A new type of multi-layer metal composite materials for preventing impact and absorbing energy in hot forming and its application

Hot forming (quenching and forming at the same time) makes the steel surface oxidation and decarburization. Stamping parts formed in this technique shows low hardness in the exterior and high hardness in the interior. The material properties exhibit the continuous functionally gradient distribution in the thickness direction. The exterior hardness and strength is low, while the interior hardness and strength is high. So, the new type of multi-layer metal composite materials is formed. The microstructure, hardness, strength and plasticity of this new metal composite material is analyzed and taking the reinforced beam for example, the three-point bending experiment is implemented. To investigate the crashworthiness of the new metal composite materials, the finite element analysis (FEA) model of the reinforced beam is established on the basis of the metallographic and three-point bending experiments. To compare the crash force and energy absorption between the metal composite materials and each phase material in the interior, it is found that the metal composite materials have the comprehensive performance of every single-phase material. So, it is a good alternative material in application of bearing impact and absorbing energy.

Keywords: *Hot forming, metal composite materials, microstructure, impact force, energy absorption.*

Introduction

Nowadays, the demand of coupling performances with cost reduction, safety, respect of environment and energy saving is stronger and stronger in the automotive industry. With regards to these aspects, the introduction of high strength steels represents the best solution to increase the strength to mass ratio of sheet components. Then HSS can meet the need of higher passive safety and weight reduction. Cold stamping allows the production of simple shapes with very high strength, up to 1200MPa, such as side impact beams[1]. Ultra-high strength steels, however, pose a major challenge in processing because of their limited formability and pronounced springback at room temperature. So, when part complexity increases, such as with B pillars, only lower strength steel grades can be used with cold stamping, and when steels' strength increases to 1500Mpa, the steel grades cannot be used with cold stamping[2,3].

The possibility of performing stamping operations at elevated temperatures represents a solution to these problems, allowing lower loads on tools and higher accuracy of formed components. Then hot stamping with die quenching of boron steels appears and the process can overcome the typical difficulties associated with cold stamping. For example, hot forming of the quenchable boron alloy steel 22MnB5 can produce complex, crash resistant parts such as bumpers, A, B and C pillars, roof reinforcements, side reinforcements and front tunnels with ultra-high strength, minimum springback and reduced sheet thickness. The tensile strength of boron steel is up to 1600MPa which is far more than the highest strength of the conventional cold stamping steels.

The traditional cold stamping technology has been effectively studied by domestic and foreign scholars[4,5]. It is the same with the theory analysis, experimental study and numerical simulation of the conventional quenching treatment[6,7]. Hot forming is the advanced technology that integrates traditional heat treatment and cold stamping. The prospect of hot forming technology has attracted the attention of researchers, which mainly focus on the high temperature mechanical properties of materials, numerical simulation and experiments[8-12].

The new hot forming technology of metal composite material is put forward in this paper. By controlling heating temperature and designing the layout of cooling pipes in hot forming process of ultra-high strength steel, the hot forming experiment of metal composite material is implemented.The research of lightweight automobile is the mainstream of modern automobile design and manufacture. The application of high-strength materials is one universal way of lightweight technology of the present automobile body. In recent years, the hot forming technology of high-strength steel plate (also called hot stamping), originated from Europe, has received the attention of the industrial world. The technical advantages of hot forming technology lie in: It can form components with

Mr. Pingping Sun, School of Mechanical Engineering, Weifang University of Science and Technology, Shouguang, Shandong, China. E-mail:2356497@qq.com

intensity as high as 1500MPa and weld high-strength automobile body bearing unit, withstanding static pressure of 6 tonnes above without damage. It can realize the lightweight and save the material consumption by reducing wall thickness or section size and reducing weight (to 18%-35%).

The principle of hot forming is to heat the special boron alloys steel, making it austenitic, and then to send the heated sheet in the mold with cooling system to stamp and form. Simultaneously, it is cooled and quenched by the mold which has fast and even cooling system. The steel plate organization transforms from austenite to marten site, thus to obtain the steel plate with high strength ratio. Hot forming technology not only has the advantage of high strength ratio, but also that under the high temperature, the material plasticity and forming is good and complex stamping pieces can be formed by one time. Forming under the high temperature can eliminate the influence of spring-back, with high components precision and good forming quality. The hot forming technology breaks free from the convention with new frame. It is the front technology in the stamping forming domain, widely used in the production of the front and rear automobile bumper, A column, B column, C column, the roof structure and bottom frame of vehicle as well as the inside board and bumper bar of vehicle door.

The huge prospect of hot forming technology has aroused researcher's interest and the research has been focusing on the aspects of theory, numerical simulation and experiments. At present, there are scholars who study the superficial against-oxidation coating of hot stamping steel plate[13-15]. However, seldom people research on the phenomenon of surface oxidation and decarburization in hot stamping project. This paper studies the phenomenon of steel surface oxidation decarburization in hot stamping project from a new angle, which is that the stamping pieces have soft exterior but hard interior due to oxidation decarburization, and the material property expresses graded in the thickness direction. The exterior hardness and strength are low, while the interior hardness and strength are high, forming the new multi-layer metallic composite materials. This paper focuses on the experiment and numerical simulation of this kind of hot forming stamping pieces. Taking the door strengthening beam as the example, three-point bending and corresponding finite element simulation are carried out. To compare the crash force and energy absorption between the metallic composite materials and each phase material in the interior, it is found that the metallic composite materials has the comprehensive performance of every single-phase material. So, it is a good alternative material in application of absorbing energy.

2. Technological process for hot forming of metal composite material

Hot forming process is of the common high strength steel. In the hot forming process of the common high strength steel process, the blank is heated in the range between 850ºC and 950ºC, austenitized for about 5 minutes and then transferred to the press where the whole deforming phase should take place in fully austenitic conditions; the use of cooled dies assures a rapid cooling of the sheet during the deformation in order to obtain a homogeneous martensitic microstructure in the sheet component at room temperature.

The material of high strength steel for hot forming in this paper is called 22MnB5, composition of which is shown in Table 1.

TABLE 1: CHEMICAL COMPOSITION'S MASS PERCENTAGE OF BORON MICROALLOY STEEL (WT%)

22MnB5	C	Mn	Cr	Si	B	P	Al
Min	0.22	1.20	0.11	0.20	0.002	-	0.02
Max	0.25	1.40	0.20	0.30	0.005	0.02	0.05

Technological process is for hot forming of metal composite material. The U-shaped part shown in Fig.1 is taken for example to carry out the hot forming experiment of metal composite. The goal of process design is to obtain U-shaped metal composite material with different material properties in A, B and C location as shown in Fig.1.

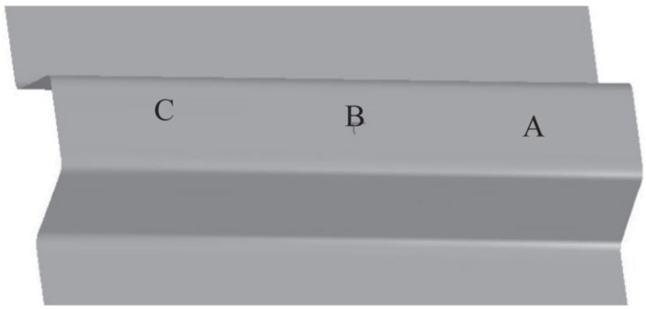

Fig.1 The U-shaped part

The blank is placed into the numerical control heating furnace with the function of heating in sections. The blank is distributed into four sections and heated to 600ºC, 700ºC, 800ºC and 950ºC respectively. The heating temperature remains for three minutes. Then the heated blank is transferred into the die with the sectional distribution of cooling pipes. Then forming and heat treatment happen at the same time. The distribution schematic diagram is shown in Fig.2. The closer the cooling pipes are, the higher are the temperature of the corresponding blank sections.

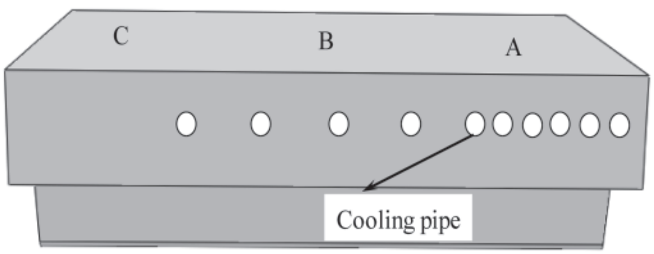

Fig.2 The cooling pipe distribution of the hot forming die

The U-shaped part of metal composite material is shown in Fig.3.

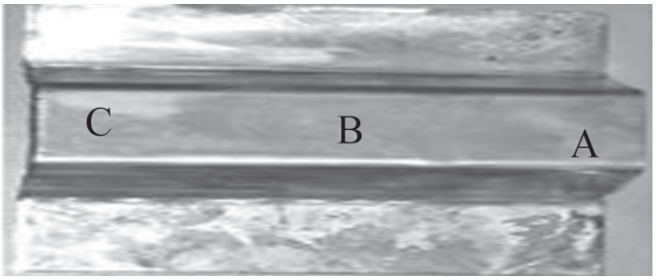

Fig.3 The U-shaped part of metal composite material

3. Hot forming craft of new multi-layer metallic composite and the analysis of microscopic structure

The material of this paper studies, one may call 22MnB5, its material ingredient as shown in Table 2. This kind of boron steel is widely applied in the hot stamping forming at present. The ingredient characteristic of such kind is increasing in certain quality of boron on the basis of C-Mn steel. The melting boron segregation in the austenite boundary retards the shape of nucleus of the ferrite and the bainite, so that the steel intensity is increased.

TABLE 2: PERCENTAGE OF MATERIAL INGREDIENT QUALITY

22MnB5	C	Mn	Cr	Si	B	P	S	Al
Min	0.22	1.20	0.11	0.20	0.002	-	-	0.02
Max	0.25	1.40	0.20	0.30	0.005	0.02	0.005	0.05

The hot forming pieces in this paper are door impact beams as shown in Fig.4:

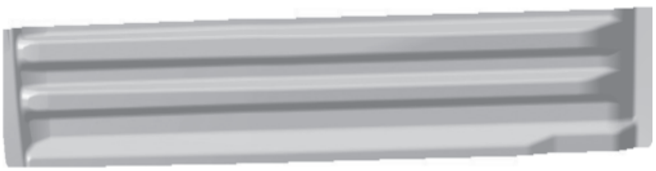

Fig.4 Picture of hot forming piece

The hot stamping craft is a two-step method, the mold diagram is shown in Fig.5.

In Fig.5, picture (a) is the mold picture of first forming while picture (b) is the mold picture of final forming with cooling pipeline.

The heating furnace of pieces is a controllable air-protection heating furnace. As to the craft of hot stamping, the design of cooling pipeline of mold is one of the key decisive factors of final forming characteristics of pieces. The design of its cooling system should simultaneously satisfy the two-aspect requests of mechanical strength and the heat transferring efficiency. At the same time, the mold temperature satisfying the uniformity request of the plate marten site shape nature and the organization distribution should be guaranteed. Through methods of optimization design,

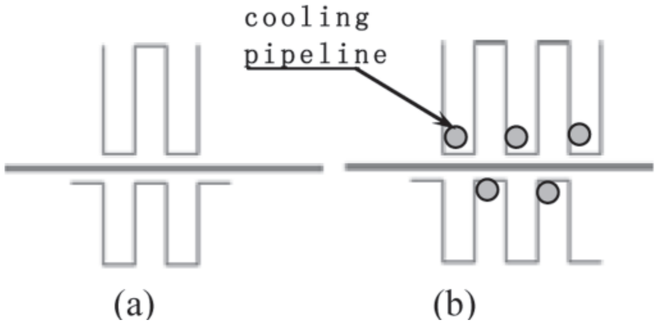

Fig.5(a) Mold picture of first forming

Fig.5(b) Mold picture of final forming with cooling pipeline

simulation and experiment[16,17] of cooling pipeline of the strengthening beam mold, the sheet is formed in the temperature range of 750ºC-800ºC, and is uniform-cooling formed at the rate of bigger than 50ºC/s.

The piece after forming is as shown in Fig.6.

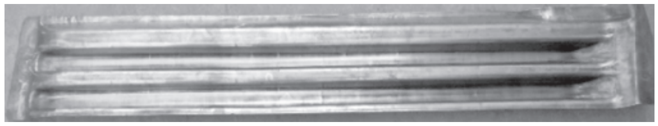

Fig.6 Inside door impact beam after hot forming

As a result of the metallographic analysis of microscopic structure on pieces after forming, typical microstructure is shown in Fig.7. There are ferrite organizations, mixture of ferrite and the martensite organization and the complete martensite organization in turn from exterior to interior. The material which consists of these three organizations is called new type of multi-layer metallic composite material of hot forming, and the thickness of each organization is decided by the air content control of the heating furnace.

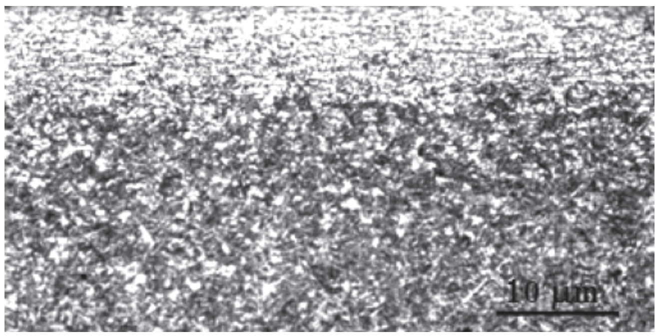

Fig.7 Metallographic analysis of microscopic structure of impact beam

4. Continuous gradient distribution of hardness, intensity and plasticity of new multi-layer metallic composite material

According to Fig.6, the hardness test to the composite material of impact beam after hot forming from exterior to interior is taken, the specimen is shown in Fig.8.

Fig.9, Fig.10 and Fig.11 respectively are hardness distribution pictures of the three test specimens. From the

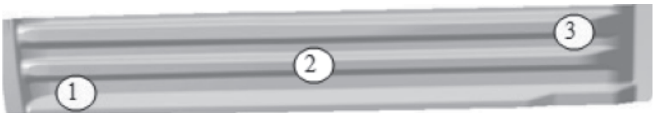

Fig.8 Three locations for testing hardness

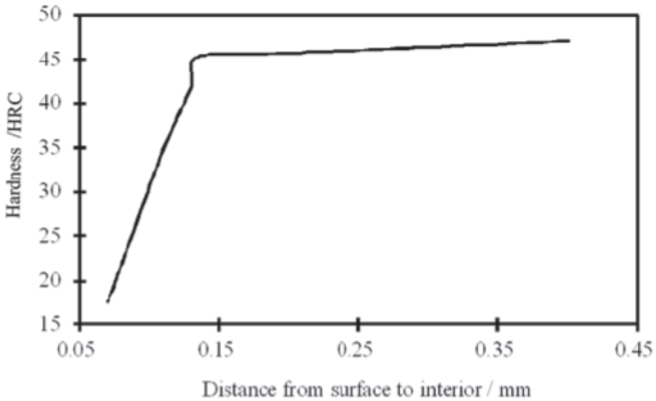

Fig.9 The no.1 hardness distribution along the thickness direction

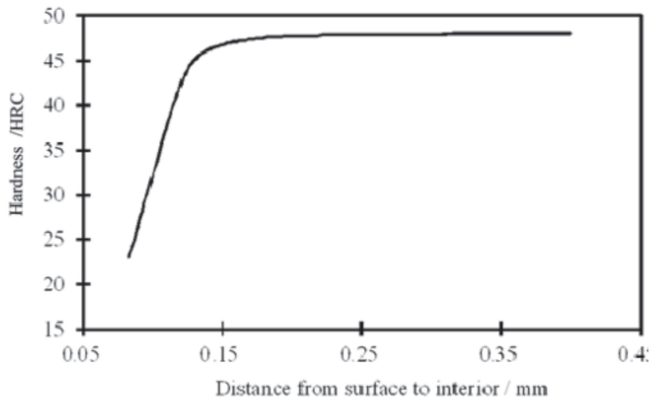

Fig.10 The no.2 hardness distribution along the thickness direction

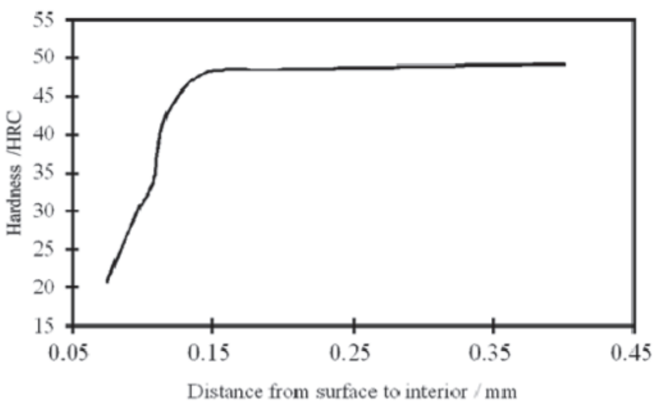

Fig.11 The no.3 hardness distribution along the thickness direction

pictures, it is found that hardness is gradually increasing from exterior to interior, HRC hardness from about 20 to 50 or so. This corresponds with the microscopic structure observed in metallographic test in the 1st part. The changing tendencies of the three specimens are basically consistent, which also indicates that the specimens have obtained even controllable forming and quenching in hot forming process.

According to the relation among hardness, intensity and material plasticity [18, 19], the tendencies of intensity distribution and hardness distribution of impact beam composite materials are the same, while the tendencies of material plastic property distribution and hardness distribution are the opposite. This indicates that metallic composite material is a new composite material with the continuous functionally gradient distribution.

5. Establishment of three-point bending and finite element analysis model

Three-point bending experiment is taken on the above stamping piece of hot forming. Meanwhile, three-point bending finite element analysis model of metallic composite material is established in terms of microscopic structure analysis of impact beam in part II and hardness distribution of impact beam in part III. The model is shown in Fig.12.

Fig.12 Picture of finite element analysis of impact beam

The material distribution of hot stamping impact beam in thickness direction is as shown in Fig.13. Sheet thickness is 1.6mm, 1st level 0.9mm, 2nd level 0.2mm and 3rd level 0.15mm. The thickness from 1 to 3 demonstrates that material's yield strength reduces in turn but the material ductility increases in turn. The material parameters are obtained in the stretching experiment and the relation among hardness, intensity and plasticity analyzed in part III. The laminates theory[20] is used to simulate the thickness distribution of metallic composite material. Simultaneously the strain failure of the material is considered.

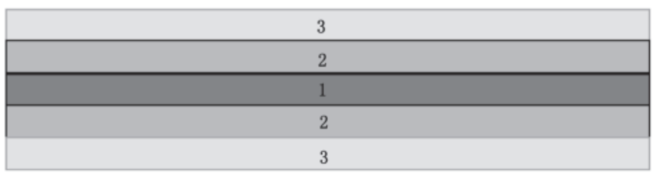

Fig.13 Material distribution of impact beam in thickness direction

Quasi-static three-point bending experiment is taken on hot stamping piece and cold stamping piece (no quenching process), and the commercial software LS-DYNA is used in the numerical simulation of finite element three-point bending.

Fig.14(a) and Fig.14(b) are impulse-displacement correlation curves in loading stage of three-point bending experiment and numerical simulation. In the pictures, A, B respectively are experimental result and numerical simulation result of hot stamping piece, while C, D respectively are experimental result and numerical simulation result of cold stamping piece. From the experimental result, the greatest bending load of the hot stamping piece is bigger than that of cold stamping (about 3 times of cold stamping piece), which indicates that the craft of hot stamping forming makes the metallic material form in multi-layer composite material assuming the gradient change in thickness direction and this greatly enhances the anti-bending ability of structure. The basic correspondence of numerical simulation result and experimental result show that the numerical simulation method and the material model used in this paper are feasible[21].

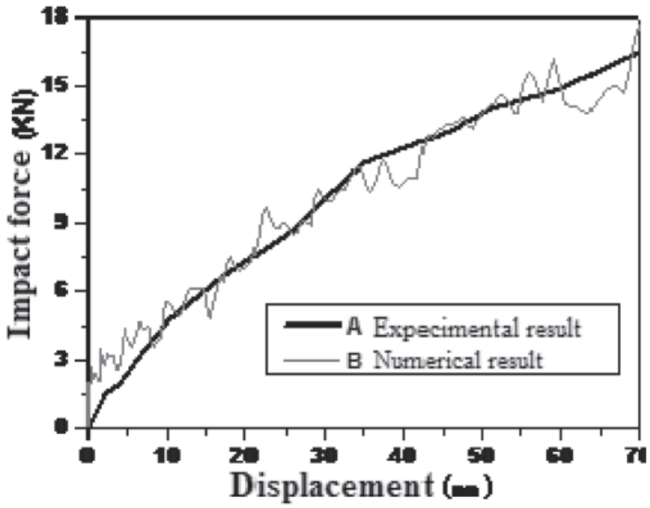

Fig.14(a) Impact force-displacement curves of hot stamping

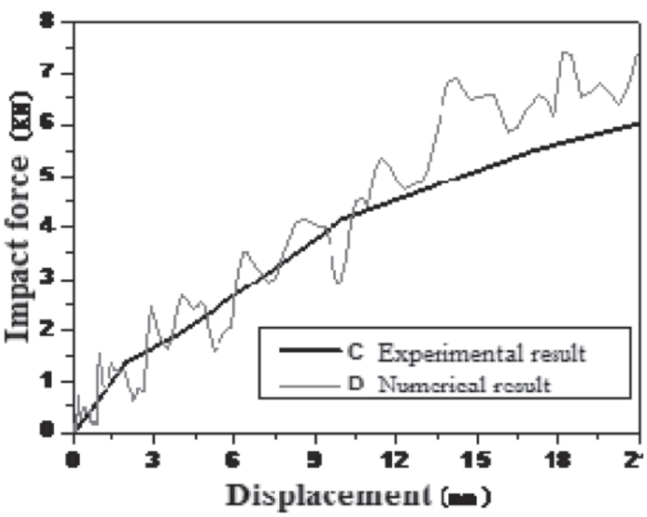

Fig.14(b) Impact force-displacement curves of cold stamping

6. Research on collision impact force and energy absorption property

Based on feasibility of the above quasistatic numerical simulation method, bending energy absorption property of hot stamping piece in the dynamic impact load is researched. With the dynamic load of 50kg drift quality and 50km/h impact speed, numerical simulation is carried respectively on the 1.6mm thick metallic composite material and each mono-layer material structure under the same working condition. Fig.15 shows the impact force-displacement curves of the material under dynamic impact load. From the picture, it is demonstrated that the impact force level of the 1st material is the highest, that of the 3rd material the lowest and that of the 2nd material and composite material in the middle, which corresponds with the material property analyzed in part III. But the peak force value of the first material is also the biggest, which is extremely disadvantageous of impact protection of the door, because the excessive peak force value will cause damage to the driver and passenger in the collision process. The ductility of the first material is quite bad, causing its untimely loss of bearing capacity in the bending process. However, the peak force value of the composite material structure is lower than the first and second material. Simultaneously, it can maintain a smooth impact force level in the entire bending process.

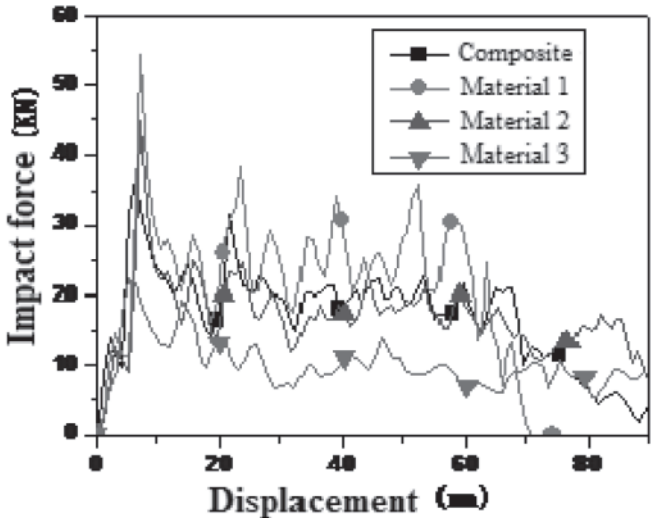

Fig.15 Impact force-displacement curves under dynamic impact load

Fig.16 shows the energy absorption-displacement correlation curves under dynamic impact load. Along with the increase of bending displacement, the energy absorption gradually enhances linearly. But when the bending displacement of the first material achieves 60mm, energy absorption begins to drop and inclines to be smooth, because the low plasticity of the first material causes the strain expiration [22,23]. Based on its characteristic of softness and hardness combination, the cascade expiration of the material property of the composite material structure i.e. soft material of the outer layer displays the characteristic of high elongation, making the martensite material with big intensity of inner layer not untimely expire, maintains high energy absorption ability.

In summary, three-point bending under dynamic impact load shows that composite materials structure is helpful for

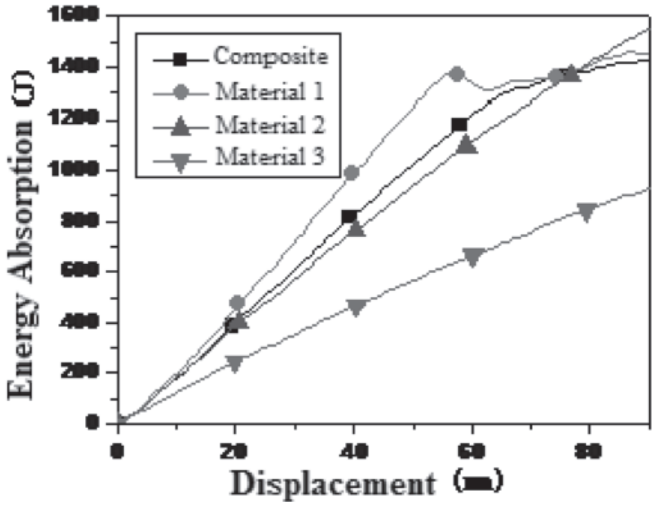

Fig.16 Energy absorption-displacement curves under dynamic impact load

reducing the peak force value of the structure. Meanwhile, the smooth impact force level and the cascade expiration of material maintain the structure high energy absorption ability. Therefore, metallic composite material has the comprehensive performance of every single-phase material. So, it is a good alternative material in application of absorbing energy, for example, the automobile door impact beam studied in this paper.

7. Conclusion

This paper has analyzed the sheet forming craft and its microscopic structure in the hot forming process. The new multi-layer metallic composite material composed of ferrite, formed under oxidation and decarburization - mixture organization of ferrite and martensite are found. The continuous gradient distribution of hardness, intensity and plasticity of this hot forming new metallic composite material is analyzed. Then three-point bending experiment and numerical simulation is taken and the superior load-bearing property of the hot forming new metallic composite material is proved (more than about 3 times of that of conventional high-tensile steel). The finite element analysis model is established. By comparing the crash force and energy absorption between the metallic composite materials and each phase material in the interior to explain that metallic composite material is helpful for reducing peak force value of the structure, and meanwhile, the smooth impact force level and the cascade expiration of material maintain the structure high energy absorption ability. Therefore, metallic composite material has the comprehensive performance of every single-phase material. So, it is a good alternative material in application of absorbing energy.

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STUDY ON THE CRITICAL VALUE OF GAS CONTENT IN REGIONAL PREDICTION OF COAL AND GAS OUTBURST BASED ON GAS ADSORPTION AND DESORPTION EXPERIMENT

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