Failure Elongation of Steel Sheets for an Auto-body at the High Strain Rate

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Abstract

This paper presents the dynamic failure elongation of conventional mild steels and advanced high strength steel sheets such as TRIP and DP steels. The failure elongation has been obtained from the high speed tensile testing machine with various strain rates ranged from 0.003/s to 200/s. The experimental result demonstrates that the tensile elongation does not simply decrease as the strain rate increases, but it decreases from the quasi-static state to the strain rate of 0.1 or 1/s and increases again up to the strain rate of 100/s. Furthermore, some high strength steels have the tendency that the tensile elongation increases as the strain rate increases. This tendency has varieties depending on the microstructure and forming history of sheet metal. Moreover, the localized strain rate hardening in the necking region induces the increase of elongation. This phenomenon is very important not only in sheet metal forming but also in the crashworthiness evaluation to predict the fracture of sheet metal members.

Keywords

Fracture elongation, Sheet metal, High strain rate

1 Introduction

The sheet metal forming process is one of the most important fabrication processes for an auto-body with development of forming techniques. Due to remarkable development of forming techniques, its capabilities have been extended to very complicated sheet metal forming and multi-stage forming. Although the formability is important and indispensable for success in very complicated sheet metal forming, few studies have been done about the formability of sheet metal at the high strain rates since it was difficult to make the tensile test of sheet metal at the high strain rate ranged from several tens to hundreds per second. The dynamic tensile properties of auto-body steel sheets are important since the range of the strain rate is under 500/s in a real auto-body crash and at which the dynamic response of steel sheets is different from static one [1-4]. Mechanical, pneumatic and servo-hydraulic loading methods have been used to measure mechanical properties of materials at this range of the high strain rates [5]. Dudder [6] and Ambur et al. [7] studied to obtain the material properties using a drop weight method and other researchers used a cam plastometer and a rotary flywheel machine and so on. Nowadays, servo-hydraulic material testing machines are employed in most research works [8, 9]. However, a few in-depth studies have been published about the dynamic material properties such as the yield and tensile strength as well as the tensile elongation at the high strain rates.

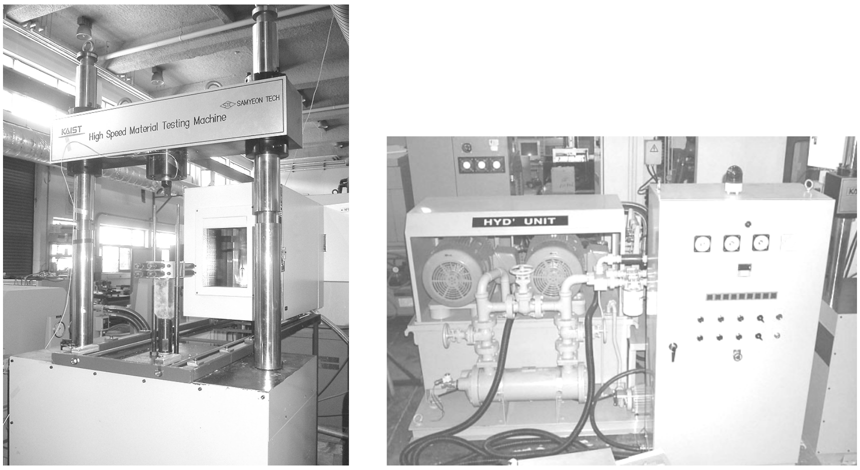
In this paper, the tensile elongation has been obtained from various steel sheets for an auto-body at the high strain rates. A high speed material testing machine was made for tensile tests at the high strain rate and the appropriate dimensions of a specimen were selected in order to induce the uniform elongation in the gauge section at the high strain rates. Dynamic tensile tests of eight different steel sheets for an auto-body such as SGACD, SPRC450R, TRIP600, DP600, TRIP800 and DP800 steels were performed to investigate the relation between the strain rate and the tensile elongation. Stress–strain curves were obtained for each steel sheet from the dynamic tensile test and used to deduce the relationship of the elongation to the strain rate.

2 Dynamic Tensile Test

2.1 High Speed Material Testing Machine

The dynamic response at the high strain rates should be obtained by adequate experimental techniques such as mechanical, pneumatic and servo-hydraulic types. Servo-hydraulic testing machines are frequently used in most recent research works due to accuracy and convenience of operation. In the present experiment, a high speed material testing machine of the servo-hydraulic type as shown in Figure 1 was utilized in order to obtain the dynamic mechanical properties at the high strain rates. The machine has the maximum stroke velocity of 7800 mm/s, the maximum load of 30 kN and the maximum displacement of 300 mm. Two electric motors are used to compress the operating hydraulic oil up to the pressure of 300 bars and two accumulators with the capacity of 5 liters are used to make the response time faster. The maximum flow rate of the servo-hydraulic unit is 4 liter/sec.

The machine equipment is set up with the Kistler 9051A piezo-electric type load cell in a specially designed loading fixture to reduce the noise level and to increase the noise frequency from the load-ringing phenomenon. The displacement is acquired by a LDT (linear displacement transducer) from Sentech company. During the operation, a function generator transmits an input signal to the servo controller to control the displacement with a feedback system by comparing the measured displacement with the input signal. Configuration file and test programs are fine-tuned for different velocities of a stroke at different strain rates. Several tests were conducted at the same condition to verify repeatability and the results were very satisfactory for repeatability with robust calibration and indicated that the machine response, testing procedure and material response were consistent.



(a) (b)

Figure 1: *High speed material testing machine: (a) loading frame; (b) servo-hydraulic unit*

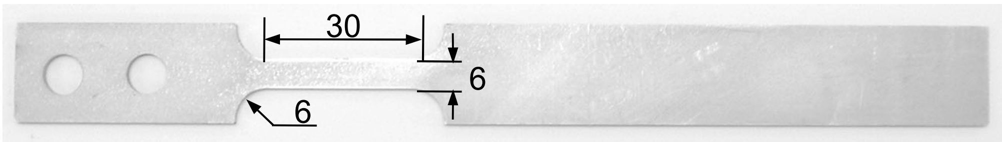


Figure 2: *Dynamic tensile specimen with the length of the parallel region of 30 mm*

2.2 Dynamic Tensile Specimen

Tensile specimens for the standard test are specified in the regulations of ASTM, BSI and KS as well as the testing method. These regulations, however, do not include the high speed tensile testing method and the corresponding specimens. Therefore, an appropriate high speed tensile testing method and specimen need to be determined for accurate tensile tests at the high strain rate ranged from 1 to 500/s. The dimension of specimen was determined from the finite element analysis result and the tensile test result considering the shape factors to induce the uniform deformation [10]. Figure 2 shows determined dynamic tensile specimen with 30 mm in length of the parallel region, 6 mm in both gauge width and fillet radius.

3 Experimental Results

3.1 Test Conditions

The materials tested were conventional steels and advanced high strength steels such as SGACD, SPRC450R, TRIP600, DP600, TRIP800 and DP800 steels prepared along the rolling direction. Experiments were carried out at room temperature of 294K at the strain rates ranged from quasi-static to the strain rate of 200/s. Quasi-static tensile tests were carried out at the strain rate of 0.003/s using the static tensile machine, Instron 5583. Dynamic tensile tests were carried out at strain rates from 0.1/s to 200/s using a high speed material testing machine developed. From the tensile test, the dynamic material properties such as the flow stress, the strain rate sensitivity and failure elongation were investigated quantitatively.

3.2 Dynamic Tensile Characteristics of Steel Sheets

The mechanical properties of auto-body steel sheets obtained from the static test are given in Table 1. Conventional mild steel, SGACD shows high failure elongation compare to other advanced high strength steels. Comparing TRIP steel sheets with DP steel sheets having similar tensile strengths, TRIP600 and TRIP800 steels have higher elongation than DP600 and DP800 steels, respectively. TRIP steels have a good ductility compared to DP steels due to TRIP effect. This effect improves the elongation and strength of materials as the phase of remained austenite transforms into the phase of martensite during deformation. The ratio of the yield stress to the tensile strength is compared to estimate the formability of the steel sheets. SGACD steel has lower yield ratio than any other steel sheets. TRIP800 steel has a lower yield ratio than DP800 steel while TRIP600 and DP600 steels have similar ratios, which means TRIP steels have better formability than DP steels.

Dynamic tensile tests were carried out at the strain rate ranged from 0.003/s to 200/s. Tests were repeated two or three times per each strain rate. Engineering stress–strain curves of auto-body steel sheets are shown in Figure 3 at various strain rates. As the strain rate increases, the flow stress of steel sheets gradually increases. The slope of the stress–strain curve for conventional mild steel such as SGACD decreases as the strain rate increases. As a result, the ultimate tensile strength occurs at the lower strain and the hardening exponent becomes smaller with the increase of the strain rate. This phenomenon seems to occur with the mechanism of grain sliding and the heat dissipated from the plastic work at the high strain rate. The yield stress of SGACD increases by more than two times while the increases of the yield stress of the advanced high strength steel, TRIP and DP steel sheets is below 1.2 times. In general, the yield stress of the mild steel is more sensitive to the strain rate than that of the high strength steel. DP600 and DP800 are more sensitive to the strain rate than TRIP600 and TRIP800 in terms of the ultimate tensile strength. This result represents that the strain rate hardening of DP sheets is more advantageous than that of TRIP sheets because the strain rate in most auto-body crashes is under 500/s.

Material	Thickness [mm]	Yield stress [MPa]	UTS [MPa]	YS/UTS	Failure elongation [%]
SGACD	0.79	166	308	0.539	56.7
SPRC450R	1.23	324	450	0.720	33.6
TRIP600	1.45	414	612	0.676	34.0
DP600	1.43	422	632	0.668	26.9
TRIP800	1.43	480	786	0.611	25.1
DP800	1.60	555	755	0.735	19.2

Table 1: *Mechanical properties from the static test*

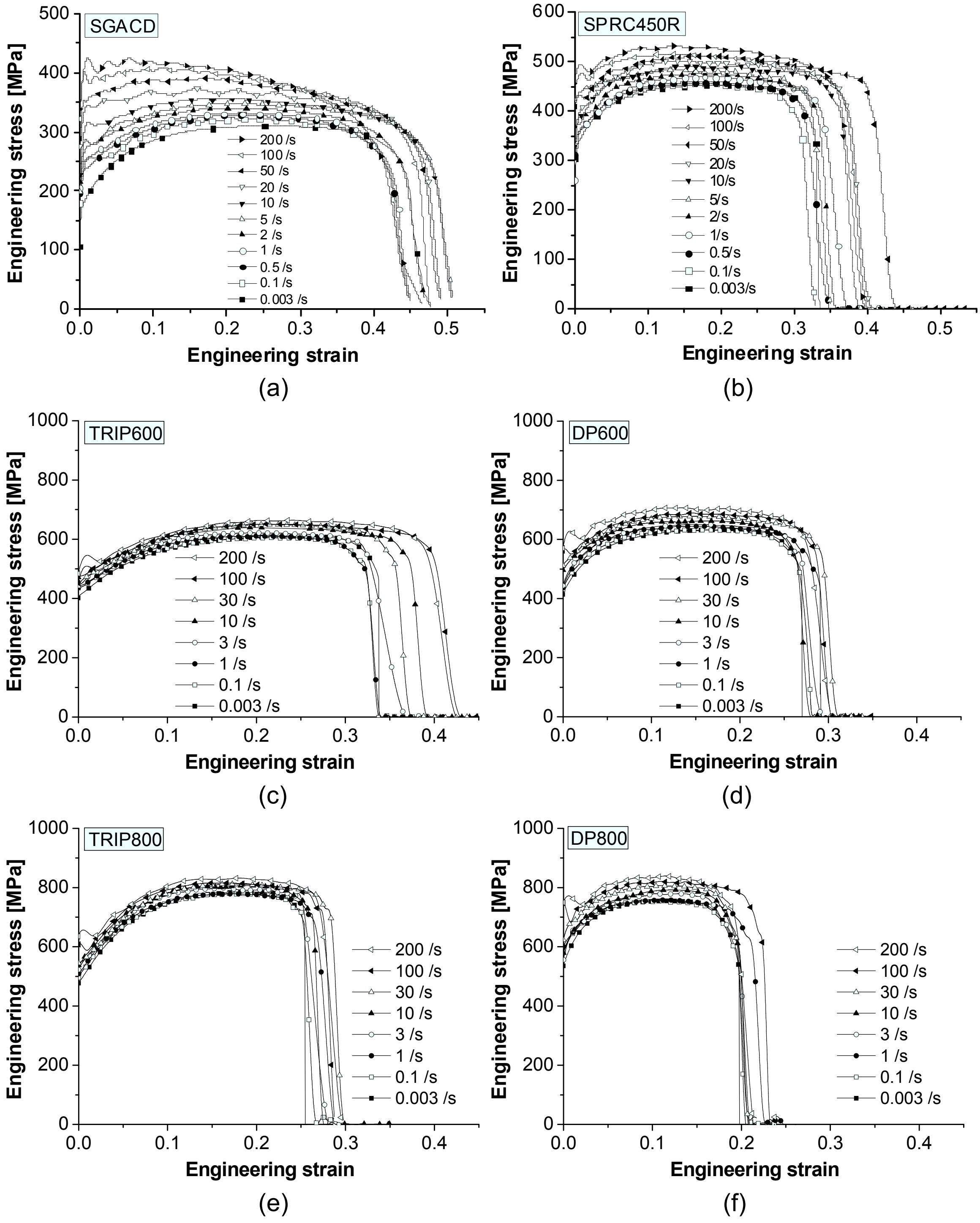


***Figure 3:** Engineering stress-strain curves of auto-body steel sheets at various strain rates: (a) SGACD; (b) SPRC450R; (c) TRIP600; (d) DP600; (e) TRIP800; (f) DP800*

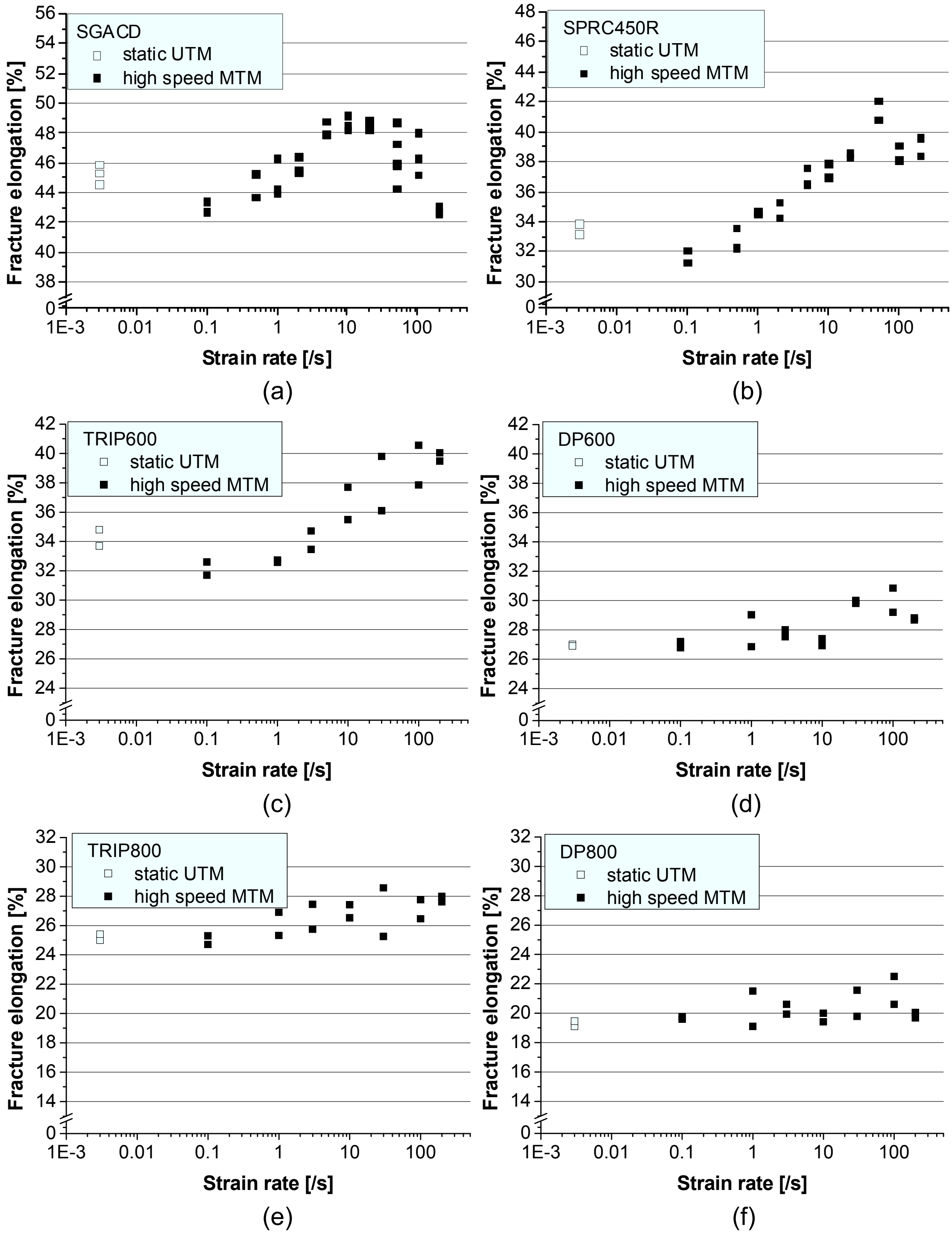


***Figure 4**: Failure elongation of auto-body steel sheets at various strain rates: (a) SGACD; (b) SPRC450R; (c) TRIP600; (d) DP600; (e) TRIP800; (f) DP800*

The failure elongation was obtained from the engineering stress-strain curves at various strain rates. Figure 4 shows the failure elongation distribution with the same elongation range of 18% against the logarithmic scale of the strain rate. It is known from classical conjecture that the strength of steel increases due to the strain rate hardening and the fracture elongation is expected to decrease as the strain rate increases. However, the tensile test results show that the failure elongation of SGACD, SPRC450R, TRIP600 and TRIP800 steels decreases with increasing strain rate from the quasi-static state to the strain rate of 0.1/s, and then increases up to the strain rate of 50 or 100/s. On the other hand, the failure elongation of DP600 and DP800 steels increases monotonically as the strain rate increases. Peixinho et al. [11] and Choi et al. [12] obtained the similar experimental result that ductility of TRIP600 and DP600 steels does not simply decrease with increasing the tensile speed. When the necking phenomenon occurs in simple static tensile tests, deformation is concentrated at the gauge region in a narrow band of the gauge region. On the other hand, in tensile tests at the high stain rates, local strain rate hardening restrains the progress of necking and diffuse necking region expands in the adjacent region forming a wide band of necking. It is because the strain rate at the necking region becomes particularly higher than the other region and the flow stress in the necking region exceeds the flow stress in the other region due to the rapid increase of the strain rate. Consequently, the necking region becomes stronger than the neighbouring region despite thinning in the necking region, and finally the failure elongation increases as the strain rate increases. This tendency is related to the microstructure of steel sheets at various strain rates. At the quasi-static state, deformation proceeds with the rounded half-loop and V-shape dislocations. These types of dislocations still prevail at the strain rate of 0.1 and 1/s, but above the strain rate, crossing dislocations which have been investigated in literature at the strain rate over 1000/sec [13] begin to generate along the specific direction with deformation. As strain rate increases to the strain rate of 100/s, dislocation density increases significantly and most of dislocations change into the straight and crossing type which generate a dislocation net. During the forming procedure of this crossing dislocation, the failure elongation increases as strain rate increases.

This experimental result is worthy of attention for the crashworthiness of an auto-body especially in terms of the fracture and tearing of auto-body members. This result is also applicable to sheet metal forming processes of auto-body members in order to enhance the formability of sheet metals. For instance, the fracture elongation of SPRC450R and TRIP600 steels becomes 39% and 40% at the strain rate of 100/s and 33% and 34% at the quasi-static state, respectively, resulting in better formability in sheet metal forming. This increment of fracture elongation is due to the strain rate hardening in the proper strain rate range. This result reveals that forming processes at an adequate strain rate can enhance the formability compared to the static forming process.

4 Conclusion

This paper deals with the tensile failure elongation that has been obtained for various steel sheets for an auto-body at the high strain rate. The high speed material testing machine and the dynamic tensile specimen has been used for dynamic tensile tests at high strain rates ranging from 0.1/s to 200/s. Dynamic tensile tests of SGACD, SPRC450R, TRIP600, DP600, TRIP800 and DP800 steels for an auto-body were performed to investigate the relation between the strain rate and the elongation from the stress–strain curves at various strain rates. Several remarks are deduced from the experimental results as follows:

The failure elongation and the formability of TRIP steel sheets are better than those of DP steel sheets at the high strain rates. The failure elongation of conventional mild steels and advanced high strength steels decreases with increasing strain rates from quasi-static to the strain rate of 0.1/s, and then increases up to the strain rate of 50/s or 100/s due to the local strain rate hardening. The elongation of DP600 and DP800 increases monotonically as the strain rate increases in contrast to the classical conjecture. This phenomenon is very interesting and important in sheet metal forming and the high speed deformation such as the auto-body crash from a viewpoint that the increment of the strain rate does not deteriorate the elongation.

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