Wear in Hot and Warm Forging: Design and Validation of an New Laboratory Test

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Abstract

A simulative wear test for hot and warm forging tools is presented which has been developed by the Authors with the twofold purpose of (i) verifying the applicability of wear micro-mechanical models in simulation of hot and warm bulk metal forming operations using FEM codes and (ii) evaluating wear parameters by an inverse numerical technique.
In its simple configuration, the test embodies many of the tribosytems encountered in industrial forging operations and relevant tool wear and failure mechanisms, such as abrasion, thermal fatigue as well as permanent deformation of tool surface.
The paper focuses on the design of the test configuration and the description of testing and measuring apparatuses, including those for temperatures and heat transfer coefficient determination. Validation of the test through test runs and determination of wear profile on tools end the paper.

Keywords: Hot-Forging, Wear, Test

1. - Introduction

Wear data, as well as friction data, are characteristics of tribological systems (hereafter *tribosystems*) consisting of interacting components, such as material pairs, interfacial elements and environment, and associated with the three groups of parameters (7):

- *structural parameters* related to physical, chemical and technological properties of the system components;
- *operational parameters*, including the loading, kinematics and temperature conditions, and
- *interaction parameters*, which characterize the action of operational parameters on the structural components of the tribosystem and define contact and lubrication modes.

Tribosystems associated with bulk metal forming operations may change substantially from operation to operation. Chemical, mechanical and micro-structural characteristics of the tribosystem components are completely different in hot, warm and cold forming operations and different geometry for the same class of operations may determine operational and interaction parameters (especially, contact sliding velocity, temperature, deformation modes and stresses) leading to different wear and failure mechanisms of dies.

Accordingly, a variety of tests must be accepted for investigation of wear in bulk forming operations, depending on the objectives of the tribotesting to be performed and the tribosystems to be analysed. Reviews of tribotests related to bulk forming operations are in (12) and (10).
Adapting the general classification of tribotesting proposed in (13) to the specific scope of tribotesting in bulk metal forming, wear experiments and tests for investigation in forging operations can be grouped into the four different categories represented in Fig.1. Each test category has a different scope and results obtained in one category cannot be directly transferred to another.
Examples of tests recently proposed for investigation of wear in hot forging and belonging to categories II, III and IV are presented in (8), (11) and (6) respectively.

This paper presents a *laboratory simulative test* (test category III in Fig.1) designed and set-up by the Authors with the twofold purpose of (i) verifying the applicability of wear micro-mechanical models in simulation of hot and warm bulk metal forming operations using FEM codes and (ii) evaluating wear parameters by an inverse numerical technique.

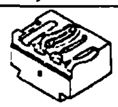
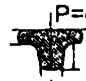
Cat.	Type of test	Symbol
i	Full-scale field tests	
ii	Full-scale bench tests	
iii	Laboratory simulative tests	
iv	Laboratory fund. tests	

Fig.1 - Wear-test categories in bulk forming (3).

This research work is part of the workprogramme of a European BRITE-EURAM project aimed at developing a DSS for predicting abrasive and adhesive wear in bulk and sheet forming operations. The design of test configuration and geometry is presented in § 2. The testing equipment and apparatus are illustrated in § 3. Procedures to monitor and evaluate wear parameters are presented in § 4. Results of the developed test are presented in § 5.

2. - Test Configuration and Geometry

The design and set-up of the laboratory wear test (5) have been carried out through the following steps:

- *Step 1.* Converting the general commitment into a list of design specifications for the test.
- *Step 2.* Identification of a number of industrial tribosystems to be simulated in wear testing.
- *Step 3.* Selection of appropriate test configuration for the test specimens of triboelements (workpiece and tools).
- *Step 4.* Selection of test geometry and specification of structural and operational parameters.
- *Step 5.* Design and setting up of testing equipment and apparatus.

To translate the general commitment into test design specifications (Step 1) a sort of QFD technique has been utilized (3). Translation has been accomplished in the four main stages: (i) organizing test requirements and assigning importance ratings, (ii) establishing design specifications, (iii) determining the relationships between test requirements and design specifications and (iv) establishing target value for design specifications. A survey of existing similar tests determining how they compare in satisfying test specifications is also included.
In the *laboratory simulative test,* model test specimens rather than actual tribocomponents are tested under practice-oriented operating conditions. The test configuration must realize a sufficient similarity of structural, operational and interaction parameters of the actual hot and warm forging tribosystems to be analysed (Steps 2 and 3). Therefore, particular care has been taken in reproducing physico-chemical nature of the model test specimens and sliding velocity, stresses and temperature at workpiece-tool interface. On these bases, the double combined piercing and upsetting of a cylindrical billet has been selected as test configuration, some of the correspondences between industrial tribosystems, wear mechanisms and test configuration being represented in Fig.2.

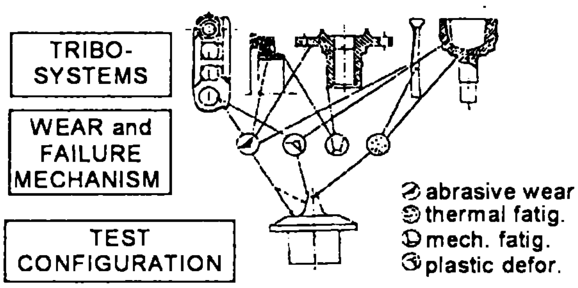


Fig.2 - Tribosystems, wear and failure mechanisms and test configuration.

As concern the test geometry (Step 4 in the test design procedure), three tribological features can be identified on the test punches. They are (i) the cone top and edge, (ii) the cone flank and (iii) the flat surface surrounding the cone.
At the cone top and edge, tool surface can reach high temperatures and pressures during the process, thermal fatigue and plastic deformation being the main failure mechanisms.
On the punch flank the contact pressure is relatively low throughout the process and a sharp peak of the wear can develop not far from the cone top, mainly due to a long sliding length.
At the cone bottom the workmaterial tends to separate from the punch, whilst on the flat surface a rather high and uniform potential wear develops, mainly with long piercing strokes.
The above tribological behaviour is strongly affected by punch and billet geometry, then a sensitivity analysis has been conducted aimed at defining punch and billet profile in detail.
Analysis has been based on physical and numerical simulations. Lead (3) and wax (14) have been used as model materials on one side and F.E.M. technique on the other. F.E.M. activity has been splitted in two parts (2). Simpler, purely mechanical simulations have been used to screen a wide range of candidate geometries, more sophisticated thermo-mechanical simulations have allowed to study thermal effects at the interface.
On the basis of the results of the sensitivity analysis, the two different profiles of Fig.3 have been selected for the two pairs of test punches, as well as the sizes (30 mm for the diameter and 48 mm for the length) of the cylindrical specimen.

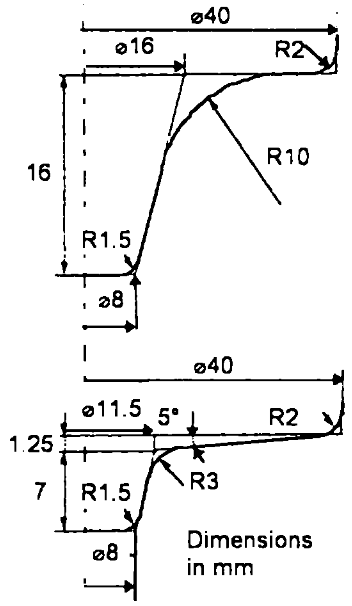


Fig.3 - Profiles of the two pairs of test punches.

On the cone top and edge of the slender punch higher temperatures are reached during the forging cycle; for this reason a plastic deformation is possible depending on the characteristics of the material and their treatment. On its flank higher abrasive wear is due to a longer sliding length and relatively low normal pressure. On the flat surface surrounding the shorter punch high wear is due to high normal pressure and short sliding length.

3. - Testing Equipment and Procedure

The general testing apparatus consists of the following subsystems:

- a heating device, to heat specimens to the test temperature at the prescribed heating rate,
- a press capable of applying the deformation load at the prescribed velocity and testing rate,
- auxiliary devices for loading and unloading of specimens,
- a programmable control unit, that controls parameters during the deformation process and synchronizes the different subsystems, and
- an acquisition subsystem to monitor mechanical and thermal parameters during testing.

The wear test is carried out on a Gleeble 2000 system equipped with the special testing device (4) designed by the Authors (Fig. 4) and integrated with an external electrical furnace. The general characteristics of Gleeble 2000 system can be summarized as follows:

- maximum force: 200 kN
- maximum punch speed: 2 m/s
- maximum punch stroke: 100 mm
- maximum counter-punch stroke: 30 mm

Fig.4 - The equipment for the wear test.

The wear test cycle consists of the following four stages (Fig.5):

- *Stage A: Heating.* The specimen is heated at the temperature prescribed for the deformation using a furnace.
- *Stage B: Lubrication and loading.* The two forming punches are in the backward position. Lubricant is sprayed on punches and, at the same time, the specimen is loaded from the furnace to the forming position.
- *Stage C: Deformation.* The specimen is deformed at the prescribed strain and strain rate between the two punches. Punch and counter-punch are controlled independently by the stroke unit and "hydrawedge" unit respectively.
- *Stage D: Unloading.* The specimen is ejected by the ejection plate during the return stroke of the forming punches and then unloaded. An air spray removes the scale on the punches.

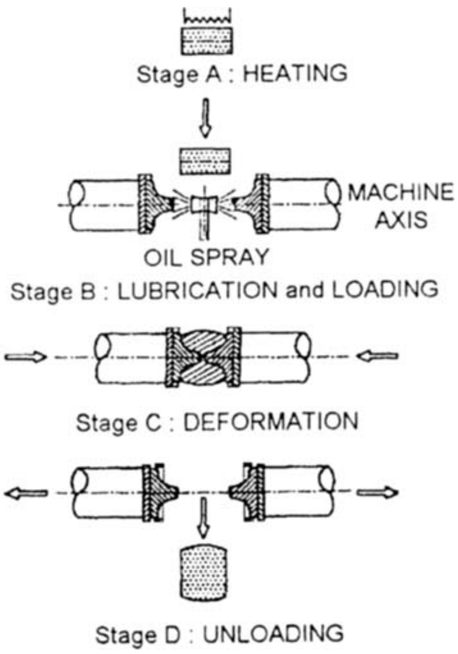


Fig.5 - Phases of the wear test cycle.

Using the Gleeble 2000 system and the equipment described above, the wear test can be performed automatically. For maximum size specimen of carbon steel the time required for each test is 15 seconds (heating from environment temperature to 1100 ° C is not included, because it is performed off-line by a furnace).

The whole test is controlled automatically by computer using Gleeble Programming Language (GPL), which allows (i) to control strain and strain rate, (ii) to synchronize the motion of punch and counterpunch with the motion of the feeding device and (iii) to time the different phases of the test cycle.

At fixed intervals, the program is stopped, the forming punches removed and their profile is measured on a coordinate measure machine. The recorded profile is compared with the original profile in order to evaluate wear distribution and its progress. This procedure is repeated until the total number of specimens is reached.

4. - Monitoring and Evaluating Wear Parameters

4.1- *Applicability of wear micro-mechanical models*

Measured wear has been compared with its numerical estimation based on the Archard's wear model (1). In this model, abrasive wear is a function of normal pressure p_i, local sliding velocity v_i and tool hardness H_i, as follows

$$Wear_i = K \cdot \int \frac{p_i \cdot v_i}{H_i} dt \qquad (I)$$

The following operational parameters have been measured :

- *Wear Distribution.* In order to evaluate wear distribution, the tool surface has been digitized using a Zeiss UMM 550 coordinate measuring machine with Holos software. The procedure for wear evaluation is based on the acquisition of the surface of the punch before starting the test and at regular intervals (50 tests).
- *Tool Hardness.* Hot hardness of the punch steel has been evaluated in the range of temperature predicted by F.E.M.. HRC hardness is measured after holding the specimen at the testing temperature for 20 minutes.
- *Pressure and Sliding Velocity.* Due to the difficulties related to the real testing conditions, the distributions of pressure and sliding velocity at the punch-specimen interface have been measured in experiments, where the proposed test has been replicated on a larger scale using layered wax as model material (14).

4.2- *Evaluation of wear parameters by an inverse numerical technique*

An inverse numerical technique has been used to improve F.E.M. prediction of the thermal field in the wear test through evaluation of the heat transfer coefficient (9).

The steps of the procedure are the following :

- Data preparation for F.E.M. simulation of the wear test. These data include : (i) surface temperature of specimen measured using a pyrometer, (ii) near surface temperature inside the punch using 3 type-K thermocouples embedded, (iii) punch stroke and (iv) piercing force.
- F.E.M. simulation of wear test. This step has led to a provisional estimation of interface temperature distribution.

- Design of a test for the evaluation of the heat transfer coefficient. Cylindrical specimens have been compressed between flat punches, one punch and the specimen being equipped with two thermocouples each. A scheme of this test is given at the top of Fig. 10. Operating conditions of this test are related to wear test conditions.
- Evaluation of the heat transfer coefficient. Heat transfer test has been simulated using F.E.M.. Experimental and numerical results have been compared in order to fit F.E.M. prediction of the temperature profile to experimental results. The value of the heat transfer coefficient, which allows the best fitting, is used in the next step.
- Application of the evaluated heat transfer coefficient in the F.E.M. simulation of the wear test.

5. - Results

5.1- *Applicability of wear micro-mechanical models*

The test has been validated through several sets of runs with different structural and operational parameters. The results obtained during a specific set of runs are presented and discussed, where structural parameters and operational conditions are summarized as follows :

- specimen and punch materials are DIN Ck40 and DIN X38CrMoV51 respectively, the latter being tempered to 54 HRC,
- the two punches are preheated at 300 °C by embedded electrical heaters,
- the temperature of specimens before starting deformation is 1100 °C,
- the lubricant (Sinol CS90) is sprayed on active surface of two punches before each stroke.

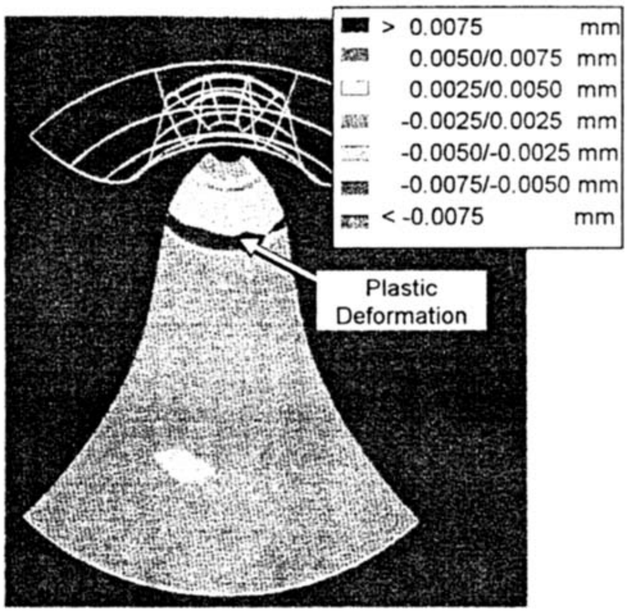


Fig.6 - Digitized punch surface after 50 strokes.

The surface of the punch has been digitized after each 50 strokes. Figs. 6 and 7 show an isometric representation of the worn surface of one of the two punches after 50 and 250 strokes respectively.
According to the classification of the tribological features given in §2, two main areas can be recognized on the worn surface:

- <u>the cone top and edge surfaces</u>, where thermal fatigue and plastic deformation are the main wear mechanisms, and
- <u>the cone flank and bottom surfaces</u>, where abrasive wear prevails.

At the cone top and edge surfaces, the temperature exceeds the punch tempering temperature, as confirmed by measurement of the temperature close to the surface, through thermocouples embedded in one of the two punches, as well as by F.E.M. prediction (Fig. 8). Further confirmation comes from the decay of the room temperature hardness measured on the cone top (Fig. 9).
Plastic deformation becomes visible after 50 strokes (see Fig. 6). The arrow in Figs. 6 and 7 shows the area of the punch where the diameter increases as a consequence of the plastic deformation.

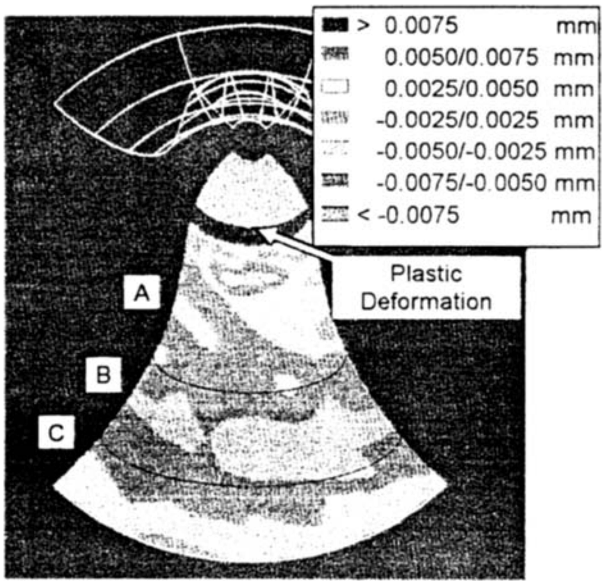


Fig.7 - Digitized punch surface after 250 strokes.

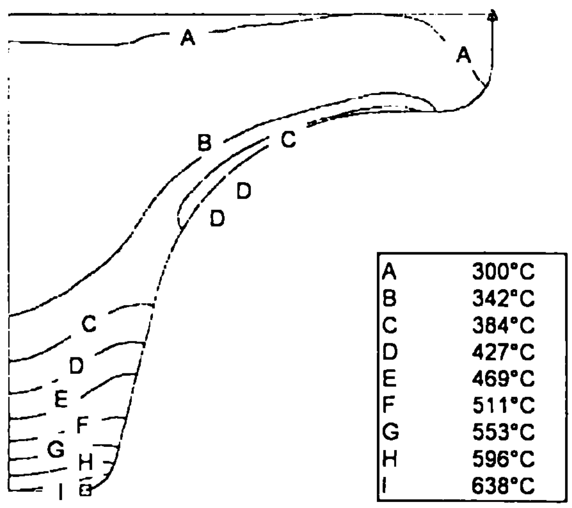


Fig.8 - Temperature distribution in the punch predicted by F.E.M. at the end of the stroke.

At the cone flank and bottom surfaces, three adjacent zones are shown in Fig. 7, where different operating conditions take place and different wear levels are measured :

- Area A (distance R from the axis in the range 7.14-7.78 mm), where plasticization is present and, during the test, a partial loose of contact between punch and billet occurs, which reduces both wear and surface temperature.
- Area B (distance R from the axis in the range 7.78-9.27 mm), where plasticization is still present, but

reduced, and there is no loose of contact, as confirmed by the increase of both surface temperature and measured wear.

- Area C (distance from the axis in the range 9.27-11.41 mm), where no plasticization is present, as well as no loose of contact.

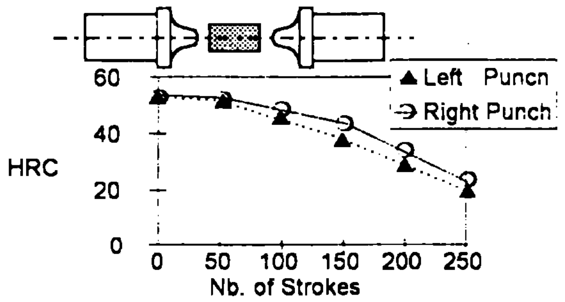


Fig.9 - Room-temperature hardness at the punch top.

In Table 1 measured (MW) and calculated (ARCH) values of the wear are compared. The calculated values have been obtained by using the Archard's model (eq. (I)), where K=1, p and v are predicted by F.E.M. and H is the hot hardness of the punch material.

Table 1

Area	R [mm]	MW [μm]	Temp [°C]	ARCH	K
A	7.14	36.00	420	0.963	37.399
	7.33	45.33	425	1.079	42.010
	7.78	55.60	442	1.114	49.897
B	8.42	80.00	424	1.087	73.567
	9.27	76.00	424	1.015	74.908
C	10.27	69.00	415	0.656	105.196
	11.41	47.17	403	0.489	116.944

As shown in Table 1, three different ranges of the factor K in the Archard's model are calculated for the three areas.

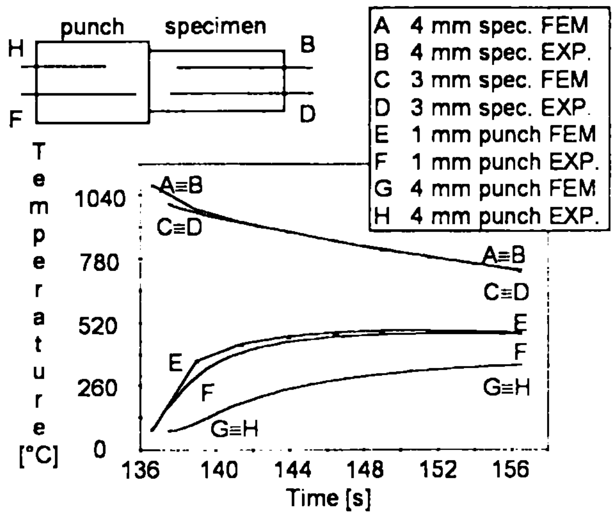


Fig.10 - Measured and calculated Temperature vs. Time for the measuring points.

5.2- *Evaluation of wear parameters by an inverse numerical technique*

Fig. 10 refers to the test specific for evaluation of the heat transfer coefficient. It shows measured and calculated temperatures during the test, the calculated values being those found at the end of the fitting procedure. The distance of the four thermocouples from the tool-specimen interface is shown in the table.

The heat transfer coefficient has been determined in the range 4700-5000 W/m^2 K. More details on the followed procedure, as well as a discussion of relevant results are given in (9).

6. - Conclusions

A simulative wear test for hot and warm forging tools has been developed with the twofold purpose of (i) verifying the applicability of wear micro-mechanical models in simulation of hot and warm bulk metal forming operations using FEM codes and (ii) evaluating wear parameters by an inverse numerical technique.

Test configuration is simple and embodies many of the tribosytems encountered in industrial forging operations and relevant tool wear and failure mechanisms, such as abrasion, thermal and mechanical fatigue as well as permanent deformation of tool surface.

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