CIRP Annals - Manufacturing Technology 64 (2015) 289–292

Contents lists available at ScienceDirect

CIRP Annals - Manufacturing Technology

journal homepage: http://ees.elsevier.com/cirp/default.asp

A compression-torsion-wear-test achieving contact pressures of up to eight times the initial flow stress of soft aluminium

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A R T I C L E I N F O

Keywords:
Tribology
Wear
Extrusion
Friction

A B S T R A C T

Different experiments exist for the characterization of friction and wear in metal forming, which try to reproduce the tribological conditions of the forming process as precisely as possible. A particular challenge arises from processes such as cold extrusion, with contact stresses that are several times higher than the initial flow stress of the workpiece material. In this paper, a new experimental setup for wear testing is presented and compared with available tests concerning contact pressure, surface enlargement and sliding velocity. Using a special encapsulation of the specimen, the newly developed compression-torsion-wear-test is able to scale the contact pressure to a multiple of the initial flow stress of soft aluminium.

1. Introduction

Friction and wear have an essential influence on the quality of final products and the life time of tools in metal forming processes. The occurring wear strongly depends on the tribological conditions in the different metal forming processes.

Cold forward rod extrusion is characterized by very high contact stresses σ_N [1] that reach a multiple (up to 6.4 times) of the initial flow stress σ_{y0} of the workpiece material [2]. Moreover, high relative surface enlargements (final surface A_1/initial surface A_0) up to four and relative velocities (material flow speed v_M/punch speed v_P) of up to 5.7 can occur [2]. For aluminium alloys the maximum true strain φ is limited to approximately 3.5 [3]. Surface enlargement, relative speed and true strain depend on the geometry of the extrusion die and strongly influence the distortion and destruction of the aluminium oxide layer. The break-up of the oxide layer enables the contact of pure and reactive aluminium with the tool surface and increases wear by adhesion. Therefore, when aluminium alloys are cold extruded, adhesion of workpiece material to the tool is mostly prevented by the use of lubricants which separate workpiece and tool [4].

In the past years efforts were made to substitute environmentally harmful lubricants by benign tribo-systems [1] in order to decrease ecological risks and disposal costs. A consequent continuation of these efforts is the current research into dry metal forming [5] and the associated avoidance of lubricants. In order to achieve this ambitious goal a reliable experiment which simulates the tribological conditions of cold rod extrusion with respect to contact pressure and surface enlargement is needed to explore the wear behaviour of, e.g. coatings and surface treatments that may enable dry metal forming. Additional requirements are simple specimen geometries and the possibility to quantify the wear volume without much effort after the test.

Especially in bulk metal forming different experiments with different advantages and disadvantages for the measurement of friction and wear conditions exist [6–8]. In general an experimental setup cannot entirely simulate tribological conditions of industrial forming processes. A particular challenge is the high contact stress in processes such as cold extrusion.

In this paper a newly developed compression-torsion-wear-test (CTWT) for the investigation of wear under the conditions of cold rod extrusion of pure aluminium is introduced and compared to the forming conditions of the process concerning contact pressure, surface enlargement and relative velocity. Moreover, the proposed test is compared to other tribological experiments for bulk metal forming processes. The newly developed CTWT is able to scale the contact stresses to a multiple (up to eight times) of the initial flow stress of pure aluminium (EN AW-1050a) and allows for surface enlargement. The key feature allowing for large contact stresses is a lateral encapsulation of the workpiece specimen. Furthermore, by the use of different specimen geometries variable forming histories can be realized. Thus, the tribological conditions on distinct parts of the die can be simulated.

2. Tribological tests for bulk metal forming

Different tribological experiments have been developed for different metal forming processes. Schey distinguishes between three different general types of tribological experiments based on the occurring plastic deformation [6]:

1. Tests involving bulk plastic deformation (e.g. ring compression test [9], spike forging test [10], sliding compression test [7,11])
2. Tests involving partial plastic deformation (e.g. pin-on-disk tests, strip-drawing tests [12] or twist compression tests [13–15])
3. Tests involving localized deformation (e.g. scratch-tests)

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http://dx.doi.org/10.1016/j.cirp.2015.04.086
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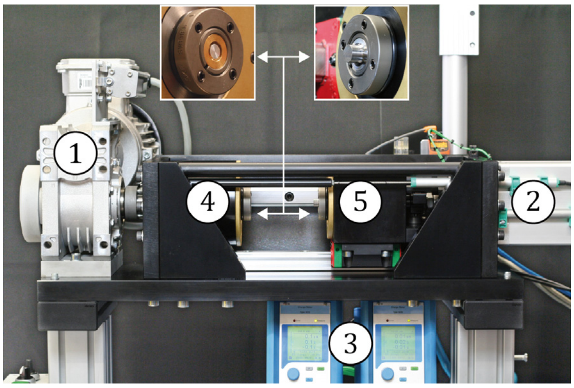

Fig. 1. Compression-torsion-wear-test with the components, ①: Engine, ②: Pneumatic cylinder, ③: Dynamometers, ④: Workpiece specimen holder, ⑤: Tool specimen holder; close-up of the specimen holders with workpiece specimen (left) and tool specimen (right) inside.

In Table 1 a comparison between a selection of different experimental setups regarding the requirements for an examination of wear behaviour within a cold rod extrusion process is given. In the ring compression and the spike forging test a remarkable deformation and surface enlargement of the workpiece takes place. The essential difference between cold rod extrusion and the ring compression and spike forging test respectively, is the low sliding distance. These experiments are more suitable for the investigation of forging processes. In contrast to cold extrusion the tribo-torsion-test [13,14] does not provide a surface enlargement. However, the possibility of large glide distances, flexible relative velocities and contact stresses are advantages of the tribo-torsion-test and representative for an extrusion process. The sliding compression test reaches large relative contact stresses and surface enlargements combined with a wide range of sliding velocities. Thus, a wide field of different forming processes can be represented within the experiment. The glide distance is limited due to the dimensions of the sliding table. Hence an investigation of wear for large glide distances is difficult.

In conclusion, the presented testing setups are suitable for an investigation of friction coefficients in different metal forming processes. To investigate wear in cold rod extrusion, a test enabling large contact-stresses in combination with surface enlargement, variable sliding velocities and arbitrary sliding distances is desired.

3. The compression-torsion-wear-test

3.1. Design of the compression-torsion-wear-test (CTWT)

The compression-torsion-wear-test from Fig. 1 (a prototype in an earlier stage of development was presented for the first time in [16]) is designed for an examination of wear in cold extrusion and the estimation of the suitability of different topographies and coatings for the use in dry metal forming.

Within the compression-torsion-wear-test (Fig. 2) an aluminium-specimen (the workpiece) rotates with a constant rotational velocity driven by an electric motor (20–80 rpm). From the opposite side a steel-specimen (the tool), mounted on a slide is axially driven by a pneumatic cylinder. The load is continuously adjustable up to a maximum of 18 kN and measured by a load cell. The bearing of the tool specimen disables a rotational motion. Thereby, a relative movement between both specimen parts is enabled. As a direct indicator for friction and wear the transferred torque from the rotated specimen to the static specimen is measured via a lever arm and a load cell over the complete testing period. The axial load, the rotational speed (relative velocity) and the glide distance are the controllable parameters of the CTWT and define the load spectrum of the test.

In contrast to the previously published prototype, the improved version of the CTWT enables an enlargement of the contact surface by a new specimen design (see Section 3.2). This improvement also requires new measurement capabilities in order to measure the deformation distance. Therefore, another sensor is integrated for the measurement of the current position of the slide and the tool specimen, respectively. Due to a mechanical re-design of the CTWT constant testing conditions can be guaranteed for high contact stresses.

In relation to the categories defined by Schey [6] the compression-torsion-wear-test belongs to the group of "twist compression tests" and "tests involving bulk plastic deformation" due to the motion-sequence and the enabled plastic deformations by the use of appropriate specimens.

3.2. Design of the specimens

Different types of specimens can be used in the compression-torsion-wear-test. The specimen holders (Fig. 1 position ④ and ⑤) have an inner diameter of 20 mm. The holders clamp the specimens over the complete lateral area with a length of 36 mm. Due to adapter plates inside the holders also specimens with less than 36 mm height can be mounted.

The main concept enabling high contact stresses that greatly exceed the flow stress of the workpiece material is to constrain the deformation of the specimen material. Therefore, a lateral encapsulation of the workpiece specimen is used (Fig. 2). The tool specimen seals the workpiece specimen on the front side after the contact of both specimens. In order to guarantee a sufficient tightness within the experiment, tight manufacturing tolerances are necessary. A minor 'leakage' (i.e. extrusion) of workpiece material to the outside can still occur. This effect was already reported by Lauterbach et al. [17] and mentioned by Schey [6] as a difficulty within previous twist compression tests. The tight manufacturing tolerances for the specimens will lead to an additional friction surface (outer lateral area of the tool specimen – inner lateral area of the encapsulation). These side effects make a distinct measurement of friction coefficients via the transferred torque complicated. However, the evolution of the transferred torque is a direct indicator for changes at the contact surface and a comparison of the wear behaviour between different surfaces via the resulting torques is possible, as long as the side effects are kept constant. This approach is presented for the CTWT in [18].

In Fig. 2a the ring design (also used in [16]) with a ring contact surface is illustrated. The two specimens consist of four parts (workpiece material, centring pin, encapsulation and tool material). Positive effects of the ring design are that the position of the centre of rotation lies outside the contact area and that an almost homogeneous relative velocity occurs across the contact surface due to the thin wall thickness of the ring. Thus, the influence of a prescribed relative velocity can be examined. Disadvantages of this design are the existence of two additional friction surfaces, the constrained deformation of material and hence the constant contact area. This behaviour is at the first glance in contrast to the conditions in cold extrusion where a surface enlargement normally

Table 1
Overview of the different selected experiments compared to the requirements of cold forward rod extrusion processes.

Properties	Ring compression [9]	Spike forging [10]	Tribo-torsion-test [13,14]	Sliding compression test [7,11]
Preferred material	Steel	Steel	Al–alloys (6xxx)	Steel
σ_N/σ_{y0}	1 to ≈1.5 [9]	>1	1 to ≈1.4 [13,14]	1–5 [11]
A_1/A_0	≈2	2–7 [10]	≈1	1.2–5.5 [11]
Large glide distances	No	No	Yes	No
Variable rel. velocity [mm/s]	Yes	Yes	0.125–24 [13,14]	20–200 [7,11]