Contents lists available at ScienceDirect

Tribology International

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

# Hot shearing processes: Correlation of numerical simulation with real wear phenomena

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## ARTICLE INFO

*Article history:*
Received 30 July 2013
Received in revised form
21 November 2013
Accepted 12 January 2014

*Keywords:*
Finite element modelling
High temperature
Wear
Shearing

## ABSTRACT

Metal sheet shearing is a necessary procedure for dimensional control during steel forming. Due to extreme operating conditions, shearing blades suffer from severe wear and need frequent repair, causing high maintenance costs. In order to increase the lifetime of cutting blades, FEM simulation of the metal shearing process was performed, implementing a hybrid friction coefficient based on data obtained from a newly developed forming tribometer. A good correlation was found between the shape of the sheared work piece as predicted by the FEM model and as found in the real application. Finally, a relationship is proposed between stress and temperature distributions as calculated by the simulation and shearing blade areas most affected by wear.

## 1. Introduction

Blade wear during high temperature sheet metal shearing is caused by a combination of several main mechanisms taking place simultaneously, such as abrasion at the cutting edge, thermal fatigue aggravated by the heat conductivity of water used for blade cooling, and environmentally assisted crack growth on rake face areas less affected by heat transfer from the high temperature sheet metal [1]. Such wear processes are responsible for decreased blade lifetime and increasing costs for steel manufacturers, as the required maintenance operations may bring the entire production to a halt.

Improvement of shearing blade lifetime and thus the reduction of associated maintenance costs requires new materials with enhanced thermal and mechanical strength. However, any prospective alloy would have to be thoroughly tested in order to ensure that the selected material is able to not only withstand harsh conditions but also to increase tool lifetime significantly [38–40]. In order to facilitate this task, finite element analysis has been regarded as a cost-effective and flexible tool for wear behaviour prediction and cutting process optimisation [2–4], being able to estimate difficult-to-measure process variables such as temperature or contact stresses parameters which are expected to offer useful information about wear processes taking place on shearing blades [1]. Due to its versatility, the use of finite element methods (FEM) for wear prediction in cutting tools has become increasingly widespread in machining processes modelling and tool life prediction since the early 2000s.

A review of the existing literature on the subject shows that, although orthogonal cutting is by far the most common machining process simulated by FEM [2,5,6], references may be found modelling alternative configurations such as die cutting [7–9], metal guillotining [10] and punching/blanking [11,12]. However, literature on intermittent cutting modelling is relatively sparse, limited mainly to machining processes such as milling [13,14], which shows wear features similar to those found in high temperature sheet metal shearing (e.g. thermal fatigue).

In particular, friction modelling at the tool-work piece interface has been reported to have a strong influence on tool wear simulation [15], especially in high speed applications. In these cases, the calculated stress distributions and temperatures at the tool surface strongly depend on frictional conditions. In fact, frictional shear stresses at the tool-work piece interface are generally considered to be a function of normal contact stresses, but the nature of such dependence is far from clear. The Coulomb friction model -which states that frictional stresses are proportional to contact stresses, with the friction coefficient as the proportionally constant- is used for low-speed cutting modelling.

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http://dx.doi.org/10.1016/j.triboint.2014.01.025

Please cite this article as: Torres H, et al. Hot shearing processes: Correlation of numerical simulation with real wear phenomena. Tribology International (2014), http://dx.doi.org/10.1016/j.triboint.2014.01.025

However, it generally underestimates tool wear in high speed applications as its validity is limited by the shear strength of the material to be deformed. Thus, a number of advanced friction models have been proposed in recent years [16–21], taking into account local conditions in tool-work piece contact. The implementation of such friction models requires a testing method capable of measuring friction under forming as well as determining simultaneously the relevant local contact conditions like loads or temperature of the samples. A more realistic friction model is expected to better correlate calculated frictional shear stresses with their corresponding values measured in the real process, also enabling the development and optimisation of high performance cutting tools using FEM simulation.

The aim of this work is the development of a FEM model for high temperature sheet metal shearing and its validation by correlating the shape of the sheared work piece as predicted by the FEM simulation and as found in the real application. The stress and temperature distributions at the upper shearing blade, as calculated, were additionally linked to blade wear after operation as reported in a previous study by the authors [1], as several important wear mechanisms show a marked dependence on temperature and contact stresses. The coefficient of friction (COF), required for the FEM simulation, was measured using a high temperature forming tribometer specifically designed to operate under the high loads and elevated temperatures found in metal forming processes.

## 2. Background

In a recent investigation by the authors [1], wear damage experienced during operation by shearing blades made from martensitic 1.2367 hot work tool steel was characterised by various techniques. During the surface damage characterisation it was found that the predominant wear mechanisms differed greatly between adjacent blade regions, suggesting very different contact conditions with the work piece over relatively short distances along the blade surface (Fig. 1). In the case of the rake face, the longitudinal cracking found along the cutting edge and its adjacent region, visible in the optical microscopy (OM) image in Fig. 1a, was attributed to thermal fatigue due to the temperature gradients arising from the contact with the high temperature metal sheet, a damage mechanism characteristic of intermittent cutting applications as in our case and which may be actually aggravated due to the presence of cooling water [14]. Additionally, abrasive wear was found in the cutting edge, accompanied by adhesion in the form of material transfer from the work piece [41]. In rake face regions further away from the cutting edge, where lower blade temperatures were expected, longitudinal cracking was mainly attributed to corrosion fatigue or more generically to environmentally assisted cracking due to the combined action of cyclical loads and chemically active environment, in our case corrosion pitting acting frequently as stress concentrators and crack initiation sites. On the other hand, plastic deformation was found in the flank face up to distances of ~8 mm from the cutting edge (Fig. 1b and c), likely related to high temperature softening of the base material.

A distinctive wear track was found in both rake and flank cutting faces, reaching maximum depths of 550 and 170 μm respectively, as seen in the 3D surface mapping images (Fig. 1c). The wear track originates at regions where material removal due to simultaneous transversal and longitudinal crack growth took place. Finally, surface oxidation was extensively found all over the blade surface, which is expected to favour decreased wear rates by reducing metal to metal tribocontact and consequently, adhesive material transfer from the work piece [22].

It is also worth noting that the severity of the mentioned wear mechanisms (abrasion, adhesion, and thermal and corrosion fatigue) may increase with temperature and the contact loads the cutting blades are subjected to during operation. The distribution of these parameters will be calculated by means of FEM simulation.

Also, sheet metal samples obtained from the real application after shearing (Fig. 2a) were characterised. OM imaging of the sheared surface (Fig. 2b) shows predominantly ductile deformation, due to the increased ductility at high temperatures that has been reported in the literature [23]. Also, visible imprints of cracking were widely found on both shearing blades' surface. A brittle fracture surface, ~2 mm wide, can be seen in the central region, with a burr attributed to the contact with the lower shearing blade (Fig. 2c).

## 3. Experimental

Tribological tests were performed under conditions simulating those of the real sheet metal shearing application. The aim of the experiments was to provide reliable values of the COF to be implemented in the simulation, as it was reported that frictional stresses at the tool-work piece interface are very important for the FEM simulation of machining processes [15].

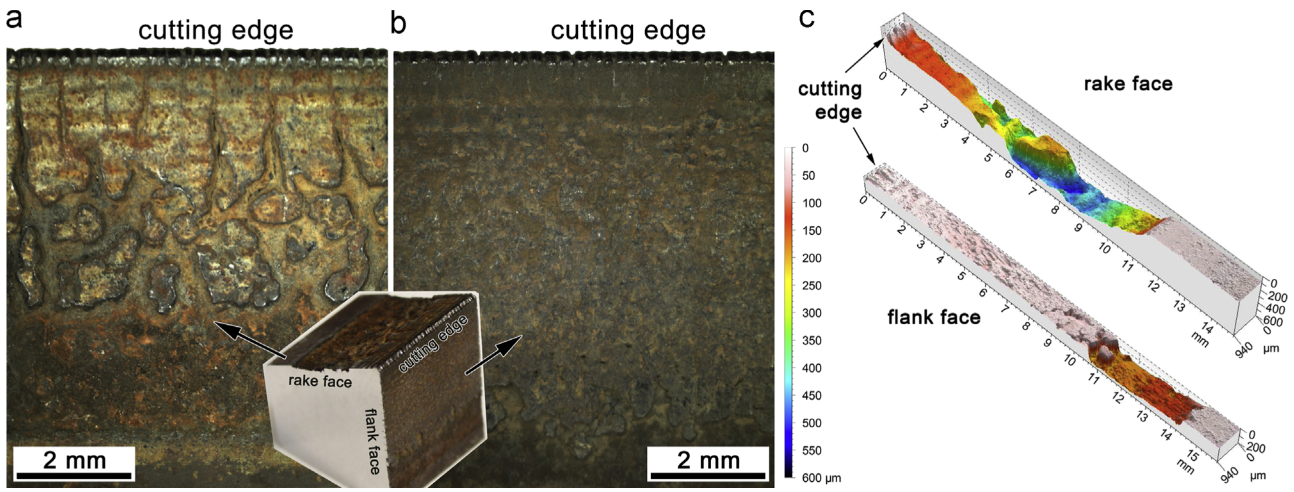

**Fig. 1.** Sample obtained from a worn upper blade: (a) OM of rake face, (b) OM of flank face, and (c) 3D surface topography of worn blade (size ~15 × 1 mm$^2$) [cf. 1].

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