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Friction assessment in uniaxial compression test: A new evaluation method based on local bulge profile

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ABSTRACT

Barreling in uniaxial compression test is widely used for friction evaluation, flow stress correction and unequal deformation quantification. However, the friction evaluation methods based on the maximum and top radii of the deformed cylinder are valid only at low level of friction because the contact of lateral surface with anvil desensitizes barreling to friction. To avoid this disadvantage, the effect of friction on bulge profile was investigated by finite element (FE) simulation and experiment. It was found that the slope of bulge curvature at the contact point is more sensitive to friction than other geometrical parameters. Though FE simulation tends to underestimate the side surface foldover, the predicted local bulge profile near the contact point is in good agreement with experiment. The slope of bulge curvature at the contact point is a good parameter to quantify friction condition and it can be measured by fitting to the local bulge profile. The calibration curves were obtained by FE simulation. The effects of material properties and initial aspect ratio on calibration were revealed. An empirical model considering the effect of material properties was developed for rapid friction estimation. The proposed method was applied to different lubricating conditions and surface states for three different materials. It shows good applicability in upsetting type deformation with normal pressure close to the flow stress.

1. Introduction

Uniaxial compression of cylindrical specimen is a simple and practical method to investigate the mechanical behavior and microstructure evolution in metal plastic working. Friction at workpiece-tool interface is a critical factor affecting the compression behavior. It would result in unequal deformation throughout the specimen and increase the apparent flow stress. A lot of work has been carried out on minimizing the friction in metal forming. However, friction is not negligible because the lubrication often deteriorates at severe contact and deformation condition. Friction testing, characterizing and modeling are still key issues for metal forming. It is important to the flow stress correction and unequal deformation quantification in uniaxial compression test.

Friction force is often quantified by the Coulomb friction model or the Tresca model (constant shear friction model) in metal forming for the convenience of process analysis:

$$\tau = \mu\sigma_n \tag{1a}$$

$$\tau = mK \tag{1b}$$

where τ is the friction stress, σ_n is the normal pressure, μ is the Coulomb friction coefficient, K is the shear yield stress and m is the Tresca friction factor. Since bulk forming processes typically involve high normal pressure, the Tresca model is applicable. Moreover, it is convenient to analyze bulk forming with the Tresca model, because it is unnecessary to obtain the normal pressure distribution on the contact surface. The friction factor is usually simplified as a constant over the interface between the workpiece and tool throughout the forming process.

The friction factor depends on the materials and surface states of workpiece and tools, normal pressure, lubrication, temperature and loading speed. Various methods have been developed to measure the friction factor. The simulative test, which characterizes the friction behavior indirectly by the geometrical change, is more applicable in bulk forming because it can reproduce the similar tribological condition (Wang et al., 2014). Groche et al. (2013) depicted the mostly used methods for friction measurement in bulk metal forming. They presented the requirements for tribological test stands and discussed in detail the applicability and flexibility of the current methods. It was found that all the tribological tests have their own limitations due to the complication of contact condition in metal bulk forming. A friction test may not be suitable

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for a specific forming process unless the tribological conditions are similar.

The uniaxial compression can also be used to quantify the friction condition. It is known as barrel compression test as friction is evaluated by the barreling shape. It can be applied to upsetting type forging with the ratio of contact pressure to flow stress close to 1. Due to its simplicity, the barrel compression test is widely employed. The determined friction factor can also be used to correct the flow stress and analyze the unequal deformation.

A key challenge in barrel compression test is to develop the evaluation method. This is because the barrel compression test is not designed for friction evaluation. The geometrical change is not as sensitive as it should be. It is almost impossible to predict the barreling geometry accurately by theoretical method. So the most important issues are to choose a geometrical parameter sensitive to friction and to develop corresponding evaluation method.

A pioneering work by Ebrahimi and Najafizadeh (2004) related the maximum radius (r_m in Fig. 1) of the specimen to friction factor based on the upper-bound solution (Table 1). However, as pointed out by Solhjoo (2010), this method greatly underestimates the friction factor because the measured r_m is much smaller than prediction. Solhjoo (2010) proposed a calibration curve based on upper-bound solution and FE simulation to correct the theoretical results. They suggested that the reduction in height should be low to reduce the errors in measuring barreling geometry. However, the degree of barreling decreases with reduction in height, which also limits the accuracy of friction evaluation.

Sivaprasad and Davies (2005) used a bulge parameter (r_c/r_m) to assess the friction factor. The calibration curve was determined by FE simulation. The bulge parameter varies little at large friction factor. As a result, it may produce large error at high level of friction. Similarly, FE simulation by Li et al. (2010a) suggested that the variation of friction factor does not have a strong effect on the shape of deformed sample. Instead, the radius of the originally flat end surface of the sample (r_t), changes greatly with friction. So a calibration variable with r_t was employed (Table 1) and the calibration function was determined by fitting to the simulated results (Li et al., 2010b). However it is difficult to measure r_t, because it is hard to trace the boundary of the originally flat end when the side surface of the specimen contacts the anvils (This phenomenon is also referred to as side surface foldover). Yao et al. (2013) examined the effects of friction, initial aspect ratio and strain hardening exponent on barreling profile and proposed a phenomenological model relating barreling profile and the three factors. The barreling profile is also depicted by r_c and r_m(Table 1), which may not be feasible at high friction.

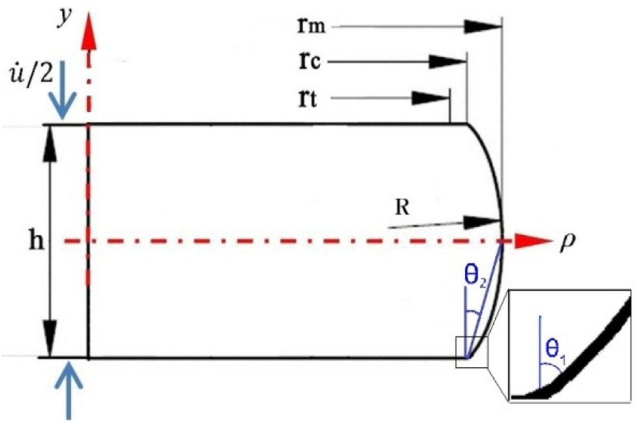

Fig. 1. Geometry of the deformed cylinder.

The current methods for friction assessments are based on the measurements of r_t, r_c and r_m. There may exist some other geometrical parameters (e.g. the curvature of the barreling profile) which can also be used to quantify friction. These parameters may be more sensitive to friction and easy to measure. Reliable friction evaluation method may be developed with these parameters.

The aim of this work is to improve the accuracy of friction evaluation in barrel compression test and extend its application by using new geometrical parameters. To this end, FE simulation was carried out to evaluate the bulge profiles under different friction conditions, initial aspect ratios, reductions in height and material properties. A new evaluation method was proposed and validated by experiment. The results can be used to estimate the friction factor in metal forming.

2. Materials and procedure

Three different materials were employed in this work to investigate the effect of material properties on friction evaluation: 304L stainless steel, 3A21 aluminum alloy and lead. The 304L stainless steel has a high working hardening rate at room temperature (strain hardening exponent n is 0.49) while the hardening exponent for 3A21 aluminum alloy is much lower ($n = 0.16$). Meanwhile, the lead is rate sensitive at room temperature. The rate sensitivity parameter (n') was determined to be 0.11 by compression tests at strain rates of 0.001 s^{-1}–1 s^{-1}.

The compression was carried out on a SANS CMT5205 electric universal testing machine at room temperature and at a constant die speed of 0.1 mms^{-1}. The initial aspect ratio was 1.5 for all specimens. Specimens were 10 mm in diameter for stainless steel and aluminum alloy. The as-received lead was a coarse-grained bar. The free surface became irregular after deformation. All the geometrical parameters were obtained by fitting to the measured profile on the free surface. The result would be more reliable if the critical size of the profile is much larger than that of surface irregularity. So the specimen of lead was 20 mm in diameter. The tests were conducted either using graphite lubricant (a graphite layer of 0.1 mm in thickness) or under dry friction. Moreover, electro-discharge textured platens were used to create high friction condition.

The specimens were sectioned axially after deformation. The bulge profile was photographed on a Leica DMI 3000 microscope at 50 times magnification and measured quantitatively using commercial software Image Pro. The radius of the top surface was measured with a Nikon MM-200 tool microscope.

Ring compression tests were employed to verify the proposed method. The proportion of ring geometry of the outer diameter, inner diameter and height was 20:10:7. The calibration curves were obtained by mean of FE simulation (Hu et al., 2015).

2D axisymmetric model was used to simulate the compression test and construct calibration curves. The material was assumed to be rigid-plastic and follow the isotropic hardening law and von Mises yield criterion. The stress-strain curves were obtained from the compression tests. FE simulation was also used to investigate the effects of material properties and initial aspect ratio on friction evaluation. The materials were assumed to be either power hardening ($\sigma = k_1\varepsilon^n$) or rate sensitive ($\sigma = k_2\dot{\varepsilon}^{n'}$).

3. A new parameter based on local bulge profile

Table 1 shows the measured geometrical parameters and corresponding calibration methods in barrel compression test in literature. r_m and r_c are the most employed geometrical parameters. The variation of r_m and r_c in compression was obtained by FE simulation. With dimensionless parameters (e.g. r_c/r_0) to exclude the effect of specimen scale, parameter sensitivity was