Materials and Design 122 (2017) 226–235

Contents lists available at ScienceDirect

Materials and Design

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

Stress-strain curve measurements of aluminum alloy and carbon steel by unconstrained-type high-pressure torsion testing

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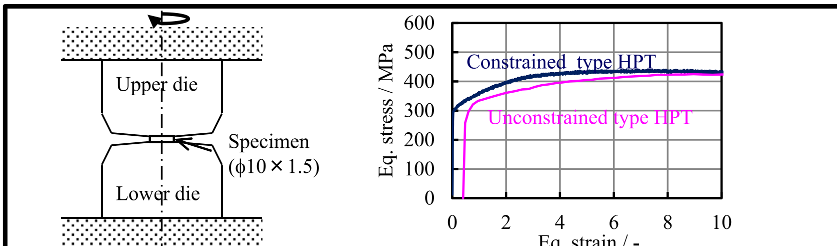
HIGHLIGHTS

- The unconstrained-type high-pressure torsion testing was applied to measure stress-strain curves in a large strain range.
- The procedure to convert a rotation angle-torque curve to a stress-strain curve was developed.
- Stress-strain curves of an aluminum alloy and carbon steel were measured up to a strain of 10.
- The difference of the unconstrained-type high-pressure torsion test was less than 10% compared to the other methods.
- No failure of dies was observed during the test.

GRAPHICAL ABSTRACT



(a) The unconstrained type HPT test (b) Comparison of stress-strain curves of A6063-T6 between the constrained and unconstrained type HPT tests.

Figure. The unconstrained type high pressure torsion test and measured stress-strain curves.

ARTICLE INFO

Article history:
Received 17 January 2017
Received in revised form 22 February 2017
Accepted 3 March 2017
Available online 6 March 2017

Keywords:
Stress-strain curve
High-pressure torsion
Aluminum
Super large strain range
Aluminum alloy
Carbon steel

ABSTRACT

In measurements of stress-strain (SS) curves, it is difficult to achieve a large strain, i.e., 5 (500%), which is introduced in actual metal forming processes. Recently, a constrained-type high-pressure torsion test was applied and allowed measurement of the SS curve up to a strain of 10. However, the testing method cannot be used for steel specimens, because a compression pressure of over 3 GPa has to be applied to a specimen via the dies, which leads to brakeage of the dies due to the stress concentration. Therefore, an unconstrained-type high-pressure torsion was applied for measurement of the SS curves of carbon steel. With this method, the rotation angle of the upper die and torque curve could be measured without breakage of the dies. After development of the methodology to convert the rotation angle-torque curve to a SS curve, the SS curves of an aluminum alloy and carbon steel were measured. The validity of the measured SS curves was examined by comparing the SS curves measured by the compression test, the constrained and unconstrained-type high-pressure torsion test. It was also confirmed that the difference of the unconstrained-type high-pressure torsion test was less than 10% compared to the other methods.

1. Introduction

1.1. Measurement methods of SS curves

The SS curve is an essential material property in the field of metal forming. There are several conventional testing methods

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http://dx.doi.org/10.1016/j.matdes.2017.03.007
0264-1275/

for measuring the SS curve, such as the tensile test, compression test [1–4], and torsion test [5–7]. Although several studies have reported extension of the strain range [8–10], achieving a large strain with those methods is difficult. This is because when the strain is increased during testing, the specimen breaks at a small strain point. In some metal forming processes, such as forging [11,12] and machining [13], the strain tends to exceed 5 (500%), which cannot be obtained with conventional methods.

Recently, a method has been proposed to cover a very large strain range up to 10 (1000%) [14]. Constrained-type high-pressure torsion (C-HPT) [15–17] is applied in this method. During the testing, a very large hydrostatic stress is applied to a specimen and the stress enhances the formability of the material. As a result, a very large strain range can be achieved. A schematic diagram of the C-HPT testing apparatus is shown in Fig. 1 (a). There are upper and lower dies, and a ring to suppress radial deformation of the specimen. The specimen is compressed to apply the large hydrostatic stress, then torsionally deformed by friction force between the dies. In measurements with pure aluminum, a pressure of 1 GPa was applied to a specimen to generate friction force [14]. When applying the method to a material having higher strength than pure aluminum, e.g., steel, a higher pressure is required. However, the die dimensions of the C-HPT facilitate breakage. When high pressure is applied to the dies, the neck of the dies tends to break due to stress concentration. Fig. 1(b) shows dies broken at the neck with a pressure over 3 GPa.

According to the authors' experiences, when the C-HPT is applied to steel, a pressure of more than 3 GPa is required to prevent slippage between the dies and the specimen. Therefore, a new method should be utilized to measure SS curves of steels in a very large strain range.

There is another high-pressure torsion test, named the unconstrained-type high-pressure torsion (UC-HPT) test [18]. In this test, radial deformation is not constrained. The schematic diagram of the UC-HPT test is shown in Fig. 2. In terms of the die dimensions, the stress concentration in the UC-HPT test is less than that of the C-HPT test. However, when the UC-HPT test is utilized for measuring flow stress, a difficulty emerges: there is no ring to suppress radial deformation. Therefore, a burr forms at the periphery during the testing. This means that the shape of the specimen shape continues to change, which does not happen in the C-HPT test.

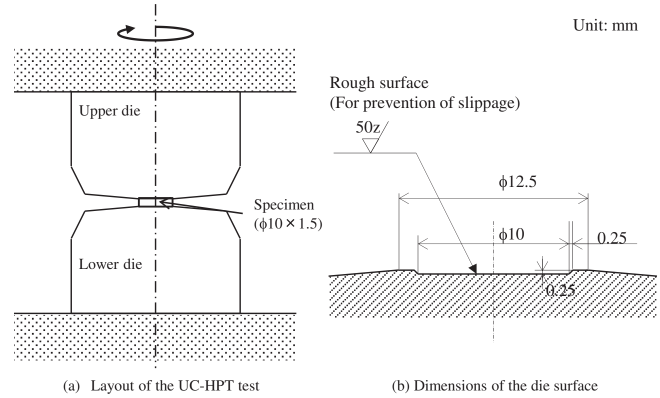

Fig. 2. UC-HPT test.

1.2. Study purpose and strategy

In this study, the UC-HPT test was utilized to measure SS curves. In chapter 2 and 3, experimental methods and results of UC-HPT tests were shown. As mentioned above, a specimen was not uniformly deformed. It led to non-uniform strain distribution in the specimen. Therefore, in chapter 4 and 5, the finite element simulation was conducted to quantify the strain distribution. In chapter 6, a modelling was made to calculate average strain from the strain distribution in the specimen without the finite element simulation to reduce computation time. Then, a methodology to apply the UC-HPT test for measurement was developed. At last, the measured SS curves were verified.

As mentioned before, it is not possible to measure SS curves by conventional methods. Therefore, there is no reliable SS curve that can be used to test the validity of the SS curves measured using the UC-HPT test. Therefore, two types of validation were performed. In the first validation, aluminum alloy A6063-T6 was chosen. The C-HPT test can be applied at a pressure of 2 GPa. The SS curves of A6063 were measured with both the C-HPT and UC-HPT tests, and the consistency was examined. In the second validation, carbon steel S10C (JIS-S10C, containing 0.1 wt% carbon) was chosen. S10C is harder than A6063-T6, and over 3 GPa is required to prevent slippage between the die and a specimen. Therefore, 3 and 5 GPa were applied to S10C in the UC-HPT test.

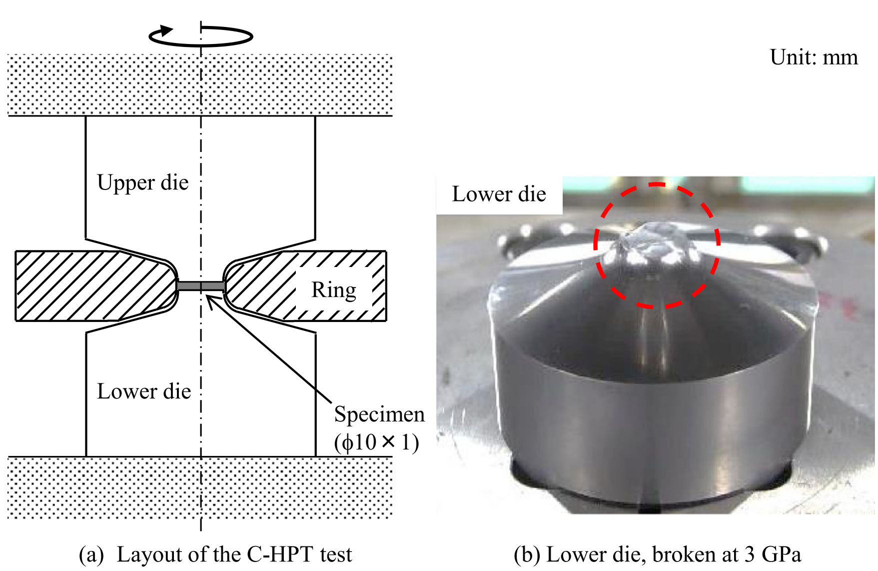

Fig. 1. The C-HPT test and failure of the lower die.