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Application of Hot Forming High Strength Steel Parts on Car Body in Side Impact

SUN Hongtu[1, 2], HU Ping[1, 2, *], MA Ning[1, 2], SHEN Guozhe[1, 2], LIU Bo[3], and ZHOU Dinglu[3]

1 *State Key Laboratory of Structural Analysis for Industrial Equipment, Dalian University of Technology, Dalian 116024, China*
2 *School of Automotive Engineering, Dalian University of Technology, Dalian 116024, China*
3 *Academy of Changan Automotive Engineering, Chongqing 401120, China*

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Abstract: Lightweight structure is an important method to increase vehicle fuel efficiency. High strength steel is applied for replacing mild steel in automotive structures to decrease thickness of parts for lightweight. However, the lightweight structures must show the improved capability for structural rigidity and crash energy absorption. Advanced high strength steels are attractive materials to achieve higher strength for energy absorption and reduce weight of vehicles. Currently, many research works focus on component level axial crash testing and simulation of high strength steels. However, the effects of high strength steel parts to the impact of auto body are not considered. The goal of this research is to study the application of hot forming high strength steel(HFHSS) in order to evaluate the potential using in vehicle design for lightweight and passive safety. The performance of HFHSS is investigated by using both experimental and analytical techniques. In particular, the focus is on HFHSS which may have potential to enhance the passive safety for lightweight auto body. Automotive components made of HFHSS and general high strength steel(GHSS) are considered in this study. The material characterization of HFHSS is carried out through material experiments. The finite element method, in conjunction with the validated model is used to simulate the side impact of a car with GHSS and HFHSS parts according to China New Car Assessment Programme(C-NCAP) crash test. The deformation and acceleration characteristics of car body are analyzed and the injuries of an occupant are calculated. The results from the simulation analyses of HFHSS are compared with those of GHSS. The comparison indicates that the HFHSS parts on car body enhance the passive safety for the lightweight car body in side impact. Parts of HFHSS reduce weight of vehicle through thinner thickness offering higher strength of parts. Passive safety of lightweight car body is improved through reduction of crash deformation on car body by the application of HFHSS parts. The experiments and simulation are conducted to the HFHSS parts on auto body. The results demonstrate the feasibility of the application of HFHSS materials on automotive components for improved capability of passive safety and lightweight.

Key words: hot forming, high strength steel, lightweight, side impact, car body

1 Introduction

There is a strong tendency to increase fuel efficiency on development of vehicles. Lightweight of structures is an important method of achieving this goal. At the same time, however, these new lighter structures must maintain the improved capability of crash safety. Multiple candidates for replacing mild steel in automotive structures have been proposed, such as advanced high strength steels(AHSS) aluminum or magnesium alloys, and composite materials[1–3]. AHSS, in particular, are attractive candidate materials, offering higher strength and the opportunity to reduce weight through use of thinner gauges. AHSS which are made of advanced manufacture and process show the characteristics of good strength, formability and weldability compared to general high strength steel(GHSS) to be currently used to reduce the weight of automobiles.

AHSS are comprehensively applied in the study of Ultralight Steel Auto Body – Advanced Vehicle Technology Porgramme(ULSAB-AVC). Hot forming high strength steel(HFHSS), which is a kind of AHSS, achieves the desired characteristics directly from the heat treatment to high strength steel by hot stamping. HFHSS are appropriate for automotive components, such as reinforcements of doors and bumpers which have good strength to decrease the deformation for the improvement of passive safety capability at the same time of lightweight.

Multiple research articles have been published on the subject of crushing of steel sections. WHITE, et al[4–5], explored the collapse features of sections made of mild

* Corresponding author. E-mail: pinghu@dlut.edu.cn
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steel when subjected to axial crushing. ABRAMOWICZ, et al[6–8], studied the dynamic axial crushing of circular and square steel tubes and compared the results with theoretical predictions. SCHNEIDER, et al[9], investigated the influence of spot-weld failure on crushing of thin-walled structural section and the difference in structural effectiveness sections made from mild steel and high strength steel. TARIGOPULAR, et al[10], studied on quasi-static and dynamic axial crushing test of thin-walled steel sections of DP800. ABEDRABBO, et al[11], investigated non-hydroformed and hydroformed structural steel tubes in component-level crash using both experimental and analytical techniques. High-strength steel may have potential to enhance crashworthiness of automobiles. Conventional drawing quality steels, high strength low alloy steel, advanced high strength steel, DP600 and DP800 were used in his study. FYLLINGEN, et al[12], studied on the behavior of top-hat thin-walled high-strength steel section from different batches subjected to dynamic axial crushing. The robustness was investigated by considering components produced from five different material batches. However, many research works focus on component level axial crash testing and simulation. The effects of high strength steel parts on auto body are not considered.

The purpose of this research is to study the material characterization and the application of HFHSS on automotive components. The material experiments are carried out to study the mechanical characteristics and microstructure of HFHSS. The finite method is used to simulate the side impact of a car with GHSS parts according to China New Car Assessment Programme(C-NCAP) crash tests. The finite model of the car is validated with the comparison to C-NCAP crash test results of the car. The deformation and acceleration characteristics of the car body are analyzed and the injuries of occupants are calculated in side impact for the car body of both GHSS and HFHSS. The results from the simulation analyses of HFHSS parts on the car are compared against that of GHSS. The intrusion displacements, acceleration, and occupant in side impact are analyzed for the passive safety capability of the auto body.

2 Materials Experiments

Boron steel sheets which contain 0.002%–0.005% Boron dissolved in C-Mn steel to enhance strength of materials are widely applied in the manufacture of HFHSS. The process of HFHSS manufacture is to stamp the hot Boron steel with the heat treatment. The Boron steel is heated to 880–950 ℃ to becoming austenitic steel. The heated Boron steel is kept for 5–10 min to 600–800 ℃ for stamping. The austenite steel changes to martensitic steel when the cooling velocity is more than 15 ℃/s. The die with cycling water quenches at the cooling velocity of 50–100℃/s to 20–200℃. The hot stamped part is taken out at 80–150℃. The hardness of HFHSS reaches 450–500 HV, and the rigidity reaches 1 300–1 500 MPa.

In order to investigate the mechanical characteristics of HFHSS, the material experiments are carried out on a HFHSS formed automotive components of auto body. The experimental examples of 22MnB5 steel sheets which are the typical high strength steel sheets for HFHSS are stamped to reinforcements of inside door with the process of HFHSS manufacture. The three experiment examples from different positions of the reinforcements are tested to analyze the mechanical performance and microstructure of HFHSS.

Material characterization is performed on the different samples used in this research in order to extract the required parameters of the constitutive models for the purpose of numerical analysis. Testing is performed on three positions on the samples. Fig. 1 shows the test positions of the experiment examples.

Fig. 1. Sample of material experiments

Materials experiments are conducted on low strain tests (0.003 33–0.1 s^{-1}) using a servo-controlled tensile machine. Table 1 lists the stress, hardness and elongation of experiments samples. The average yield stress of samples is 1 120 MPa, average tensile stress is 1 416 MPa, and average hardness is 447 HV which are typical for AHSS sheets. But the average elongation is 7.4% which is relatively low.

Table 1. Mechanical characteristic of HFHSS experimental samples

Sample No.	Yield stress σ_s/MPa	Tensile stress σ_b/MPa	Hardness H/HV	Elongation δ/%
1	1 131	1 431	435	8.0
2	1 121	1 407	438	6.8
3	1 107	1 401	467	7.3

Fig. 2 shows a sample of the measured true stress vs. true strain for all the materials used in this research.

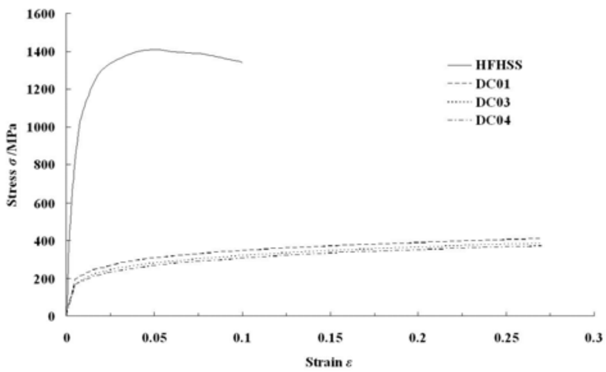


Fig. 2. True stress vs. true stain for materials

DC01, DC03 and DC04 are kinds of GHSS, and they are generally applied on the car body parts. The strength and hardness of HFHSS which are appropriate for reducing the deformation in crash are much higher than GHSS, but the elongation of HFHSS is relatively lower than GHSS, which is appropriate for absorbing energy in a crash.

The microstructure of an experimental sample is shown in Fig. 3. The martensitic phases in HFHSS are more than 97% of the material microstructure, which shows that the HFHSS parts satisfy the requirement of AHSS to be applied on the car body.

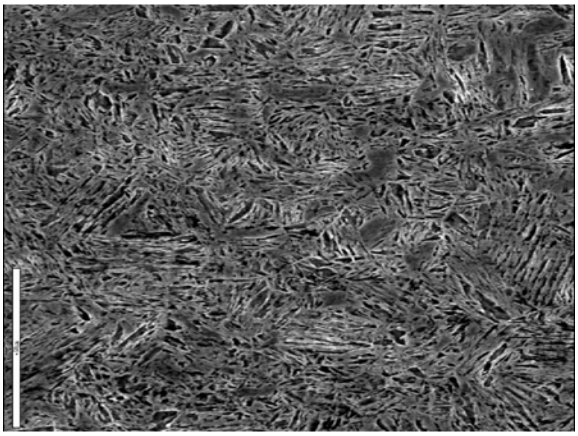


Fig. 3. Microstructure of materials sample

The mechanical characteristics of HFHSS indicates that the GHSS sheets on a car body can be replaced by thinner HFHSS sheets for the lightweight car body with the improved mechanical performance.

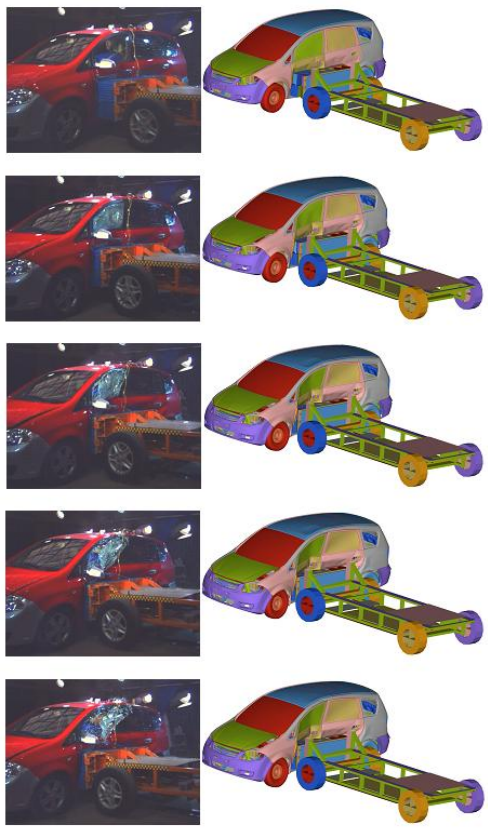
3 Simulations and Analysis

The HFHSS parts are appropriate for the automotive components which are used to reduce the deformation in crash. The side impact of a car is employed to study the application of HFHSS. The finite element model of the car is verified with the crash test of C-NCAP[13]. Some parts of the side structure on the car body are improved with the GHSS parts replaced by the parts of HFHSS. The results of crash are analyzed to verify the feasibility of the application of HFHSS on automotive components.

3.1 Finite element model verification

The models of the car and barrier are discretized with material properties of steel assigned for use in the contact treatment. The materials applied in the models are GHSS materials which are used on the car before. The parameters of GHSS materials are shown in Fig. 2. The nonlinear explicit dynamic finite element code LS-DYNA[14] is used to simulate the crash tests performed on the car. The parts of auto body are meshed by using shell elements of 3–10 mm size with material properties of steel assigned for use in the contact treatment. The model of auto body has 1 530 709 nodes, and 1 548 661 elements. There are 6 blocks of energy absorption on the side barrier. The relations of deformation and energy in crash are also built for the blocks on the barrier according to the C-NCAP. The finite element model of the car and barrier are validated with comparison to the results of the C-NCAP crash test.

Fig. 4 shows the deformation histories of test and simulation at 20 ms, 40 ms, 60 ms 80 ms and 100 ms. The occupant is not included in the simulation of a side impact. The deformation history and intrusion displacement of the car body in simulation are similar with that of C-NCAP crash test. It represents the accuracy of the finite models in side impact.



(a) Test (b) Simulation

Fig. 4. Deformation of car in side impact.

The injury criteria of occupants in an impact are also calculated to evaluate the safety of an occupant. The finite models of occupant and side structure of the car body are shown in Fig. 5.

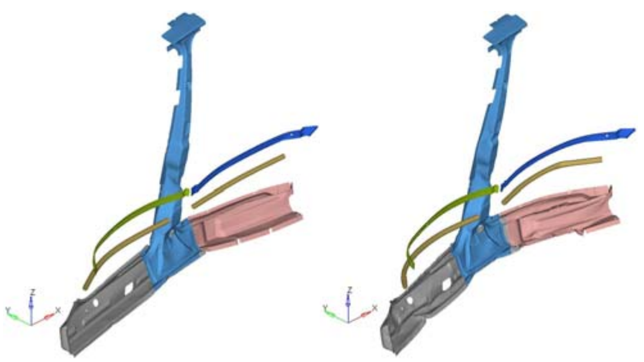
Fig. 5. Model of occupant injury criteria calculation

The method of prescribed structure motion is employed in simulation of occupant injury. The related parts in side impact are used with the results of deformation in crash. The ES2-FEQ occupant is employed in the simulation. The finite models for occupant injury calculation are inputted into MADYMO[15] to calculate the occupant injury criteria. The score of the occupant in simulation is 9, which is same to that in C-NCAP crash test to validate the finite model of occupant and body side structure.

3.2 Analysis of crash results

The HFHSS parts are applied on the car body with the GHSS parts of B pillar, threshold, and reinforcement replaced. The side structures of the car are expected to decrease body deformations to achieve better passive safety capability at the same time of lightweight on car body. The thickness of the replaced GHSS parts is 2 mm. While the thickness of HFHSS parts is 1.6 mm, which reduce the weight of parts by 20%. At the same time, the manufacture and materials costs of HFHSS parts are approximately 1.5 times higher than GHSS parts.

The side impact of auto body with HFHSS parts is simulated to compare the results with GHSS parts. The finite model of auto body with HFHSS parts is built by the materials parameters of GHSS replaced with that of HFHSS. Fig. 6 shows the deformations of GHSS parts and HFHSS parts from the whole car crash in side impact at 120 ms. The HFHSS parts reduce the deformation of car body dramatically. Table 2 lists the maximum intrusion displacements at 3 different positions on the threshold, reinforcement and B pillar.



(a) HFHSS (b) GHSS

Fig. 6. Deformation of parts in side impact

Table 2. Maximum intrusion displacement of car body

Materials	Threshold d_t/mm	Reinforcement d_r/mm	B pillar d_b/mm
HFHSS	269	287	258
GHSS	297	331	315

The maximum intrusion displacement of the body decreases by 57 mm, which is 18% lower than that of GHSS parts. This result indicates that HFHSS parts can protect the car body from deformation to injury the occupant for the passive safety capability.

The acceleration histories of the car body on HFHSS parts and GHSS parts are shown in Fig. 7. The peak acceleration of HFHSS parts increases 9*g* than GHSS parts at 5 ms. The acceleration histories of HFHSS at 10 ms, 38 ms and 51 ms have higher peaks compared to those of GHSS. The reason for the higher peak acceleration of HFHSS parts is that the plastic deformation and absorbing energy of the auto body decrease with the application of HFHSS parts due to the high strength. At the same time, the HFHSS parts elastic deformation recovers higher than the GHSS parts. The acceleration history of HFHSS fluctuates more intensively than that of GHSS. Therefore the acceleration peaks of HFHSS appear higher at these moments.

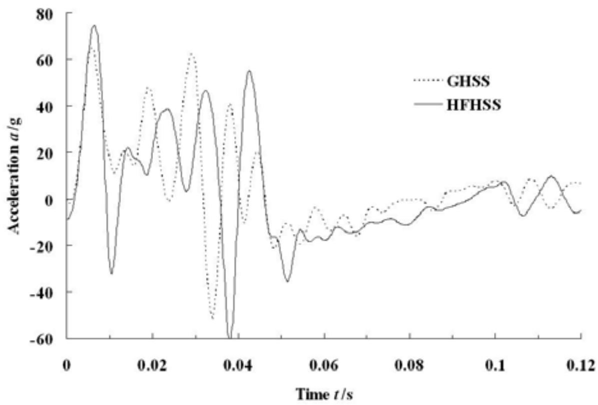


Fig. 7. Acceleration histories of car body in side impact

The increased acceleration peak may cause the possibility of higher injury to an occupant. In order to evaluate the injury of occupants in side impact of the car body with HFHSS parts, the occupant injury criteria in side impact of HFHSS parts body are calculated to compare to that of GHSS.

Table 3 lists the occupant injury criteria in side impact. HIC_{36} of HFHSS parts body increases by 3.7% because of the increased peak acceleration of car body. But the injury of an occupant is lower than the tolerance limitation of the human body to obtain the same score as before. The deformation of the thorax decreases by 18% due to the decreased deformation of the car body. The injuries of abdomen and pelvis are also lower than those of GHSS. The total score of HFHSS parts body in side impact is 11, which is 2 higher than the score of GHSS parts body. We can see that the application of HFHSS parts improves the passive safety capability of occupant at the same time of lightweight.

Table 3. Injury criteria of occupant in side impact

Criteria		HFHSS	GHSS
HIC_{36}	Injury I_h	325.56	313.92
	Score S_h	4	4
Thorax	Iniury I_t/mm	24.78	30.22
	Score S_t	3.4	2.4
Abdomen	Injury I_a/kN	2.07	2.23
	Sore S_a	1.1	0.5

Pelvis	Injury	I_p/kN	4.16	4.38
	Score	S_p	2.5	2.1

The thicknesses reduction of HFHSS parts may have the possibility to decrease the rigidity of white body. In order to verify the effect from HFHSS parts, the white body rigidity of HFHSS parts is calculated to compare with that of GHSS parts. The finite elements models are simulated in MSC/Nastran[16] to calculate the bend rigidity and torsion rigidity. Table 4 lists the white body rigidity of HFHSS and GHSS parts.

Table 4. White body rigidity of HFHSS and GHSS parts

Materials	Bend rigidity k_b/(N•m•rad^{-1})	Torsion rigidity k_t/(kN•m•rad^{-1})
HFHSS	9 560	686
GHSS	9 490	668

The white body rigidities of HFHSS parts are lower than those of GHSS parts. The bend rigidity of HFHSS decreases by 0.73%, while the torsion rigidity of HFHSS decreases by 2.62%. The small variation of white body rigidities indicated the feasibility of HFHSS materials as well.

4 Conclusions

(1) Analyses of the material experiments show that the HFHSS materials offer higher strength and hardness than GHSS materials. The microstructures of HFHSS show martensitic phases in HFHSS materials.

(2) The thicknesses reduction of HFHSS parts reduces the weight of parts by 20%, which indicates the HFHSS materials are appropriate for lightweight of auto body.

(3) The maximum intrusion displacements of an auto body decrease by the application of HFHSS materials. The HFHSS parts protect the auto body from deformation as well as the occupant from injury during a crash. And the application of HFHSS parts can improve passive safety capability for the lightweight auto body in side impact.

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Biographical notes

SUN Hongtu, born in 1977, is currently a lecture in School of Automotive Engineering, Dalian University of Technology, China. His research interests include safety and fuel efficiency of vehicle.
Tel: +86-411-84706475; E-mail: sunhongtu@hotmail.com

HU Ping, born in 1956, is currently a professor and the dean of School of Automotive Engineering, Dalian University of Technology, China. His research interests include computational solid mechanics and automotive panel dies and materials.
Tel: +86-411-84706473; E-mail: pinghu@dlut.edu.cn

MA Ning, born in 1977, is currently a PhD candidate in School of Automotive Engineering, Dalian University of Technology, China.

SHEN Guozhe, born in 1973, is currently an assistant professor in School of Automotive Engineering, Dalian University of Technology, China.
E-mail: Shengz@jlu.edu.cn

LIU Bo is currently an engineer in Academy of Changan Automotive Engineering, China.
E-mail: ptmoutain@changan.com.cn

ZHOU Dinglu, is currently an engineer in Academy of Changan Automotive Engineering, China.
E-mail: ptmoutain@changan.com.cn