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Fatigue of reinforced-polyurethane-based, sheet metal forming dies

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Abstract

Fatigue in metal forming dies is an important issue in the manufacturing industry. Fatigue failure leads to repair or replacement of the die, which interrupts and slows down the manufacturing process. Fatigue of bulk metal forming (such as, forging and extrusion) dies has been the focus of most die failure studies because the nature of the process tends to subject the die to high stresses, thus increasing the likelihood of die failure. However, as polymer composite tooling materials are making inroads into rapid tooling technologies, die failure in sheet metal forming, in which the dies are subjected to significantly lower stresses, is drawing attention. This paper presents a fatigue failure analysis of V-bending dies machined from a polyurethane-based tooling board. The mechanical properties of the tooling materials are characterized to identify the underlying failure mechanisms. Various fatigue failure criteria, namely, maximum tensile principal stress, effective stress, Smith–Watson–Topper, and critical plane approaches are investigated as die life prediction methods, among which the latter two approaches were most accurate. Finite element analyses and experiments are performed to verify the results.

Keywords: Polymer composite; Fatigue life prediction; Damage parameter; Stress analysis

1. Introduction

In metal forming, wear and fatigue are the major mechanisms that cause tool failure. Wear occurs in a gradual, progressive manner and determines the service life of the tool. On the other hand, fatigue failure often is characterized by a catastrophic rupture of the tool in a fraction of the service life. The often-unexpected fatigue failure tends to render tool scheduling difficult, and thus to disrupt the entire production schedule. Therefore, it is critical to design the tool in such a way that tool life terminates by wear rather than by fatigue [1].

Active research on tool life prediction of metal forming dies began in the early 1990s, and numerical process simulation became an essential component of the studies. A number of studies aimed at the mechanical fatigue life estimation of cold forging or extrusion dies, which did not involve thermal effects. These studies, pioneered by Taylan Altan at the Ohio State University and Kurt Lange at the University of Stuttgart, Germany have been summarized by Altan and Vazquez [2].

In their early work, Knoerr et al. [3] presented a concept that combined 2-D forging simulation and die stress analysis into an integrated approach for tool design. Knoerr et al. [1] extended their research to a computer-aided fatigue analysis concept for cold forging, with the aim of estimating tool life in the tool design stage. It was found that the formation of a plastic zone in the tooling generates microcracks due to cyclic loading and that the maximum principal stress state in the transition radius region enhances the formation and propagation of cracks. Geiger et al. [4] developed, a method for improving the fatigue resistance of cold forging tools by finite element simulation and computer-aided die shape optimization. The basic idea was to modify the geometry of the die to eliminate critical stress concentrations in order to reduce the effective stress and strain amplitudes at the tool surface. Nagao et al. [5] investigated the fatigue failure of a tool insert used in the backward extrusion of constant velocity joint outer races. The formation of a plastic zone at the transition radii was identified as the cause of crack initiation, and the maximum tensile principal stress was found responsible for crack propagation. A comparative

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study was performed by Falk et al. [6], who assessed the applicability of different fatigue failure concepts for a closed cold forging die. The study showed that the local energy approach, which offers the advantage of taking into account multiaxial stress conditions, yielded the most satisfactory results in predicting the number of cycles to crack initiation. Most of these studies assumed tool and die steels as the die materials.

Unlike bulk metal forming, sheet metal forming has not been a subject for developing tool life estimation methods. For one thing, more focus has been on the formability and failure of the workpiece because the die was assumed to have infinite life. However, with the advent of polymer composite rapid tooling materials, die life has become an important issue in sheet metal forming because the dies often experience premature failure due to their lack of strength. In addition, the previous research on the failure of brittle and semi-brittle materials, into which most of these tooling materials are classified, provides the basis upon which the tool life prediction method can be developed.

A number of studies investigated fatigue in brittle solids and suggested constitutive models [7–14]. Ratner and Potapova [11] proposed a model of multicycle fatigue of brittle polymers—namely, caprolon and its composites—based on the hypothesis of self-simulation. The authors found out that in the case of brittle failure in multicycle fatigue, the maximum principal stresses that occur in the failure zone determine the number of cycles to failure. Suresh [12] addressed the possibility of stable tensile fatigue in brittle solids and suggested further work on the effects of microstructure, environment, temperature, cyclic frequency, and mean stress on the mechanisms of crack initiation and growth in a wide range of brittle materials. Ritchie [13] distinguished the mechanisms by which fatigue cracks grow in ductile and brittle materials from the viewpoint of intrinsic and extrinsic mechanisms. In addition to brittle solids, many research efforts have been devoted to understanding the fatigue behavior of polymer composites [15–19], most of which discuss the toughening mechanisms of fillers.

This paper presents a unique study, as a brittle thermoset polymer filled with particulates, whose applications are in metal forming is considered. The paper presents a method to estimate the fatigue life of a die fabricated from such a polymer composite. In order to establish, a foundation for developing the method, the mechanical properties and fatigue behavior of the die material are characterized. In addition, the microstructure of the material and the fracture surface of the failed die are examined. The die life prediction method developed involves process simulation using finite element analysis (FEA) techniques. A 90° V-die bending process is investigated, and a successful numerical simulation yields the overall stress distribution in the stamping components, which, in turn, allows the application of the developed fatigue analysis approach. Section 7 verify the method.

2. Material characterization

This research deals with a polymer composite tooling material specifically developed for metal forming applications known as Ren Shape™ 5166 by Huntsman Advanced Materials (formerly, Vantico Inc.). Ren Shape™ 5166 is supplied in the form of a block from which metal forming dies can be machined in a relatively short amount of time. The material has a thermoset polyurethane base and is filled with aluminum trihydrate (ATH). The spherical ATH is dispersed randomly and uniformly in the matrix during the block fabrication process to impart material isotropy and adhesion. More importantly, ATH serves to increase the overall compressive strength and to improve tribological characteristics. The weight and volume percents of ATH in Ren Shape™ 5166 are approximately 68.7 and 83.5%, respectively [20].

2.1. Basic mechanical behavior

Fundamental mechanical properties of Ren Shape™ 5166 were measured from tension, compression, flexure, torsion, fracture toughness, and fatigue tests. The measured tensile, compressive, and flexural properties supplemented by manufacturer's data are summarized in Table 1 [21]. The general conclusion that can be drawn from the tests is that Ren Shape™ 5166 is brittle and that little plastic deformation takes place before failure [20].

Torsion tests were performed in order to investigate the fracture response of Ren Shape™ 5166 under torsion. The actual specimen after the test is shown in Fig. 1. Further material characterization, including plane strain fracture toughness tests and fractographical studies are reported in Ref. [20].

2.2. Fatigue behavior

Flexural fatigue tests were performed to obtain the $\varepsilon - N$ data for Ren Shape™ 5166. The fatigue tests were performed in flexural mode rather than in tensile mode for several reasons. First, V-die bending emulates three-point bending in terms of the loading conditions and the stress

Table 1
Mechanical properties of Ren Shape™ 5166 [21]

Property		ASTRM standard	Tested	Manufacturer
Elastic modulus		D 638	7.2 GPa	7.2 GPa
Yield strength (0.2% offset)			32 MPa	32 MPa
Ultimate tensile strength			33 MPa	34 MPa
Compressive modulus		D 695	N/A	5.8 GPa
Compressive strength			91 MPa	86 MPa
Flexural modulus	3-point	D 790	6.8 GPa	6.7 GPa
	4-point		6.2 GPa	N/A
Flexural strength	3-point		62 MPa	55 MPa
	4-point		54 MPa	N/A

The number of specimens in each test was five.