

Mechanical Properties and Crash Worthiness of Ultrafine Grained Multi-Phase Steel Sheets for Automotive Body Applications

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ABSTRACT

Mechanical properties, formability and crash worthiness of a new sheet steel having an ultrafine grained (UFG) multi-phase (MP) microstructure are shown. The fabricated UFG-MP steel showed significant work hardening caused by deformation induced martensitic transformation of retained austenite, which resulted in a combination of high strength and large tensile elongation. It was confirmed by dynamic collapse test and FEM simulation that the large work hardenability of the UFG-MP steel promoted compact mode collapse that improved the absorbed energy.

INTRODUCTION

High strength steels (HSS) are widely applied to automotive body structures [1, 2]. Recently HSS having tensile strength higher than 1000 MPa have been developed [3,4,5] and applied mainly to the parts surrounding passengers' cabin such as pillars and rails. However, those ultra high strength steels (UHSS) [6] stronger than 1000 MPa have not been applied to front or rear frames which are loaded along the longitudinal direction and heavily deformed during car crash. There seems to be two major reasons which prevent UHSS to be applied to front or rear frames. One is early fracture of the material due to decreased elongation [7]. The other is occurrence of unstable deformation in axial collapse, which means the change in deformation configuration from compact to non-compact mode [8, 9]. The ideal deformation shape in axial collapse for impact energy absorption is a stable deformation through the formation of a series of continuous folds like accordion, which is called "compact section" [8] or "compact-behavior" [9]. On the other hand, "Non-compact"

[8, 9] means an unstable deformation through the formation of a series of folds separated by remaining straight regions in the column walls which is sometimes accompanied by declining of the column. The change in deformation mode from compact to non-compact, which reduces the efficiency of energy absorption, is caused by the decreased work hardenability of the material highly strengthened [10]. Commercially available UHSS generally have low work hardening rate (n value) [6] because of increased amount of hard phases such as martensite in the microstructure. Uenishi et al. [10] showed by FEM simulation that the desirable compact-mode deformation of hat columns during axial collapse could be promoted by improving the work hardenability of the material. However, this concept has not been confirmed yet because UHSS having large work hardenability have not been obtained. Recently the present authors [11] showed that a microstructure composed of ultrafine grained (UFG) ferrite matrix and hard second phases containing retained austenite could achieve both high strength and large work hardening. The UFG multi-phase (MP) steel, which were fabricated through rolling and annealing of a duplex microstructure composed of soft and hard phases [12, 13], showed both high tensile strength of 1320 MPa and significant work hardenability. However, it contained 0.4% C which would result in poor spot-weld strength. In the present paper, focusing on the work hardenability and the spot-weldability, a new variation of UFG-MP steel based on low-C steel has been developed by controlling the chemical composition and microstructure. First of all, the effect of stress-strain (s-s) curve on the impact energy absorption of hat columns is clarified by numerical analysis and work hardening property is identified to achieve high impact

Table 1. Material parameters and calculated 0.2% offset stress of two different model steels for FEM simulation

Steel	a (MPa)	b (MPa)	n	D (s ⁻¹)	p	σ_{max} (MPa)	0.2% offset stress (MPa)
A	392	2058	0.3	1x10 ⁹	6.53	1299	711
H	784	1960	0.15	1x10 ⁹	6.53	1621	1556

energy absorption. Then, a new variation of UFG-MP steel based on low-C steel are shown. The mechanical properties, formability and axial collapse properties of the obtained UFG-MP steel are described.

NUMERICAL SIMULATION

FINITE ELEMENT MODEL AND MATERIAL PARAMETERS

Numerical simulations were carried out using RADIOSS dynamic explicit commercial finite element code. A finite element model of a rectangular hat column was developed. The cross section and general view of the model are shown in Fig. 1. The hat column was composed of a hat part bent by a radius of 5 mm and a flat back plate, both of which were connected by spot-welding which were expressed by rigid beams binding the facing nodes on the flanges. The pitch of the spot-welding was 40 mm. On the bottom end of the hat column, all nodes were constrained for all translation, and on the top end several nodes are constrained for rotation in four places. A rigid wall having a mass of 110 kg hit the top of the hat column at a velocity of 50 kmh⁻¹. In order to clarify the effect of work hardening rate of the materials on the deformation behavior, two sets of material parameters were generated to explain different s-s curves; one with large work hardening rate while the other low work hardening rate. The equation expressing s-s curves was defined by using Ludwik type static s-s curve and Cowper-Symonds type strain rate sensitivity index as

$$\sigma = \left(a + b \varepsilon^n \right) \left(1 + \left(\frac{\dot{\varepsilon}}{D} \right)^{\frac{1}{p}} \right) \quad (1)$$

where a, b and n are parameters which describe the static s-s curve and D and p are strain rate sensitivity parameters. Besides those parameters, σ_{max} was defined for each material to explain the maximum stress permitted. The material parameters for two model steels and calculated 0.2% offset stress are listed in Table 1. In Fig. 2, true s-s curves at a strain rate of 0.01 s⁻¹ which were calculated using the two parameter sets in Table 1 are shown. Steel A had relatively low 0.2% offset stress and significant work hardening up to a strain around 0.07. On the other hand, steel H showed higher 0.2% offset stress but low work hardenability. Using the two

material properties, deformed shape of the hat columns, load and absorbed energy were evaluated in the FEM simulations.

<table 1 here>

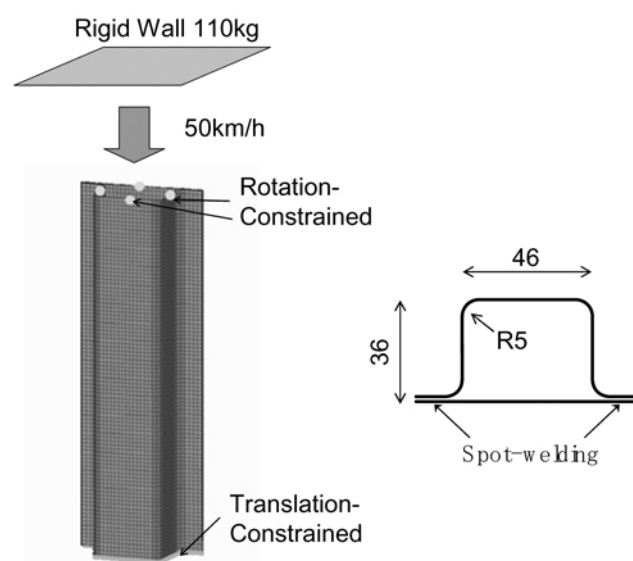


Fig. 1. General view of the finite element model and conditions

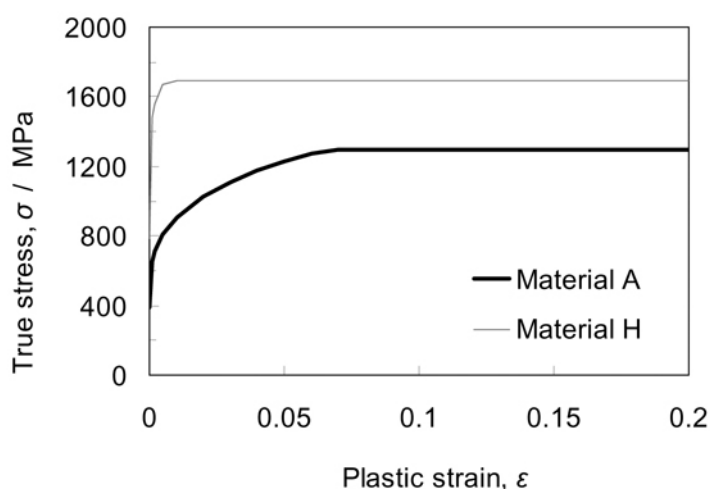


Fig. 2. Stress-strain curves of the model steels having different work hardening rate

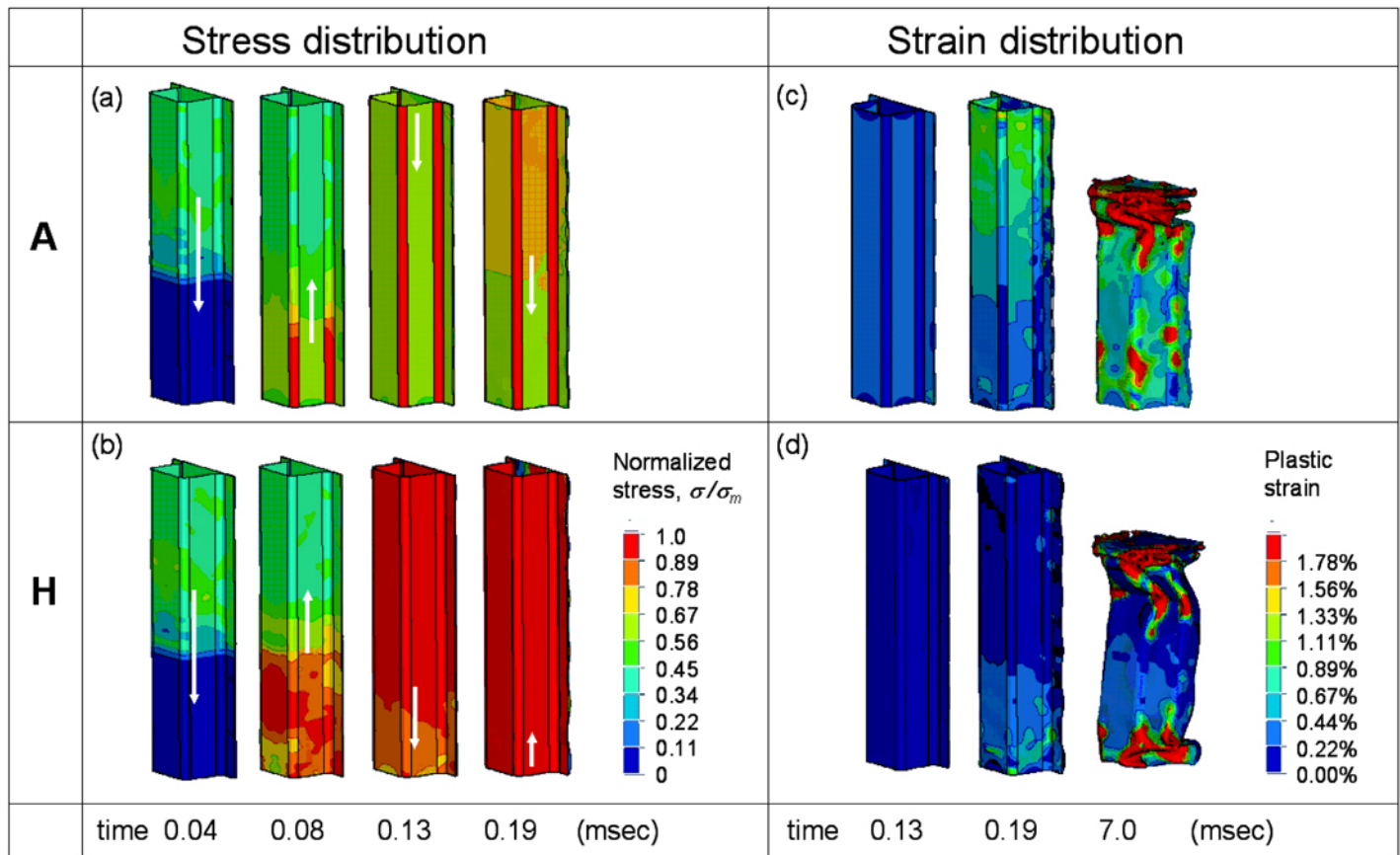


Fig. 3. Changes of stress and strain distributions at early stages of deformation. Stress distributions of (a) material A, and (b) material H. Strain distributions of (c) material A, and (d) material H.

RESULTS AND DISCUSSION

Effects of 0.2% offset stress

Figure 3(a) and (b) show stress distributions in the deformed hat columns before the first buckling; (a) for material A and (b) for material H. The stress was normalized by following equation;

$$\sigma_N = \sigma / \sigma_m \quad (2)$$

where σ_N is the normalized von Mises stress and σ_m is the maximum value of von Mises stress calculated in the FEM analysis. The calculating periods are also shown in the figure. Stress waves traveling downward from the top to the bottom were observed at 0.04 msec in both materials. At 0.08 msec stress waves amplified by reflection at the bottom end were seen going upward and then next reflected waves going downward at 0.13 msec. Figure 3 (c) and (d) show strain distributions. Significant plastic deformation began near the top end in material A at 0.19 msec but began near the bottom end in material H. This is caused by the difference of 0.2% offset stress. In material A the column began deforming at the top end after the second reflection of the stress wave between 0.13 and 0.19 msec. On the other hand, in material H, the

amplitude of stress wave after the second reflection at the top end was smaller than the 0.2% offset stress so that the deformation started at the bottom end after the third reflection at the bottom end, where the amplified stress wave exceeded the 0.2% offset stress (0.19 msec). This difference in deformation behavior affected the deformation shape at 7 msec. The column with material A exhibited stable progressive plastic buckling. As a result, each wrinkle generated by buckling piled up like accordion, which is called “compact” behavior [8, 9]. On the other hand, in the column with material H the straight region between deformed areas remained. This is called “non-compact” behavior [8, 9]. In Fig. 3 (d) strain concentration at the buckling area was observed, which will be discussed in the next paragraph. As well as the strain concentration, the additional buckling near the bottom end in material H is one of the factors to decide the deformation mode.

<figure 3 here>

Effects of work hardening rate

In order to clarify the effect of work hardening rate of materials on the deformation behavior, strain distributions at 5 and 8 msec are shown in Fig.4. At 5 msec, both in material