International Journal of Mechanical Sciences 130 (2017) 174–187

Contents lists available at ScienceDirect

International Journal of Mechanical Sciences

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

Measurement uncertainty evaluation with correlation for dynamic tensile properties of auto-body steel sheets

M.K. Choi[a], H. Huh[b,*], S. Jeong[c], C.G. Kim[d], K.S. Chae[d]

[a] Carbon & Light Materials Application R&D Group, Korea Institute of Industrial Technology, 222 Palbok-ro, Deokjin-gu, Jeonju, Jeollabuk-do 54853, Republic of Korea
[b] Department of Mechanical Engineering, KAIST, 291 Daehak-ro, Yuseong, Daejeon 34141, Republic of Korea
[c] Hyundai Heavy Industries, 1000 Bangeojinsunhwan-doro, Dong, Ulsan 44032, Republic of Korea
[d] National Center for Standard Reference Data, Korea Research Institute of Standards and Science, 267 Gajeong-ro, Yuseong, Daejeon 34113, Republic of Korea

ARTICLE INFO

Keywords:
Auto-body steel sheet
Correlation
Dynamic tensile properties
Measurement uncertainty
Uncertainty evaluation

ABSTRACT

This paper is concerned with evaluation of the measurement uncertainty of true stress–true strain curves of auto-body steel sheets at various strain rates considering correlation of input quantities. The measurand is defined as the true stress at strain rates ranging from 1 to 100 s^{-1}. The true stress has a functional relation with the tensile load, the initial width and the initial thickness, the initial and deformed length of a specimen. Since the initial and deformed lengths of a specimen are measured by the exactly same procedure, the two quantities are correlated and considered in the uncertainty evaluation model. An analytic model to evaluate the measurement uncertainty is established properly by considering the correlation with the guidelines suggested by the GUM, ISO/IEC Guide 98-3. The standard uncertainties of the input quantities and influence factors are evaluated for dynamic tensile properties of DDQ, TRIP980, and TRIP1180 steel sheets as well as the covariance associated with the correlated input quantities. The standard uncertainty of the true stress is also evaluated to consider the change of the strain rate during the test. The combined standard uncertainty is then evaluated including standard uncertainties of the input quantities and influence factors. The expanded uncertainty is obtained by choosing an appropriate coverage factor. The absolute amount of the measurement uncertainty decreases with consideration of the correlation between the initial and deformed length since their uncertainty contributions are almost canceled during the calculation of combined uncertainty. Finally, the reliability of dynamic tensile properties of auto-body steel sheets is presented with a statement of the expanded uncertainty.

1. Introduction

Auto industries make steady and persistent efforts to develop lightweight vehicles for improvement of fuel efficiency. Lightweight vehicles, however, must be designed with enhanced crashworthiness of the auto-body for passenger safety. The Insurance Institute for Highway Safety (IIHS) introduced a challenging small overlap frontal crash test in 2012 but some models still needed improvement, even though vehicles are generally safer now than ever. For lightweight and crashworthy auto-body design, numerical analyses are usually conducted, which need reliable material properties. For accurate numerical analyses, it is important to acquire the material properties of auto-body steel sheets with an appropriate measurement procedure. The material properties need to be precisely measured with the variation of the strain rate ranging from the quasi-static to about 500 s^{-1} as observed in a car crash test, since the flow stress of a steel sheet tends to increase as the strain rate increases [1–3].

Conventional material testing machines [4] are usually used to measure the material properties at the quasi-static state under 0.1 s^{-1}. At higher strain rates over 1000 s^{-1}, split-Hopkinson pressure bar techniques which are also called Kolsky's bar [5,6], are utilized to obtain the tensile properties. Several experimental methods were proposed to obtain the material properties at intermediate strain rates ranging from 1 to 200 s^{-1}; such as a rotary flywheel machine, a cam plastometer which uses a rotating cam to compress the specimen [7] and a drop-weight method which deforms the specimen by dropping a heavy object [8,9]. Recently, servo-hydraulic machines are utilized to measure the material properties at intermediate strain rates with advantages of precise control of test speed with various strain rates [10–17]. Huh et al. developed a servo-hydraulic machine and designed gripping jig fixture for accurate acquisition of tensile loads with reduction of the load-ringing phenomenon at high strain rates [10]. Othman et al. suggested a modified servo-hydraulic machine which measures the transmitted stress wave to avoid the load-ringing phenomenon [11]. Cao et al. investigated effect of strain rate and temperature on mechanical behavior of rephosphorized steel by utilizing a servo-hydraulic machine [12]. Durrenberger et al. carried out tensile tests of auto-body steel sheet at wide range of strain rates and a servo-hydraulic machine

* Corresponding author.
E-mail address: hhuh@kaist.ac.kr (H. Huh).

http://dx.doi.org/10.1016/j.ijmecsci.2017.05.041
Received 29 December 2016; Received in revised form 16 May 2017; Accepted 20 May 2017
Available online 8 June 2017

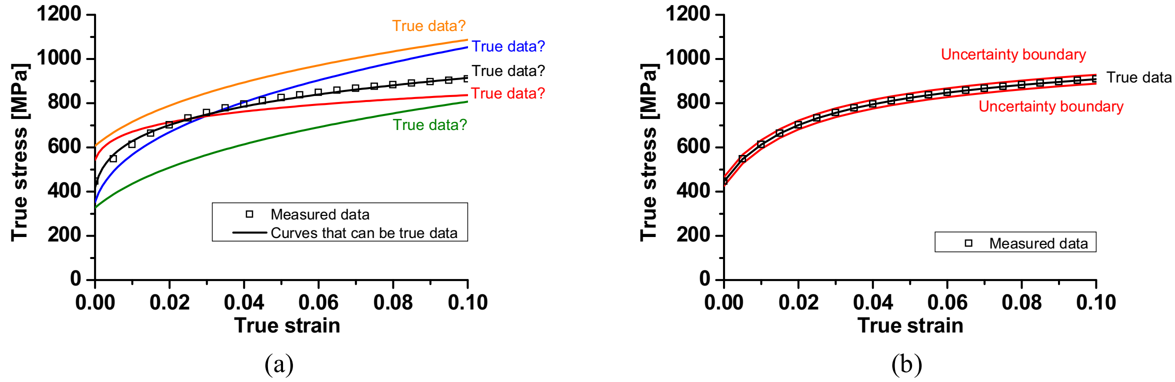

Fig. 1. Measured dynamic tensile properties: (a) when there is no standard uncertainty evaluated; (b) when the standard uncertainty is evaluated.

is utilized in the intermediate strain rate tensile test [13]. Huh et al. [18] and Choi et al. [19] proposed a measurement procedure for dynamic tensile properties with the use of a servo-hydraulic machine, which included indirect displacement measurement methods such as digital image correlation method with a high speed camera. They also proposed a method of eliminating unnecessary signals by the load-ringing phenomenon with a special smoothing technique using an FFT filter.

The dynamic tensile properties must be measured by a standardized experimental method considering the standard uncertainty [20] as well as the reliability and the traceability of the experiment. As every measurement is prone to error, error analysis has long been a part of the practice of a measurement. However, the error is an idealized concept and cannot be precisely known while the true value is not known. The concept of uncertainty as a quantifiable attribute has been proposed and the measurement result is complete only when it is accompanied by a quantitative statement of its uncertainty [21]. The measurement result can be expressed by the evaluation of standard uncertainty with a proper margin of confidence. The guide to the expression of uncertainty in measurement (GUM) [22–25] was published to provide general rules for evaluating and expressing the uncertainty in measurement. In addition, some other methods enabling to evaluate the measurement uncertainty have been proposed using probabilistic approaches such as the polynomial chaos methods [26] and a Monte Carlo method [24] for the cases when the GUM [22,23] is inadequate. The verification methods for high speed tensile tests, however, have not been established until Huh et al. [18] proposed a measurement procedure and evaluated the standard uncertainty for the high speed material properties in reference to the GUM [22,23]. They evaluated the standard uncertainty with the proper measurement procedure announced in ISO 26203-2 which explains standard methods for tensile testing of metallic material at the strain rate ranging from 10^{-2} to 10^{3} s^{-1} using a servo-hydraulic test system [27]. They defined the measurand as the true stress and then investigated uncertainty sources in determining the true stress to evaluate the standard uncertainties of the input quantities and influence factors of the true stress. With this approach, the combined standard uncertainty of the true stress data with respect to the true strain was estimated to verify the reliability of the proposed measurement procedure according to the guideline for uncertainty propagation. Fig. 1 (b) explains the address of the dynamic tensile properties when the standard uncertainty is evaluated and thus the uncertainty boundary is specified. On the other hand, Fig. 1 (a) shows the ambiguity of the measured data when there is no standard uncertainty evaluated and thus no difference between the measured data and the true values which cannot be obtained. The true values could be one of the four possible cases in Fig. 1 (a) where the yield stress could be smaller or larger than the true one; the strain hardening rate could be smaller or larger than the true one; both of the yield stress and the strain hardening rate could be smaller or larger than the true one. The paper, however, lacks in consideration of the correlations between input quantities which are any of the relationships among several input quantities. Some of the input quantities are obtained from the same measurement devices or the same reference and it needs to be proved whether these input quantities are independent or correlated. The GUM [23] states that the correlations must be taken into account to evaluate the combined uncertainty when some of the input quantities are correlated. In addition, there is also a necessity to consider the standard uncertainty of the change of the strain rate for the uncertainty evaluation. During high speed tensile tests, it is difficult to maintain a constant strain rate because the length of the gauge section of a specimen increases during the test. Therefore, the change of the strain rate needs to be considered in the measurement uncertainty evaluation for the dynamic tensile properties.

In this paper, the measurement uncertainty of dynamic tensile properties is evaluated with the modification of the uncertainty evaluation model considering the correlations between input quantities and the standard uncertainty of the change of the strain rate in order to establish the measurement procedure more reliably. This paper builds on the work by Huh et al. [18] in considering the proposed measurement method of the dynamic tensile properties and standard uncertainty evaluation of each measurement procedure. Based on the previous procedure, a proper uncertainty evaluation model is supplemented with consideration of the correlations between input quantities. Sources of uncertainty of the change of the strain rate are also investigated to evaluate the standard uncertainty of the true stress by the change of the strain rate. Finally, the reliability of the dynamic tensile properties on a prescribed strain rate condition is presented with a statement of the expanded uncertainty. The measurement uncertainty of the true stress decreases when the correlations between input quantities are considered. For demonstration, DDQ (Deep drawing quality), TRIP (Transformation induced plasticity)980, and TRIP1180 steel sheets were selected as typical steel sheets and their true stress–true strain curves are shown with the corresponding measurement uncertainties.

2. Measurement of the dynamic tensile properties

2.1. Measurand, input quantities and influence factors

Huh et al. [18] defined the true stress as the measurand which is destined object being measured. In this measurement, the measurand is the true stress for uniform elongation before necking at a specified strain rate. As shown in Huh et al. [18], the true stress is a function of the five input quantities: the load F; the initial thickness t_0; the initial width w_0; and the initial length l_0 and deformed length l_d of the gauge section in a specimen as shown in Eq. (1). σ_t denotes the true stress and A_d denotes the cross-sectional area of the gauge section in the deformed specimen, respectively. The current cross-sectional area can be expressed with the deformed length and initial dimensions by the assumption of an incompressible continuum: