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Effect of material properties of advanced high strength steels on bending crash performance of hat-shaped structure

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ABSTRACT

Systematic dynamic and quasi-static bending crash tests were conducted with high strength steels using a hat-shaped structure in order to investigate the effect of material properties on crash performance. Materials with a wide range of tensile strengths from 270 MPa to 1470 MPa and various microstructures such as interstitial free (IF), dual-phase (DP) and transformation induced plasticity (TRIP) steels were examined. Hat-shaped structures were prepared by two different processes (bending and draw-bending processes) to investigate the influence of strain-hardening on crash performance. The experimental results clarified the effects of sheet thickness, material strength and strain-hardening on crash characteristics. The effects of bending crash conditions, including crash speed and bending span, were also studied to understand how these factors influence crash behaviors. The sequence of the dynamic bending crash was investigated to elucidate the mechanism of crash performance. As a quantitative index of crashworthiness, the bending moment *Mb* was calculated from the mean force and bending span. The effects of both yield strength and sheet thickness on bending moment were investigated. Based on the experimental results, a simple method for estimation of bending crash performance using material strength and thickness as parameters was proposed in order to understand the relationship between the weight reduction effect and improvement of crashworthiness in automotive parts when using advanced high strength steels.

1. Introduction

Achieving an optimized combination of crash safety performance and a lightweight structure has been an important challenge in automotive body engineering [1]. Applications of high strength steels to the auto body structures have been considered as an effective solution to this problem, which is feasible at relatively low cost in volume production in the automotive industry [1]. High strength steels need to provide not only higher strength but also sufficient formability in the press stamping processes. The strengths of the steel materials have been traditionally limited to 440 MPa considering the formability of the automotive parts. The advanced high strength steels with improved formability have been recently developed by optimizing the metallic microstructures. As a result, the advanced high strength steels with strengths over 590 MPa are now widely used in the crucial parts [1–4] for safety performance. The range of the applications of the high strength steels has been expanding in the auto body structures. Ultra-high strength steels with strengths ranging from 980 MPa to 1470 MPa have also been developed considering the optimum balance between the material strength and the formability [5].

Various types of high strength steels are used, corresponding to the function of each individual member in a crash event. For example, in the case of frontal crash event, the frontal structures should absorb crash energy by axial crushing modes [6]. For effective energy absorption, steel materials must have the capability to deform without fracture during the crushing process. For this reason, 440 MPa or 590 MPa grade steels are generally selected for parts subject to frontal crashes. Many studies on the axial crushing performances of the steel structures have been reported and discussed [7–15]. In a previous study [4], the authors carried out axial crash tests using simple hat-shaped structures with various material strengths. The study focuses on the strain-rate sensitivity of high strength steels and the effect of the material strength and the thickness on energy absorptions. Tarigopula et al. investigated the collapse characteristics of spot-welded top-hat sections and square tubes made of dual-phase (DP) steel sheets [7]. In their study, a DP800 steel was selected for dynamic tensile and

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crush tests. The difference between the quasi-static and the dynamic deformation was discussed based on the experimental and the numerical simulation results. L. Durrenberger et al. investigated the effects of pre-strains induced by the forming processes on the axial crush performances of TRIP780 steel parts [8].

In the case of side crash events, the side sill and the center pillar structures have key roles in maintaining the occupant's survival space [1]. For this reason, the deformation resistance of these structures is a crucial factor for the safety. To minimize the deformation, advanced high strength steels with much higher strength of over 980 MPa are required. In this case, the deformation mode is generally a bending deformation. The bending deformation of a steel section involves a combination of the local collapse and the global bending of the structure. Although the axial crush deformation has been examined in many studies, few of them have focused on the bending crash deformation in the simple section structures [3]. In particular, studies on the bending performances of high strength steels of over 980 MPa grade are seldom dealt with.

In the current study, the quasi-static and the dynamic bending tests were carried out to investigate the crash behaviors of hat-shaped section parts. The parts were made of a variety of steel sheets with tensile strengths from 270 MPa to 1470 MPa and material thicknesses from 1.0 mm to 2.0 mm. Hat-shaped structures were made by the processes of bending and draw-bending to investigate the effects of strain-hardening on crash performances [2]. These experimental studies demonstrated the effects of the material strength, the material thickness and the strain-hardening on the crush force. The effects of the bending crash conditions, including the crash speed and the bending span, were also studied to understand how these factors affect the crash behaviors. Finally, the capability of advanced high strength steels in improvement of crashworthiness and auto body weight reduction is discussed by proposing an empirical equation for estimation of the bending crash performance.

2. Experimental procedure

2.1. Materials

In these experiments, various grades of sheet steels were selected to investigate the effect of material properties on crash performance. Table 1 shows the mechanical properties and the thicknesses of the steel sheets used in this study. The mechanical properties, including yield strength, tensile strength and elongation, were examined by static tensile tests based on Japan Industrial Standard (JIS). The geometry of the specimen used in the tests has a gauge length of 50 mm and a width of 25 mm. The tensile tests were performed with a constant velocity of 10 mm/min. The material thicknesses were selected in the range of 1.0 mm–2.0 mm, considering the steel sheets commonly used in the automotive body structures. The steel grades, which indicate the tensile strengths, are listed in Table 1 as well. The sheet steels with a wide range of tensile strengths from 270 MPa to 1470 MPa were selected for the study. The material types shown in the table indicate the microstructures of the steels. IF stands for an interstitial-free steel, low-C for a low carbon steel, P for a precipitation strengthening steel, which is a common conventional high strength steel, and DP for a dual-phase steel with a microstructure consisting of a soft phase of ferrite and a hard phase of martensite. The DP steel is known as a type of advanced high strength steels and has a higher elongation than the precipitation strengthening steel. TRIP represents a transformation induced plasticity steel and is a class of advanced high strength steels with a higher elongation than the DP steels. Steel No. 17, 18, 19, 20, 21 and 22 are 980 MPa grade steels with various combinations of the yield and the tensile strengths. M indicates a full-martensitic steel with a higher yield strength than the DP steels of the 980 MPa grade. Steel No. 25 and 26 have tensile strengths of 1470 MPa, the highest strength level currently available in the commercial sheet steels for automotive applications. The martensitic steels have the lowest elongations among the steels used in this study.

Table 1
Mechanical properties and sheet thicknesses of steel sheets.

Material no.	Thickness (mm)	Yield strength (MPa)	Tensile strength (MPa)	Elongation (%)	Grade	Material type
1	1.0	165	295	49.9	270	IF
2	1.2	154	287	51.0	270	IF
3	1.4	165	295	51.7	270	IF
4	1.2	244	341	41.4	270	Low-C
5	1.6	165	295	53.2	270	IF
6	1.0	312	447	37.9	440	P
7	1.2	314	457	38.1	440	P
8	1.4	298	456	38.4	440	P
9	1.6	285	460	38.3	440	P
10	1.0	422	642	27.8	590	DP
11	1.2	462	680	26.8	590	DP
12	1.4	440	637	26.0	590	DP
13	1.6	425	628	28.4	590	DP
14	1.6	405	624	29.6	590	DP
15	1.6	418	623	39.6	590	TRIP
16	1.2	443	631	28.5	590	P
17	1.2	680	997	16.1	980	DP
18	1.6	677	984	19.7	980	DP
19	1.6	719	993	15.5	980	DP
20	2.0	729	990	16.0	980	DP
21	1.2	955	991	15.3	980	P
22	1.2	995	1068	4.9	980	M
23	1.6	906	1214	14.5	1180	DP
24	1.6	1242	1300	6.0	1180	M
25	1.6	1296	1525	8.8	1470	M
26	1.6	1115	1535	7.2	1470	M

Strain rate sensitivity data of the steel sheets were obtained from a set of dynamic tensile tests. In this study, a dynamic tensile test machine based on One-Bar-Method [3,16] was selected for high strain-rate tensile tests. Fig. 1 shows the overall appearance of the machine and dimensions of the test piece. Dynamic yield strengths of the selected materials were measured at the strain-rate of 100/s. Fig. 2 shows the relationships between the dynamic and the static yield strengths for various types of materials. The dynamic yield strengths are higher than the static yield strengths for all materials. The ratio of the dynamic yield strength to the static yield strength decreases with the increase of the static yield strength. The microstructures of the steels have little effects on the strain-rate sensitivity. In other words, the dynamic strengths of the steel sheets largely depend on their static strengths.

2.2. Hat-shaped specimens

The shapes and the dimensions of the specimen were determined in reference of actual automotive structural members such as a center pillar component or a side sill part. Fig. 3(a) shows the dimensions of the hat-shaped specimen used in this study. The cross-section is a simple trapezoidal geometry with weld flanges for joining the specimen to a flat plate. The corner radii at the top edges and near the weld flanges were approximately 5 mm. The length of the specimen was 500 mm. The hat-shaped part and the flat plate were joined together by spot-welds at intervals of 30 mm, as shown in Fig. 3(b). Table 2 shows the condition of spot-welding for this study. The welding force and time were set according to the material thickness. The welding current was adjusted from 6 kA to 8 kA in order to make the spot-weld diameter as approximately