversing the direction of the dies according to Egan [10] and Egan et al. [11]. The present research endeavors to quantify the effects of reverse rolling through FEM analysis.
3. *Barreling*: The deformation caused severe barreling in the part. Die fill is less at the ends than the middle of the part causing the tooth profiles to be worse on the ends than the middle. FEM shall be used to determine if this problem can be alleviated by modifying blank geometry.

2. Experimental baselines

The part chosen for the study was pinion gear from a North American automotive plant. The gear design conforms to AGMA 112.05 & ANSI B6.1. It is an 18-tooth, left-handed, involute helical gear with a 21° helix angle and a pitch diameter of 26.993 mm. It also has a 20° pressure angle and is about 26 mm long. The parts are currently produced by hob and roll operations. Prototypes of the same gear design were produced by flat-rolling. The machine used in the study was an Anderson Cook-MARAND S-350 equipped with special dies. The steel used in this research was AISI 4620. The material behavior was assumed to follow power law [12], and the following equation was developed to describe the stress–strain relationship [13]:

$$\sigma = 772\varepsilon^{0.13}, \tag{1}$$

where σ is true stress (MPa) and ε is true strain (mm/mm). Designed experiments were performed and results used as a baseline for FEM evaluation. Feedback from the experiments was used to validate, and supplement the models.

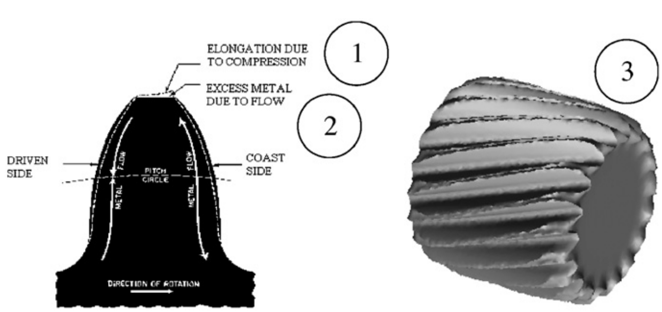

Fig. 1. Three quality issues in flat-rolling: (1) rabbit ear, (2) asymmetric flanks, and (3) barreling (right).

3. ABAQUS 2D and 3D modeling

In the automotive industry most FEM analysis is concerned with the behavior of materials in the elastic zone. Plastic deformation happens when the part fails. Therefore, the FEM software is only expected to determine the boundary conditions for the failures. General purpose software such as ABAQUS is in common use for these applications with practical success. This was the software available for this research without any new licensing expense. Therefore, the standard software was used in the initial phase of the research. This decision was made with the understanding that the software was not designed for analysis of bulk deformation. However, it was believed that the results would be a useful benchmark for future FEM. An unstated goal of this action was to determine the necessity of investing in more than one software package for the same organization.

A simple 2D model of the process was developed as the first FEM analysis tool. Complexity was added by developing a 3D model as the next step in the analysis. Many numerical difficulties arose in this simulation of bulk deformation. Mesh elements became distorted to the point that the characterization of elemental stiffness was no longer accurate. This, and local contact difficulties, resulted in the failure to converge in many instances. Fig. 2 illustrates the output from two of the ABAQUS simulations.

2D model did not have sufficient detail to predict tooth geometry to the accuracies required for this research. The elements distorted excessively which resulted in misshapen gear teeth and inaccurate metal flow modeling of the forming process. 3D model had higher mesh density, but did not run to completion. The larger file size caused slow

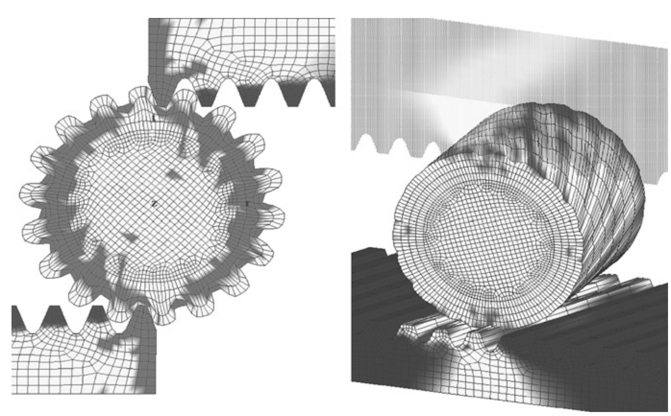

Fig. 2. 2D and 3D ABAQUS simulation results.