Journal of Materials Processing Tech. 251 (2018) 65–72

Contents lists available at ScienceDirect

Journal of Materials Processing Tech.

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

Stress correction method for flow stress identification by tensile test using notched round bar

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ARTICLE INFO

Keywords:
Tensile test
Notched specimen
Image analysis
Inverse analysis
Flow stress
Large strain

ABSTRACT

In this paper, a stress correction method for flow stress identification using notched round bar tensile test is proposed. Flow stress is evaluated in uniform elongation and local elongation until final fracture in a tensile test with circumference notched round bar tensile test specimens. Tensile load and change in the shape of the notch are measured by image analysis. In order to correct the average tensile stress to the flow stress, inverse analysis is applied to the tensile test. For the validation of the inverse analysis, numerical tensile tests are performed by FEM. As a result of applying the inverse analysis for the numerical tensile tests, the corrected flow stress completely reproduces the two types of reference flow stress curves which are determined by Swift's and Voce's law. On the other hand, the flow stress corrected by Bridgman's method, which is a conventional stress correction method, overestimated these reference flow stress curves. In the case of the actual tensile test of low carbon steel SS400 (in JIS), the flow stress corrected by inverse analysis corresponds to Swift's law determined in uniform elongation. As well as numerical tensile test results, the flow stress corrected by Bridgman's method is higher than that of obtained by the inverse analysis.

1. Introduction

In forging and plate forming, plastic working simulations by the finite element method (FEM) have been increasingly applied to shorten the time required for product development and cost reduction. The improvement of the prediction accuracy of the simulation of various factors, including machining force and product shape, is demanded. The improvement of the accuracy of the identification of flow stress curves is required because the prediction accuracy of plastic working simulation is significantly affected by flow stress curves, which represent the work hardening behavior of materials. In general, the flow stress curves of materials are obtained by a tensile test using dumbbell-shaped specimens because of its simple method. Fig. 1 shows the relationship between flow stress and average tensile stress and schematics of round bar specimens used in the tensile test. Once necking occurs in a specimen, the necking area is subjected to multiaxial stress. Therefore, the average stress in the direction of the tensile axis obtained by continuous measurement (hereafter, average tensile stress), $\sigma_{zave} = P/A$, does not agree with the flow stress of the material, σ_{flow}, where P is the tensile load and A is the minimum perpendicular cross-sectional area during continuous measurement. The direct measurement of flow stress after the occurrence of necking is not possible.

In the plastic working of actual products, a large strain exceeding the uniform elongation strain is mostly applied to products. Thus, σ_{flow} for large strains exceeding the uniform elongation strain is usually predicted by extrapolation on the basis of work hardening models, such as the Swift's law (Swift, 1952) and Voce's law (Voce, 1948). However, problems related to the selection of an appropriate hardening model and the prediction accuracy of parameters still remain.

As the method of identifying σ_{flow} from σ_{zave} after the occurrence of necking, Bridgman's stress analysis (hereafter, Bridgman's method) has been proposed. Bridgman (1952) analyzed the stress state at the necking area in a round bar used in the tensile test by elementary analysis assuming that the stress state is an axisymmetric problem. He demonstrated that σ_{zave} can be corrected to σ_{flow} by continuously measuring the radius of curvature R and the minimum cross-sectional radius a at the bottom of the necking area. A similar analysis was carried out by Davidenkov and Spiridonova (1946). Tsuchida et al. (2012) measured R and a by the stepwise tensile test, flow stress until just before fracture of various metals and alloys was evaluated using Bridgman's method. Yoshida et al. (2004) automated the measurement of the shape of the necking area by image analysis and succeeded in identifying σ_{flow}

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http://dx.doi.org/10.1016/j.jmatprotec.2017.08.008
Received 16 March 2017; Received in revised form 29 July 2017; Accepted 5 August 2017
Available online 08 August 2017
0924-0136/

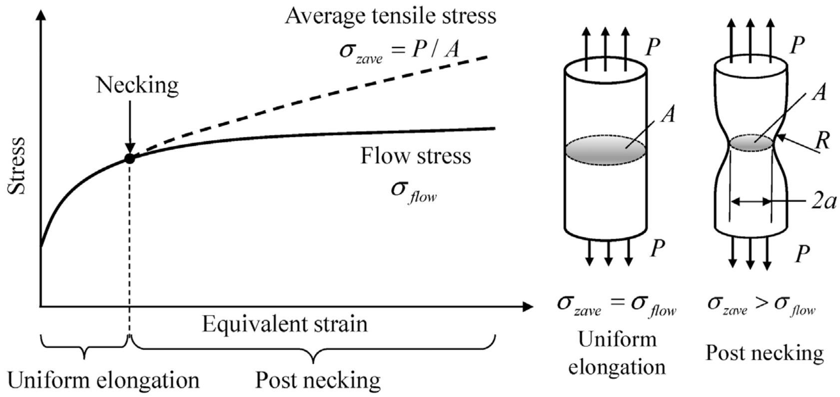

Fig. 1. Difference between the average tensile stress and the material flow stress in local elongation after necking.

until fracture and the critical damage values. Cabezas and Celentano (2004) applied Bridgman's method to uniaxial tensile test in order to obtain σ_{flow} after necking occurs. By comparing the tensile test and its FEM analysis, the validity of the obtained σ_{flow} was evaluated. Stress correction by Bridgman's method consists of simple equations; however, many assumptions are made during the derivation of the equations, which may lead to a low accuracy of stress correction. La Rosa et al. (2003) performed FEM analysis using the corrected flow stress curves obtained by the Bridgman's method. The magnitude of the approximations intrinsic to the Bridgman's method was quantified from the detailed comparison of the experimental and FEM results. Mirone (2004) pointed out that the radius of curvature at the necking area is not always necessary for stress correction by comparing experimental results with the FEM analysis results in detail. Mirone (2004) also developed empirical equations for stress correction with higher accuracy than that of Bridgman's method. However, there is no guarantee that these equations can be applied to all materials.

Along with the recent significant improvement of computer performance, the number of cases in which inverse analysis by FEM is applied to determine the unknown parameters of materials has been increasing. Hasegawa et al. (2009) identified the strain hardening exponent of the power law hardening model, with the aim of reproducing the relationship between elongation and load of a uniaxial tensile test by FEM. The agreement was improved by assuming the strain hardening exponent as the first and second order functions of the strain. Coppieters et al. (2011) identified the parameters of the Swift's and Voce's law by inverse analysis using the strain measurement data of digital image correlation (DIC). Kim et al. (2013) applied virtual fields method (VFM) and inverse analysis to the uniaxial tensile test of the sheet specimen, and identified the parameters of Swift's and modified Voce's law. These attempts were premised on work hardening models to express the work hardening behavior of the material after occurrence of necking. However, there is a problem that the accuracy of flow stress curves to be identified depend on the selected work hardening model when the parameters of the work hardening model are the target of identification.

On the other hand, other attempts have also been made to predict σ_{flow} after occurrence of necking without using the work hardening model. Dunand and Mohr (2010) calibrated the hardening modulus in each strain section of piecewise linear hardening model divided into three sections, in order to reproduce experimentally-measured force–displacement curve of low ductility aluminum plate. However, parameter calibration is considerable complicated for high ductility materials that many divided sections are required. An attempt using similar piecewise linear hardening model are also performed by Kajberg and Lindkvist (2004). In this case, the number of section divisions is four. Joun et al. (2008) reported an attempt to increase the number of section divisions. They developed an iterative algorithm to correct the piecewise linear flow stress curves, in order to reproduce experimentally-measured force–displacement curve of uniaxial round bar tensile test. However, since the calibrated data does not include deformation information of the necking, there is no guarantee that deformation of the necking is consistent.

In this study, we propose a new stress correction method to identify σ_{flow} until fracture including after the necking with high accuracy which does not depend on any work hardening model. We focus on a notched round bar tensile test which is simple in shape of specimen and can easily change stress loading path with change in the initial notch radius. Tensile load and change in the shape of the notch are measured by the tensile tests with image analysis. σ_{flow} is then identified by correcting the obtained σ_{zave}. For the determination of the amount of stress correction, inverse analysis by FEM is used. We conducted a study which consists of actual experiments and numerical experiments. In the actual experiment, tensile tests were carried out using notched round bar specimens which were made of low carbon steel SS400 (in JIS) with high ductility and the proposed method was applied to identify σ_{flow} until fracture. In addition, to demonstrate the validity of this method, numerical experiments by FEM using notched round bar specimens were carried out to confirm if the reference flow stress curve σ_{ref}, which is the correct curve prepared beforehand, can be appropriately reproduced. Stress correction using the conventional method (Bridgman's method) was also carried out by experiment and by numerical experiments to compare the accuracy of stress correction between the two methods. In this study, in order to confirm the effectiveness of the proposed method, all experiments and numerical calculations are limited to cold and quasi-static conditions.

2. Experimental method

2.1. Materials and shape of specimens

Specimens used in the tensile test were obtained by cutting a low carbon steel SS400 (in JIS) round bar and used in the experiment. Table 1 is a summary of the chemical composition of SS400. As shown in Fig. 2, four notched round bar specimens (a)–(d) and a smooth round bar specimen (e) were used. Table 2 is a summary of the material properties of the smooth round bar specimen obtained by the tensile test and the parameters of the Swift's law identified in the range of uniform elongation. Here, ε_p is the equivalent plastic strain. The necking occur at the notch on round bar specimens every time, it is easy to measure the shapes of necking specimens. In addition, by changing the initial notch radius R_0, the history of the stress applied to the necking area can be changed during the test. If the obtained flow stress

Table 1
Chemical composition of SS400.

C	Si	Mn	P	S
0.07%	0.16%	0.6%	0.024%	0.041%