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EXPERIMENTAL STUDY ON HOT BENDING OF ULTRA HIGH STRENGTH STEEL 22MNB5 AND ITS LIGHTWEIGHT APPLICATION

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Hot stamping temperature has significant effect on the mechanical property especially bending formability of 22MnB5. Focus on the optimal forming temperature zone of process, special V-shaped hot bending experiment was designed and different thicknesses sheets after heating to 950°C, 5 min were bended at different quenching conditions. The hardness and microstructure features after hot bending and spring-back behavior for sheet through temperature changes were investigated. The result showed that forming temperature between 600 − 700°C would contribute 22MnB5 sheet bending formability which spring-back angles are the smallest and the martensite texture formed was much finer. The real hot forming anti-collision beams test validated the optimal forming temperature between 600 − 700°C contribute the real hot forming process simultaneously. Furthermore, 22MnB5 hot forming parts through body mass optimal process are applied to analyze the potential mass reduction valuation of the BIW under bending condition, by using VCD_ICAE, a self-developed and entirely parameterized BIW concept design system. The conclusion showed the application of hot forming component replace traditional part not only raise the stiffness and modal index, but also could reinforce strength of body of BIW and make vehicle more lightweight and safer at the same time.

Keywords: Hot forming, 22MnB5, Hot bending formability, Lightweight, VCD-ICAE.

1. Introduction

In the automotive industry, the demand of coupling performances with cost reduction and respect of environment is stronger [Turetta *et al.*, 2006], [Hoffmann *et al.*, 2007], [Wang *et al.*, 2007] and [Xing *et al.*, 2009]. Studies have shown that lightweight is the most effective measure to achieve that goal for reducing vehicle mass by 10% can save fuel by 3% $\sim$ 7% [Kondratiuk *et al.*, 2011] and [Senuma, 2007]. Therefore more advanced-high (AHSS) and ultra-high strength steels (UHSS) are increasingly used in the automotive industry for lightweight and safety. The application of ultra-high strength steel in the body-in-white has increased dramatically during the last two decades, which improved automotive safety standard and reduced emissions [Naderi, 2011]. The most widely utilized sheet material for hot stamped parts in the automotive industries is boron steel 22MnB5, which has good ductility during stamping and has tensile strengths up to 1500MPa after quenching. It can be manufactured by reducing the materials thickness simultaneously. In the project of Ultra-light Steel Auto Body-Advanced Vehicle Technology Program (ULSAB-AVC) of International Iron and Steel Institute (IISI), the body in white (BIW) is lightweight by 30% for applying hot forming parts[Bok *et al.*, 2011]. In 1984, Saab Automobile AB was the first automobile manufacturer to adopt a hardened boron steel component for the Saab 9000 [Berglund, 2008].

Nowadays, Hot stamping was developed as an advanced industrial process to produce complex automotive structural reinforcement components such as A pillar, B pillar, C pillar, door and roof reinforcements, bumpers and et al. [Lee *et al.*, 2009]. In hot stamping process, complicated thermal-mechanical-transformation coupled relations and multi-scale problems are involved and there are lots of thermal parameters such as optimal stamping temperature affecting mechanical properties of the hot forming components. The martensite evolution during quenching causes the tensile strength up to 1500 MPa which is verified by using tensile tests [Naderi, 2007] and hardness measurements [Akerstrom, 2006]. The microstructure investigations have shown that the martensite transformation is the precondition for the mechanical strength of the material. Due to the effect of the cooling rate and the phase transformation, the final mechanical properties have relationship with the process control. When forming take places at elevated temperatures, the material formability is greatly influenced not only by the strain but also by temperature, strain rate, and microstructural evolution during deformation [Pellegrini et al., 2009], [Merklein et al., 2009] and [Karbasian, 2010]. All of the research only discussed the basic mechanical properties of hot forming material in lab environment at elevated temperature. The related conclusions are in the development phase, and laboratory investigations must verify them for industrial application. Neither considerate the actual manufacture process nor combining the product properties in lightweight application requirement.

In this paper, we focus on the need for the hot stamping as a process of metal sheet bending so that the bending properties and its formability of hot stamping sheet influence are investigated. a special V-shaped heat bending test is designed for investigating the bending formability at different temperatures due to the mechanical properties depend on the thermal and forming history of the part, which purpose was for optimal temperature zone for bending forming. In the continuous cooling process, the cooling rate and hardness are investigated as the relevant parameters which contribute to present guidance function on actual hot stamping process. Besides, real anti-collision beams are stamped by researchers, pure bending test is conducted on the anti-collision beam for comparison, which shows its higher bending strength and impact resistance at the optimal temperature zone. Furthermore, the potential mass reduction of a concrete BIW with 22MnB5 hot stamping parts under bending condition is evaluated by VCD_ICAE, the self-developed and entirely parameterized BIW concept design system to comprehend the perspective of its lightweight application evaluation.

2. Material and Experimental Setup

In this paper, a new style hot forming steel (SPFH) named 22MnB5 is investigated of three thicknesses, included 1.2 mm, 1.6 mm and 2.0 mm. The composition of sheet as shown in Table 1. A bit of boron chemical element added in order to enhance the quenching harden-ability and strength of C-Mn steel. As shown in Fig. 1, microstructures of original 22MnB5 material consist of ferrite, pearlite while strip-shaped martensite is the main microstructure of quenched samples.

Through typical tensile experiment, 22MnB5 steel basic mechanic properties are shown in Table 2. It shows that yield and tensile strength of quenched samples, around 1000 Mpa and 1500 Mpa, which 3 times higher than original sample, the former elongation is just 7%, much less than 32%. Besides, the poor characteristic

Table 1. Composition of 22MnB5 (Mass %)

22MnB5	C	Mn	B	Cr	Si	P	S
Maximum	0.25	1.40	0.0050	0.30	0.24	0.025	0.015
Minimum	0.19	1.10	0.0008	-	0.18	-	-
Measured	0.22	1.24	0.0040	0.11	0.22	0.016	0.006

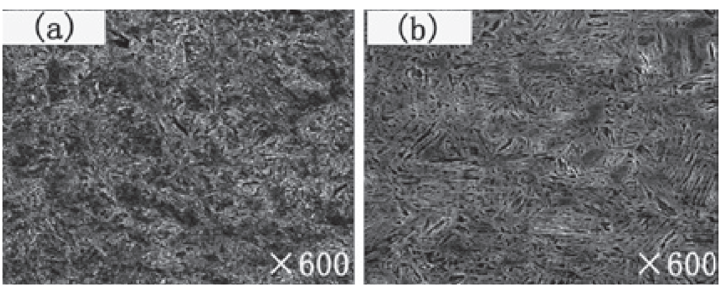

Fig. 1. Microstructures of (a) original samples (b) quenched samples

Table 2. Mechanical properties of no-quenching and quenching 22MnB5

22MnB5	Yield Strength [MPa]	Tensile Strength [MPa]	Yield Ratio	Elongation [%]	N Value
Original	300	500	0.62	32	0.21
Quenched	1000	1500	0.65	7	0.11

of formability after quenched can be explained by strain hardening coefficient value decreases from 0.21 to 0.11.

2.1. *V-shaped thermal bending*

It's known that hot forming process is introduced to stamp 22MnB5 and quench it at the same time for ultra-high strength parts. The optimal hot stamping temperature zone (OTZ) is so significant that can affect blank formability and mechanical properties of hot forming parts. To get the OTZ, special V-shaped thermal bending experiment is designed for imitating the real hot stamping process, see Fig. 2.

The temperature acquisition system of V-shaped test is shown in Fig. 2. three Ni-Si thermocouples are individually placed in the sheet middle, the punch and the die surface for the temperature detected. The sheet is transformed to V-shaped die quickly, after holding 5 min in the furnace at around 950°C to austenize fully. When the sheet temperature reaches the set temperature such as 500°C, 600°C, 700°C and 800°C, the universal tensile testing machine is started to stamp at 500 mm/min speed and V-shaped heat bending parts are formed. Also samples of 1.2 mm, 1.6 mm and 2.0 mm are involved.

The temperature-time curve is shown in Fig. 3. It's found cooling rate reaches 103°C/s when stamping at 800°C, and it decreases to 23°C/s at 500°C, which will affect martensite forming and mechanical attributes obviously.

Meanwhile spring-back angles of specimens are measured, which is shown in Fig. 4. It shows that the spring-back angle is the smallest when bending at around

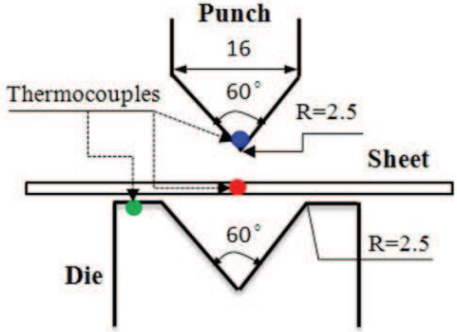

Fig. 2. Special V-shaped Bending.

600 – 700°C. Besides, hardness of bending samples is measured, as shown in Fig. 5, which also indicates samples have higher hardness when bended at 600 – 700°C.

To probe into the theory, microstructures of thermal bending specimens are analyzed. As found in Fig. 6, strip-shaped martensite is hard to find when bending at 500°C; strip-shaped martensite is filled with the microstructure of sheets stamped at 600°C and 700°C and the texture is more finer than sheets formed at 800°C, although whose main microstructure is also martensite. Combine our other issue research [Hu *et al.*, 2010], we can see the 22MnB5 sheet has better plasticity and formability between 600 – 700°C forming temperature zone.

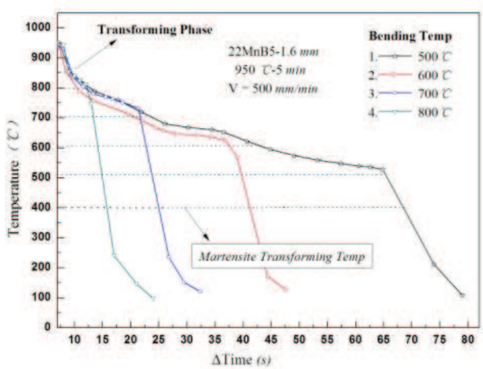

Fig. 3. Correlation of temperature and time in V-shaped bending.

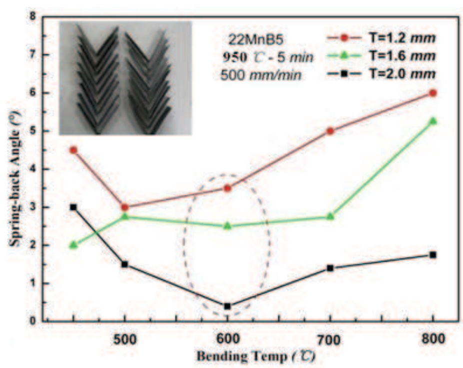

Fig. 4. Spring-back angles of hot stamping

3. Bending Test of Anti-collision Beam Formed at Different Temperatures

To verify the test conclusion, comparison test is conducted focused on the OTZ. Real anti-collision beams are hot stamped at around 650°C and 800°C, based on 1.6 mm blank, as shown in Fig. 7(a).

Then pure bending test is conducted on the hot stamping beams, including cold stamping ones, shown in Fig. 7(b). As shown in Fig. 8, the deformation-load curve peak of beams formed at 650°C is slightly higher than that of beams stamped at around 800°C, and through 300 mm deformation the former beam is intact but obvious cracks are developed in the latter beam as shown in Fig. 9, the condition showed the OTZ temperature range should be from 600 to 700°C. Moreover, another V-shaped heat bending test is demonstrated with bending strength of cold stamping beams, 44 Mpa, is only one third of hot stamping ones', 115 Mpa. The maximum bending load of hot forming specimens is as high as 11000 N, but that of cold stamping ones is only 5000 N. It reveals that hot stamping significantly enhances bending strength, energy absorption capability and passive safety of auto parts.

4. Lightweight Evaluation in VCD_ICAE

Vehicle Concept Design-Intelligent CAE (VCD_ICAE) software system is developed on NX platform by UG OPEN API language. This system can improve and optimize the vehicle concept design quickly [Cui *et al.*, 2007]. To evaluate hot forming lightweight effect, 22MnB5 hot stamping parts studied in the paper are applied to a concept vehicle body and its mass is optimized in VCD_ICAE.

As shown in Fig. 10, 12 structure components of a concept body are formed by hot stamping with 22MnB5 steel. They are front anti-collision beam (B1), threshold beam (B9), A pillar (B11), front roof beam (B12), middle roof beam (B15), rear roof beam (B18), front side roof beam (B13), rear side roof beam (B16), C pillar (B19), B pillar upper beam (B21), B pillar lower beam (B21) and front seat beam

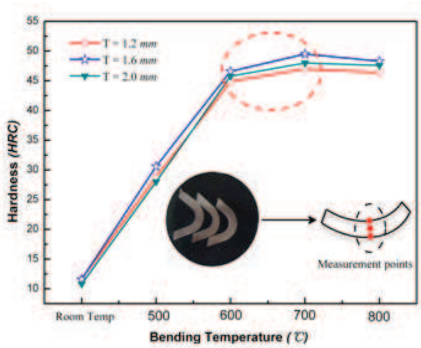

Fig. 5. Hardness of bending samples

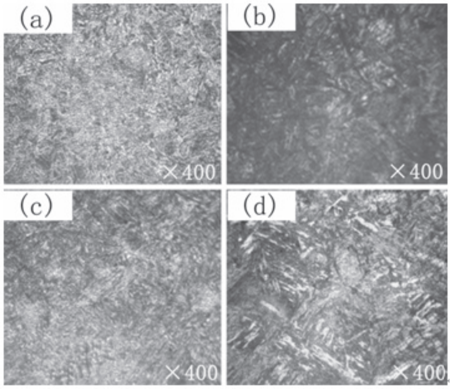

Fig. 6. Microstructure of sheets bending and quenching at the temperature point. (a)500° C (b)600° C (c)700° C (d)800° C

(B22). In the evaluation, the body mass as the optimization goal, thicknesses of these beams' panels, outer panel, the inner panel and reinforcing panel, are the optimization variables, and bending stiffness is the optimization constraint.

While optimizing, front and rear spring supports are constrained properly. The concept body is under bending condition and bending load is acted on four body locations as shown in Fig. 10. Load imposed on the body is 8852.8 N totally and its distribution is as below.

(1)Front longitudinal is imposed 2100N for engine gravity,

(2)Front seat beam is loaded 1764N for passenger gravity,

(3)Passenger gravity 2646N is acted on rear seat beam,

(4)Luggage is assumed 480N and its gravity is enforced on the trunk beam.

Usually, vehicle body beam consist of three kinds of panels, outer panel, inner panel and reinforcing panel. For large amount of variables, sensitivity analysis of these panels' thicknesses to the auto body mass is necessary for heightening optimizing efficiency. The thickness-to-mass sensitivity of consisted panels of 12 hot stamping beams shown in Fig. 10 is computed and sensitivity values are as shown

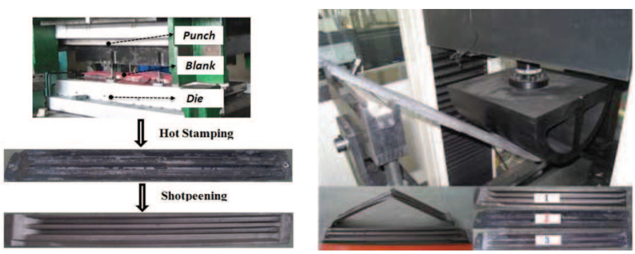

Fig. 7. (a) Hot stamping for the beams (b) anti-collision beams bending test

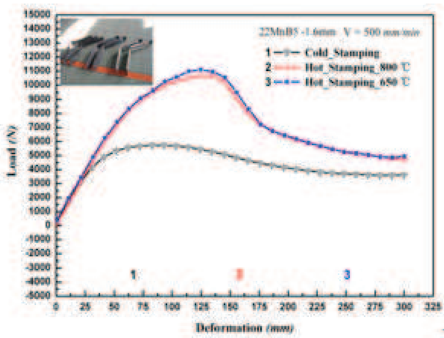

Fig. 8. Correlation of deformation and load

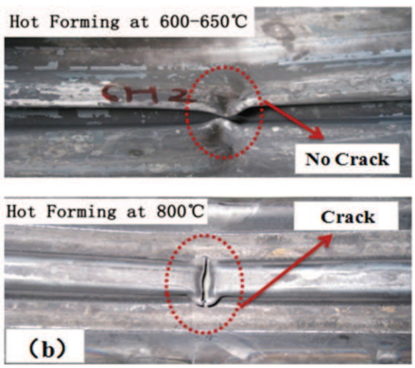

Fig. 9. Comparison of the bending result

in Table 3. It's shown that every panel has different sensitivity value signifying different influence on auto body mass. Variables whose sensitivity value is beyond 1.0

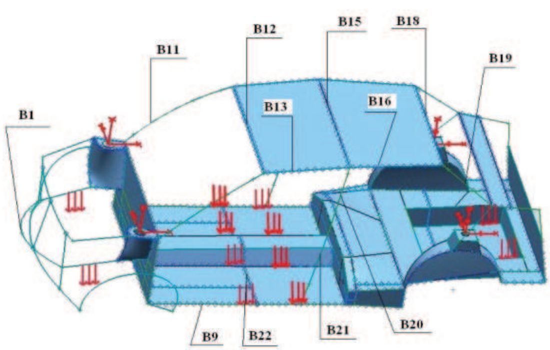

Fig. 10. Concept vehicle body with hot forming parts and its load distribution

Table 3. Sensitivity values of hot forming beam panels

Variables	Sensitivity value	Variables	Sensitivity value
T_B1_O	2.128123	T_B19_O	1.250924
T_B1_I	0.766887	T_B19_I	0.882013
T_B11_O	1.937444	T_B19_R1	1.036298
T_B11_I	1.182576	T_B20_O	1.210539
T_B11_R1	1.430408	T_B20_I	1.396874
T_B12_O	1.568472	T_B20_R1	1.138198
T_B12_I	1.781522	T_B20_R2	0.831113
T_B13_O	1.383223	T_B21_O	2.173775
T_B13_I	0.831773	T_B21_I	0.714839
T_B13_R1	1.071244	T_B21_R1	2.086043
T_B15_O	1.307375	T_B21_R2	1.493516
T_B15_I	1.511508	T_B22_O	4.847929
T_B16_O	1.701928	T_B22_I	2.171561
T_B16_I	1.036186	T_B9_O	6.913873
T_B16_R1	1.344283	T_B9_I	5.060672
T_B18_O	1.631824	T_B9_R1	5.154398
T_B18_I	1.751500		

are selected as optimization parameters. As a result, 28 panel thickness variables are optimized in VCD_ICAE, T_B1_O, T_B11_O, T_B11_I, T_B11_R1, T_B12_O, T_B12_I, T_B13_O, T_B13_R1, T_B15_O, T_B15_I, T_B16_O, T_B16_I, T_B16_R1, T_B18_O, T_B18_I, T_B19_O, T_B19_R1, T_B20_O, T_B20_I, T_B20_R1, T_B21_O, T_B21_R1, T_B21_R2, T_B22_O, T_B22_I, T_B9_O, T_B9_I and T_B9_R1. In the variable name, O, I, R1 and R2 represent outer panel, inner panel, reinforcing panel 1 and reinforcing panel 2, and T stands for thickness.

While all constraints and variables are set, the body mass is optimized by 2.7%, from 427.9 kg to 416.4 kg, after 30 iterations as shown in Fig. 11. And all 28 panel thicknesses are redesigned and optimized. Fig. 12 shows 30 iterations of all thickness variables and it's clear that almost panel thicknesses are brought down, which is good for auto body lightening [Yim *et al.*, 1964] and [Vivek *et al.*, 2004].

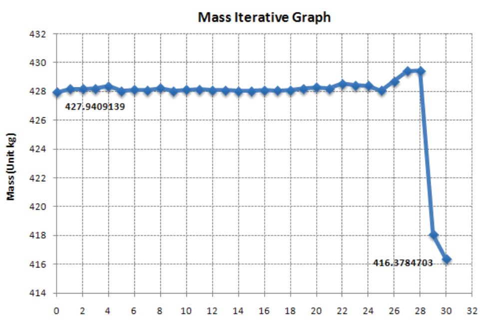

Fig. 11. The body mass optimization iteration curve

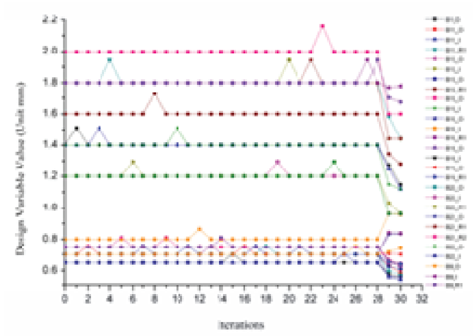

Fig. 12. The panel thickness optimization iteration curve

Table 4. Detailed optimization result [mm]

Variables	Initial Value	Optimal Value	Variables	Initial Value	Optimal Value
Vehicle Mass [kg]	427.94	416.38	B18_O	0.750	0.637
Bending Stiffness [N/mm]	4357	4472	B18_I	0.650	0.558
B1_O	1.400	1.147	B19_O	0.700	0.700
B11_O	0.700	0.586	B19_R1	0.700	0.640
B11_I	1.400	1.120	B20_O	0.700	0.574
B11_R1	1.800	1.440	B20_I	1.200	0.960
B12_O	0.750	0.626	B20_R1	1.800	1.440
B12_I	1.200	0.960	B21_O	0.700	0.560
B13_O	0.700	0.610	B21_R1	1.800	1.440
B13_R1	1.600	1.281	B21_R2	2.000	1.600
B15_O	0.750	0.642	B22_O	1.200	0.960
B15_I	1.400	1.120	B22_I	0.650	0.541
B16_O	0.700	0.836	B9_O	0.700	0.739
B16_I	0.800	0.956	B9_I	1.800	1.780
B16_R1	0.700	0.837	B9_R1	1.800	1.674

Table 4 shows the detailed optimization results by applying hot forming components. It's shown that nearly all beam panel thicknesses decline. As a result, vehicle mass decreases remarkably. Simultaneously vehicle bending stiffness is raised from 4357 N/mm to 4472 N/mm, which demonstrates that the auto body safety is improved combined with its lightweight for using 22MnB5 hot stamping parts.

To validate the optimization, the optimal concept body, whose panel thicknesses are redesigned for applying 22MnB5, is investigated under the same bending condition. And its stress and deformation cloud charts are obtained and compared with those of the original body model, as shown in Fig. 13 and Fig. 14. It's seen that both stress and deformation of the optimal model are improved while 22MnB5 hot forming components are brought into use for the auto body. And the optimal model

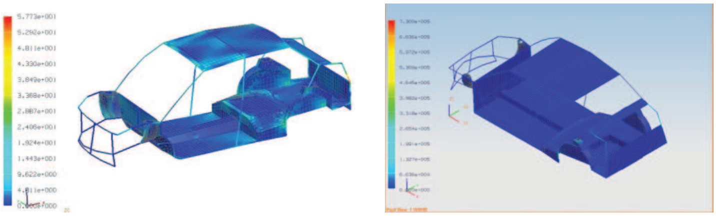

Fig. 13. The comparison between stress distribution of original and optimal model (a) Original model stress distribution (b) Optimal model stress distribution

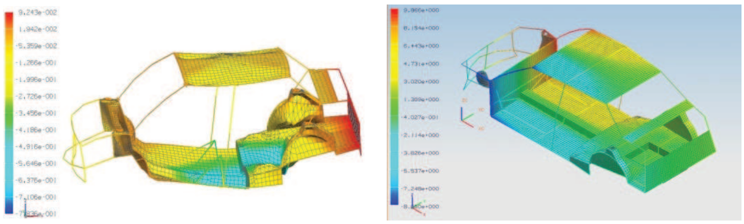

Fig. 14. The comparison between deformation distribution of original and optimal model (a)Original model deformation distribution (b) Optimal model deformation distribution

stress and deformation range safely under the bending condition, which shows the hot forming parts application and optimization are essential for automobile design.

5. Conclusion

Hot forming technology enhances component strength significantly to make vehicle more lightweight and safer at the same time. The temperature zone between 600 – 700°C, is optimal for 22MnB5 bending forming due to more fine martensite texture and smaller spring-back amount. The real hot forming component bending test also shows that anti-collision beams formed at 600 – 700°C has more qualified mechanical characteristics. Due to ultra-high strength, hot stamping components provide attractive lightweight potential for vehicle which is evaluated and verified by VCD_ICAE will be contribute to apply widely in automotive industry.

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