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A method to investigate strain rate effects on necking and fracture behaviors of advanced high-strength steels using digital imaging strain analysis

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ABSTRACT

Quasi-static and dynamic tensile tests are performed to investigate the effects of strain rate on the necking and fracture behavior of high-strength steels for automotive structures. A newly developed strain analysis system is applied to quasi-static and dynamic tensile tests to measure the strain propagation with a digital camera or a high-speed video camera. For the dynamic tensile test, a Hopkinson bar method utilizing a high-speed video camera is developed for the visualization of the strain propagation under a high strain rate of 10^2 s^{-1}. The effect of strain rate on the stress–strain relations and strain localization behavior is investigated for steel sheets with tensile strengths ranging from 270 MPa to 1470 MPa, including advanced high-strength steels. To improve the strain measurement technique of the Hopkinson bar method, the digital imaging strain analysis method is applied to determine the dynamic stress–strain relations using the high-speed digital images. Regarding the strain-rate dependence of fracture behavior, the limit strains corresponding to the fractures are evaluated by measuring the fractured shapes. The local true stress–strain relation and the strain rate history in a necking region are investigated to estimate the material properties at large strains and high strain rates. Finite element analyses simulating the dynamic strain localization is performed for a mutual assessment of the experimental result and the numerical prediction.

1. Introduction

Achieving an optimized combination of crash safety performance and a lightweight structure has been an important challenge in automotive body engineering [1,2]. The application of high-strength steel to auto-body structures has been considered an efficient solution to this problem and is feasible at a lower cost in volume production in the automotive industry [1]. As the formability of high-strength steels has been improved by optimizing the metallic microstructure, the range of applications of high-strength steels has been expanding into auto-body structures [3–5]. Thus, advanced high-strength steels with strengths of 980 MPa–1470 MPa are now used in structural parts [4], which play a crucial role in crash safety performance.

While advanced high-strength steels both reduced the body weight and improved crashworthiness [6], the fracturing of these materials in a crash event has been a critical issue for the reliable design of the structural components [7]. High-strength steels are often more prone to necking or failure in crash deformation than conventional mild steels because the elongation of the steel decreases as its strength increases [4]. The failure behavior in various types of steels needs to be considered in material selection and body design to realize the maximum potential of advanced high-strength steels [7].

Regarding the optimization of materials and structures in the body component, the finite element method has been considered a powerful tool to estimate the crash performance [7]. However, there remains a need to continually study and improve the material models in the numerical simulations due to the ever-increasing demands for more accurate predictions of the deformation and material failure.

Recently, a considerable number of studies have been conducted on the dynamic deformation and fracture of high-strength steels using experimental and numerical analysis approaches. To measure the dynamic response of materials, various types of testing methods have been proposed depending on the strain-rate range.

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B.L. Boyce et al. developed a dynamic servo hydraulic method to perform tensile tests with cylindrical bar specimens over this entire range from quasi-static to dynamic [8]. The experimental results showed the effect of strain rate on the stress–strain curves of high-strength steel alloys at strain rates from 0.0002 s^{-1} to 200 s^{-1}. Akhtar S. Khan et al. also investigated the quasi-static and dynamic responses of advanced high-strength steels, including TRIP800 and DP800 using the split Hopkinson pressure bar (SHPB) method [9]. The typical strain rates that can be achieved using this technique range from 500 s^{-1} to 1000 s^{-1}.

To improve the accuracy of the dynamic measurement, many technologies have been developed by modifying the original split Hopkinson bar method [10–12]. G. Solomos et al. proposed a modified Hopkinson bar method with a pressure-bar loading device for tensile tests to obtain a stable elastic wave in the bars [10]. P. Verleysen et al. indicated the difficulty of the strain measurement in the original split Hopkinson [12]. Their optical strain measurements revealed that the classical measurement techniques tend to overestimate the actual strain depending on the definition of the gauge length of specimens. Y. Li et al. proposed an optical technique to directly measure a local strain in a deformed specimen in the Hopkinson bar method for the accurate estimation of the true stress–strain relation [13].

To validate the dynamic response measured by the Hopkinson bar methods, numerical analyses were performed to simulate the material deformation during the tensile tests [14,15]. Y. Chen et al. proposed a technique to compare the results from experiments and simulations for mutual verification [14]. In these papers, the necking and fracture behaviors of materials in dynamic deformation were investigated by numerical simulations using material parameters obtained from the tensile tests. The numerical results improved the understanding of the necking and fracture behaviors under high strain rates.

Many previous studies have experimentally clarified the necking and fracture behaviors in both static and dynamic deformation [16–23]. Regarding static deformation, S. Coppieters et al. focused on the post-necking hardening behavior of mild steel [16], observing that standard tensile tests only allow for the identification of the hardening behavior up to the point of maximum uniform elongation because of difficulties in measuring the actual strain after necking. To address this issue, the application of the digital image correlation technique (DIC) was proposed to measure the strain in the necking region during a quasi-static tensile test [16,18]. In terms of dynamic tests, J.P. Noble et al. measured the necking behavior of a round-bar specimen using a Hopkinson bar method with high-speed photography [19]. Giuseppe Mirone performed a numerical simulation under the same conditions used in Noble's experiments, revealing the effects of the strain rate on the necking behavior for Remco iron [20]. J. Peris et al. proposed a combined experimental–numerical approach using a DIC system to determine the stress–strain behavior at large strains in a high-strain-rate tensile test for Ti6Al4V titanium alloy [21]. V. Tarigopula et al. presented a study on strain localization in the tensile specimens using a DIC system with high-speed photography for DP800 steel [22]. G. Besnard et al. also analyzed the necking behaviors of cylindrical samples using stereo high-speed cameras [23]. The measuring systems were successfully applied to track the strain field from initial plasticity to fracture and thus provided substantial information concerning the localization and inception of the ductile failure at high strain rates.

The objective of this study is to evaluate the stress–strain relations and the strain localization over a wide range of strain rates for various types of steel sheets, including mild and advanced high-strength steels. The previous studies [6,9] have revealed certain of the dynamic properties of automotive steel sheets. Thus, a newly developed strain analysis system was applied to perform both quasi-static and dynamic tensile tests to measure the strain propagation. Using the digital imaging strain analysis system, the dynamic strain localization for various types of high-strength steels was investigated using a Hopkinson bar method utilizing a high-speed video camera. In addition, the limit strains corresponding to fracture were evaluated by measuring the fractured shapes with a 3D laser microscope. To improve the strain measurement technique of the Hopkinson bar method, the strain analysis method was applied to determine the dynamic stress–strain relations using the high-speed digital images. The local true stress–strain relation and the strain rate history in the necked region were investigated to estimate the material properties at large strains and high strain rates. Finite element analyses simulating the dynamic strain localization was performed using a material constitutive model with parameters that were identified with the measured local stress–strain relation. The validity of the measured material properties were discussed based on mutual assessment of the experimental results and the numerical predictions.

2. Experimental procedure

2.1. Materials

Various grades of steel sheets were selected to investigate the effect of the material properties on the stress–strain relations and strain localization behavior. Table 1 lists the mechanical properties along rolling direction and thickness of the steel sheets used in this study. The mechanical properties, including the static yield strength, tensile strength, and elongation, were determined by static tensile tests based on the Japanese Industrial Standard (JIS) [24]. The specimen used in the tests had a gauge length of 50 mm and a width of 25 mm. The tensile tests were performed with a constant displacement velocity of 10 mm/min. Considering the specifications of steel sheets commonly used in automotive body structures, a material thickness of 1.6 mm was selected. Table 1 also lists the steel grades, which correspond to the tensile strength levels. The material types listed in the table describe the steel microstructures: IF represents interstitial-free steel, low-C represents low-carbon steel, and DP represents dual-phase steel with a microstructure consisting of a soft phase of ferrite and a hard phase of martensite. DP steel is an advanced high-strength steel and has a higher elongation than conventional steel. M represents full-martensite-phase steel. Material No. 6 had a tensile strength of 1470 MPa, which is currently the highest strength available in commercial steel sheets for automotive use [4]. Fig. 1 presents the static nominal stress–strain curves for the six materials measured by the JIS tensile tests [24]. The strain was measured using a differential transformer type extensometer with a gauge length of 50 mm. As shown in the figure, the selected materials had a wide range of strengths and elongations.

2.2. Digital imaging strain analysis method

A digital imaging strain analysis system was developed to measure the strain distribution and the propagation during tensile tests. The evaluation of the strain localization behavior and the strain distribution before the fracture motivated the development of an in-house system for a wide range of applications. Many strain measurement systems based on the DIC method are in practical use [16,18,21–23]. In the DIC method, a random pattern is painted on the sample to determine the displacement of objects on the sample using the imaging correlation calculation. Based on our experience, the painted pattern occasionally causes instability of the