Tribology International 104 (2016) 64–72

Contents lists available at ScienceDirect

Tribology International

journal homepage: www.elsevier.com/locate/triboint

Wear behavior of tribologically optimized tool surfaces for incremental forming processes

P. Sieczkarek [a], S. Wernicke [a], S. Gies [a], A.E. Tekkaya [a], E. Krebs [b,*], P. Wiederkehr [b], D. Biermann [b], W. Tillmann [c], D. Stangier [c]

[a] Institute of Forming Technology and Lightweight Construction, TU Dortmund University, Baroper Straße 303, D-44227 Dortmund, Germany
[b] Institute of Machining Technology, TU Dortmund University, Baroper Straße 303, D-44227 Dortmund, Germany
[c] Institute of Materials Engineering, TU Dortmund University, Leonhard-Euler-Str. 2, D-44227 Dortmund, Germany

ARTICLE INFO

Article history:
Received 11 May 2016
Received in revised form
18 August 2016
Accepted 23 August 2016

Keywords:
Sheet-Bulk Metal Forming
Tribology
Bionic surface structures
Incremental gear forming process
Micromilling
PVD-coating

ABSTRACT

The mechanical wear behavior of forming tools is the limiting factor during an incremental gear-forming process. These forming tools with a simply shaped geometry are exposed to high forming forces. Additionally, the necessary workpiece chambering, which is characteristic for this incremental process restricts the dimensioning of the tools. Thereby, the geometrical design of the forming tools is limited, which leads to a decreased lifetime. Functional structures on the tool surfaces can influence the occurring loading and wear behavior by reducing the contact area, the supply of lubricant pockets, and by a controlled influence and adjustment of the occurring material flow. For the extension of the tool's lifetime, different surface concepts and combinations with CrAlN PVD-coatings are investigated. To offer conditions with a high tool load, the investigations are focused on an incremental gear forming process with a simple one-wedge forming tool.

The results show abrasive and adhesive wear characteristics, as well as outbreaks, and crack formations. The crack propagation on the flank leads to a chipping of the tool tip, hence limiting the tool life. Compared to the reference tool, a surface structure combined with a PVD-coating provides a significant increase of the tool life of 84%.

1. Introduction

Due to the industrial demands for complex functional components with a load-adapted shape, reduced weight and locally increased strength, new technologies like Sheet-Bulk Metal Forming (SBMF) are developed [1]. Compared to conventional sheet forming processes, the main difference of this technology is the three-dimensional material flow that occurs during the application of bulk forming operations onto sheets. The prediction and control of the material flow are the main challenges of this new technology [1].

A field of application for SBMF processes is the manufacturing of parts with gear elements. Compared to conventionally produced gearings by means of machining processes, the production of gears with forming operations (e.g. rolling) can lead to advantageous surface strengths, an uninterrupted material fiber, as well as an increased surface quality [2]. Thus, industrial challenges of shortening the process chains and improving the material and energy efficiency could be considered and the costs could be reduced when compared to the state-of-the-art processes [3]. Gröbel et al. [4] give an overview of existing processes to manufacture various gear elements with forming operations investigated within the Transregional Collaborative Research Center on Sheet-Bulk Metal Forming (TCRC 73). The incremental procedure enables a flexible production of load- and weight-adapted components, e.g. synchronizer rings, starter gears, or seat adjusters. The focus of this technology is to process thin sheets (2–3 mm) by means of different local forming processes, and changing the material thickness as well as the material properties in specific areas. A multi-axis press provides the required process flexibility for repeatable and sequential motions. This is explained in detail by Sieczkarek et al. [5].

Beside the high flexibility, an additional advantage of the incremental process is the fact that simple and cheap forming tools can be used due to repeatable and sequential motions. Despite the

---

* Corresponding author.
E-mail addresses: peter.sieczkarek@iul.tu-dortmund.de (P. Sieczkarek), sebastian.wernicke@iul.tu-dortmund.de (S. Wernicke), soeren.gies@iul.tu-dortmund.de (S. Gies), erman.tekkaya@iul.tu-dortmund.de (A.E. Tekkaya), krebs@isf.de (E. Krebs), wiederkehr@isf.de (P. Wiederkehr), biermann@isf.de (D. Biermann), wolfgang.tillmann@tu-dortmund.de (W. Tillmann), dominic.stangier@tu-dortmund.de (D. Stangier).

http://dx.doi.org/10.1016/j.triboint.2016.08.028
0301-679X/

incremental procedure, these tools are still exposed to high contact pressures and resulting stresses of about 2000 MPa. The tool loads are further increased by the limited tool thickness which is restricted by the workpiece chambering. The chambering was proved to be necessary for both processing as well as a sufficient thickening of the sheet-edge areas [6]. Thus, the thickness of the tool is already predetermined by the sheet thickness or the aspired thickening section [5]. These process characteristics necessitate a decrease of the occurring forming forces. One possibility to obtain such a decrease is to modify the tool surfaces using micromilled bionic structures. The positive aspects of these surfaces were already investigated and proved by the authors. In Sieczkarek et al. [6], micromilled bionic structures were applied to double-wedge gear-forming tools. A force reduction of up to 20% was observed. This can be explained by the reduced contact area and thus by a smaller influence of the occurring friction. Hence, the Cr-based PVD hard coating was necessary to protect the filigree structures. Furthermore, a directional influence on the occurring material flow could be observed with different structure patterns [7]. Due to fundamental investigations, previous experiments were only conducted with a small number of forming steps (up to 50 per tool). Regarding the application in a real manufacturing process, the number of strokes of the forming tools is much higher and the wear mechanisms would differ as well. To transfer the incremental gear forming process to production conditions, it is necessary to investigate and determine the maximum possible lifetime and the resulting wear or damage of gear forming tools structured and coated this way. In this paper, it is proved that structured and coated forming tools are beneficial for forming applications with a high repetition ratio. Furthermore, the emerging effects on the occurring wear behavior and its evolution due to different surface properties are investigated and discussed. A comparison to a reference tool is complemented to give an overview although the focus of the investigations is on the incremental gear forming tools with modified surfaces and its abovementioned positive properties.

2. Experimental procedure

The investigations involve three types of forming tools with the same initially eroded macroscopic geometry (illustrated in Fig. 1) but with different modified surfaces generated by micromilling. Two bionically-inspired structures were analyzed for this investigation. The third tool was additionally coated with a CrAlN PVD-coating. The following chapters present the incremental gear forming process, the used tool and workpiece materials, the machining process of microstructures, the application of the coating system, and finally the used measurements methods.

2.1. Incremental gear forming process

The experiments were carried out with a five-axis forming press that was designed to meet the flexible demands of the incremental Sheet-Bulk Metal Forming technology [5]. The different forming axes offer a wide variety of possible motions. Fig. 2a shows the experimental setup. The circular blank ($D=95$ mm, $s=3$ mm, S 355 MC – 1.0976) was clamped inside a blankholder, thus limiting the axial material flow. In order to avoid side effects and geometrical influences, the incremental gear forming process was performed with a single-wedge tool geometry. The dimensions of the workpiece and the tool are given in Fig. 2b. Additionally, the procedure of the forming process is illustrated. To avoid interactions between the forming zones, the indentations were formed into the blank edge with an offset of 18°. Thus, 20 indentations were embossed into one chambered workpiece and the number of necessary sheets could be decreased. The feed rate was 1 mm/s.

2.2. Materials for tools and workpieces

The high-speed steel ASP®2023 (material number 1.3344) was used to manufacture single-wedge forming tools. The material was heat-treated in a vacuum and subsequently annealed three times at 560 °C for one hour, thus reaching a hardness of 11.31 ± 0.13 GPa (62 ± 0.2 HRC). Due to the high contact stresses and loads applied during SBMF operations, powder metallurgically processed steels offer the advantages of a few segregations and non-metallic inclusions. Furthermore, the annealing temperature of ASP®2023 is higher than the necessary process temperature during PVD-coating and thus does not lead to an undesirable reduction of the hardness. For the wear investigations, the dual phase ferritic-martensitic steel S 355 MC (material number 1.0976), which is commonly used in cold forming operations, with a thickness of

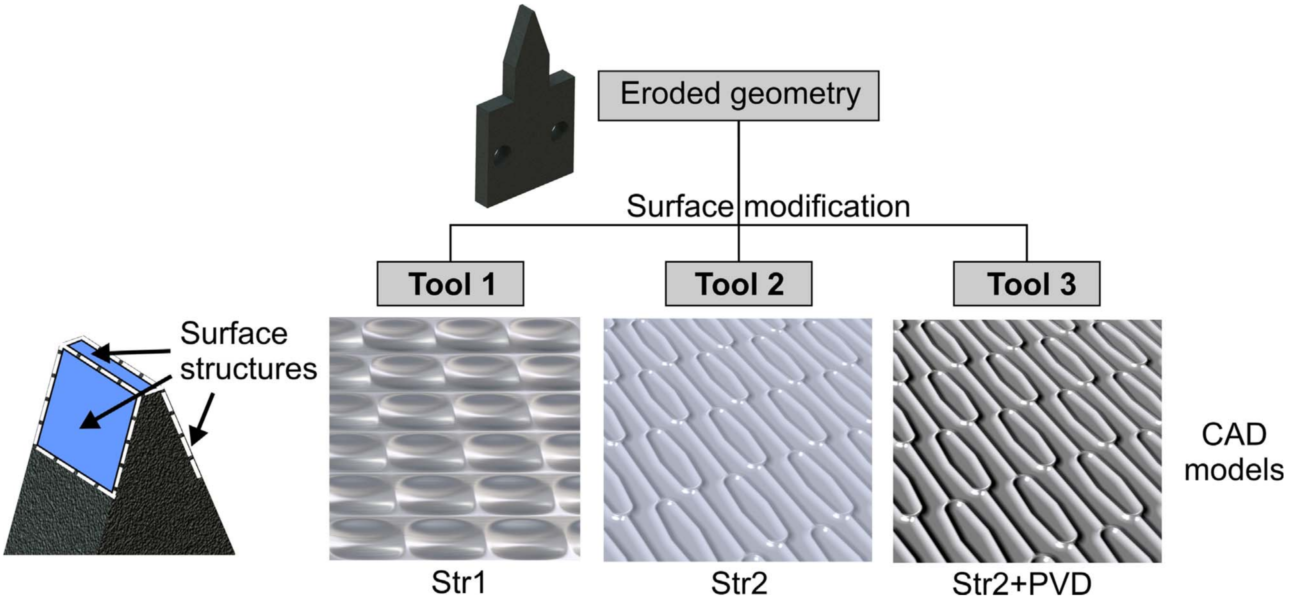

Fig. 1. Surface modifications of the gear forming tool.