Research on hot metal gas forming characteristics of 1.5GPa ultra-high strength steel and lightweight of torsion beam

Baochuan Wang[1,2], Xuetao Li[2], Chunguang Li[2], Xuebin Zheng[1,2], Lang He[2], Xiaoqiang Li[1,†],
Wenyu Ma[2] , Chen Song[3] and Dechao Xu[2]

[1]*Research Institute of Technology, Shougang Group Co., Ltd., Beijing 100043, China*
[2]*School of Mechanical Engineering & Automation, Beihang University, Beijing 100191, China*
[3]*AutoForm Software (Shanghai) Ltd, Shanghai 200001, China*
[†]*E-mail: lixiaoqiang@buaa.edu.cn*
www.buaa.edu.cn

Hot metal gas forming (HMGF) of tubular profiles showed an immense manufacturing potential, due to the excellent strength, lightweight and integrated manufacturing of the formed parts. In the work the influence of forming temperature, pressurization rate and bulging pressure on the of forming law of CR1000/1500HS ultra-high strength steel was studied. Furthermore, the torsion beam design for the hydroforming part optimized as hot metal gas forming was completed, based on the forming characteristics of 1.5GPa ultra-high strength steel, the hot metal gas forming process design, simulation analysis and optimization, Fatigue Strength and life were complete. Compared with the hydroforming part, the hot metal gas forming part had a lightweight effect of more than 28%, and the fatigue life was 36.75 ten thousand times. Thus, the research results provide the basis and reference for the torsion beam to adopt hot metal gas formed parts for 1.5GPa ultra-high strength steel.

Keywords: 1.5GPa ultra-high strength steel; Hot metal gas forming; Torsion beam; Forming characteristics; Lightweight.

1. Introduction

In the context of national security strategy and the Double Carbon Policy background, the demand for energy conservation and emission reduction in the automotive sector is more urgent. Lightweighting is currently the most realistic and effective way to achieve energy conservation and emission reduction in the automotive industry. Studies have shown that reducing vehicle weight by 10% can improve fuel efficiency by 6-8%, and reduce emissions by 10%. At the same time, lightweighting of vehicles should not come at the expense of safety performance. In recent years, automotive safety regulations have become increasingly stringent, such as the new collision standard set by the Insurance Institute for Highway Safety (IIHS) in the United States, which has reduced the offset collision overlap ratio from 40% to 25%[1]. This requires lightweighting while also improving the safety of the entire vehicle.

Automobile lightweighting includes material lightweighting, structural lightweighting and lightweight forming processes [2-4]. The Lightweight Technology Roadmap released by the Society of Automotive Engineers proposes that high-strength steel sheet using the traditional cold stamping forming process will still be the preferred material for automobile lightweighting in the next decade. When using traditional cold stamping processes, ultra

Y. Zhang and M. Ma (eds.), *Proceedings of the 7th International Conference on Advanced High Strength Steel and Press Hardening (ICHSU 2024)*, Atlantis Highlights in Materials Science and Technology 3,
https://doi.org/10.2991/978-94-6463-581-2_12

high-strength steel is prone to problems such as springback deformation, wrinkling, cracking, and poor dimensional accuracy, which seriously affect the quality and reliability of the parts. To solve the problems existing in cold stamping forming, advanced forming technologies such as hydroforming, roll forming, hot Stamping and hot metal gas forming have been developed both domestically and abroad. The hot metal gas forming originated earliest from the "Advanced Technology Program" project funded by the National Institute of Standards and Technology (NIST) and the Advanced Technology Program (ATP) of the United States in 1999 [5], which account the advantages of both hydroforming and hot Stamping. Compared with hydroforming, the hot metal gas forming can achieve integrated forming of complex structures by increasing the forming temperature and overcomes large deformation resistance of the pipe [6]. Compared with hot stamping, it can reduce the number of parts and eliminate the adverse effect of solder joints on the strength of the vehicle body strength. The adoption high-rigidity tubular beam and structure of the ultra-high strength can significantly improve the 25% offset crash safety performance [7].

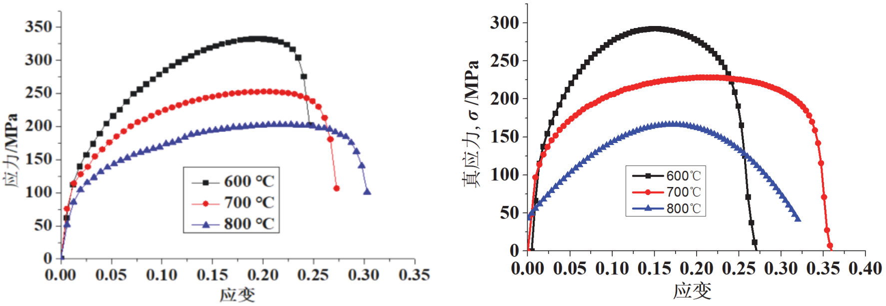
The torsion beam part is the most important structural component in the rear suspension device of the car, which plays a very important role and provides a safety guarantee for keeping the vehicle stable and damping during driving. The forming methods of torsion beam mainly include cold stamping, hot stamping and hydroforming [8]. The hot metal gas forming of the tubular torsion beam can obtain an ultra-high strength of 1.5GPa, which is conducive to achieving lightweighting of the vehicle body and performance improvement.

This paper is based on hydroforming design scheme of the torsion beam, and adopt hot metal gas forming method for optimized design. Through the thermomechanical coupling numerical simulation, this study investigates the effects of forming temperature, gas bulging pressure and pressurization rate on the wall thickness distribution and dimensional accuracy of the torsion beam during the hot metal gas forming process. The aim is to determine the optimal process parameters for achieving the best forming results. Through the simulation analysis of fatigue life and fatigue strength, the lightweight design of torsion beam based on 1.5GPa strength level by hot metal gas forming is feasible, which makes it have good economic benefits and lightweight effect.

2. Materials and Specimens

2.1. *High-temperature tensile test of materials*

The experimental material used is CR1000/1500HS, with a thickness of 1.5 mm. The high-temperature tensile tests were conducted adopts the thermodynamic simulation testing machine Gleeble3800. During the experiment, the samples were first rapidly heated to 930 °C, then cooled to 800°C, 700°C, and 600°C, lastly tensile tests were conducted under the conditions where the strain rates ε were 0.01, 0.1 and $1s^{-1}$ respectively. The distribution of flow stress under different temperatures and strain rates is shown in Figure 3. It can be observed that the flow stress of CR1000/1500HS at high temperatures is significantly influenced by both strain rate and temperature. As the temperature increases, the stress continuously decreases. This is because the increase in temperature leads to a rise in the original activation energy of the material, which results in dynamic recovery during the deformation process. This dynamic recovery weakens the strain hardening effect, which causing a reduction in flow stress. As the strain rate increases, the stress continuously increases. This is due to the fact that the higher strain rate leads to an increased amount of deformation and a greater number of dislocations in the material. In this case, the work hardening effect of the material is greater than the dynamic recovery effect, which resulting in an increase in flow stress.



(a). strain rates $1s^{-1}$ b). strain rates $0.1s^{-1}$.

Fig. 1 stress-strain curves at different temperature and strain rates

It is well known that the material model has a significant impact on the accuracy of forming simulations. Many scholars at home and abroad have conducted intensive study on the high-temperature mechanical properties and material models. The descriptions of flow stress-strain behavior of materials at high-temperature are divided into two types by different finite element software[9]. One approach is to use constitutive equations that incorporate temperature, while the second approach involves inputting stress-strain cur-ves at different temperatures and the software calculates the stress-strain relationship at other temperatures through the interpolation function. This article adopts the second approach based on the finite element analysis software Autoform.

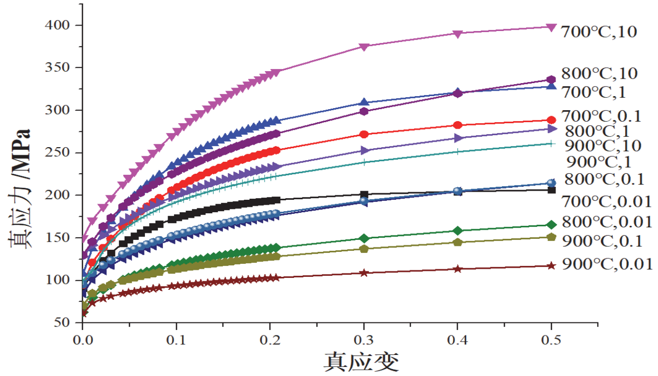


Fig. 2. True stress-true strain curves under different temperatures and strain rates

2.2. *Part Structure Design and Forming Scheme*

The material grade of the inner high-pressure forming part is SAPH440, with a typical cross-sectional shape shown in Figure3. The workpiece has a left-right symmetrical structure, with an average wall thickness of approximately 3.5 mm. The A-A cross-section represents the symmetrical plane, and section A to B has the same section shape, while section B to G has a large variation along the axis, gradually changing from an approximate V-shaped section to an approximately trapezoidal section. The perimeter of the cross-section also exhibits considerable variation along the axial direction. The minimum perimeter is found at the G-G section, with an outer surface perimeter of 321.559 mm, while the maximum perimeter occurs at the E-E section, with an outer surface perimeter of 324.832 mm. The maximum rate of change in cross-section perimeter for the part is approximately 1.31%.

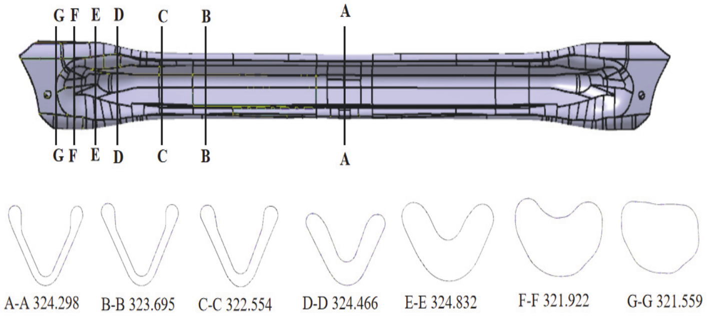


Fig. 3. Mathematical model and cross-section of torsion beam part by hydroforming

Considering the usage requirements of the torsion beam in terms of strength, torsional stiffness, and fatigue performance [10], the thickness of the tube is selected as 2.5mm. Considering the problems of rapid air pressure unloading and difficult of axial feed in hot gas forming, the change rate of the perimeter of the designed tube should not exceed 5%. The shape of the tube has been redesigned as shown in Figure 4. The A-A cross-section represents the symmetrical plane. The section shapes from A to E vary greatly along the axis, gradually transitioning from an approximately V-shaped section to an approximately trapezoidal section at the end. The Outside perimeter, equivalent diameter, and expansion factor of the 6 typical sections are analyzed as shown in Table 2. It is concluded that the perimeter of the section D-D is the smallest, which is 324.44mm, while the perimeters of the adjacent sections C and E increase sharply. Based on the structural analysis, the initial outer diameter of the original tube blank is selected as Φ103mm. The expansion factor of the part section is approximately 1.61%.

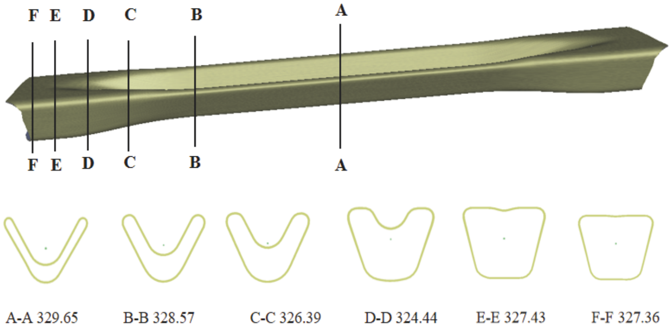


Fig. 4. Distribution of key section positions for tube torsion beam by hot metal gas forming

Table 1. Cross-sectionsizes of tube torsion beam

section	A	B	C	D	E	F
Outside the perimeter/mm	329.65	328.57	326.39	324.44	327.43	327.36
equivalent diameter/mm	104.93	104.54	103.87	103.27	104.21	102.2
expansion factor /%	1.61	1.27	0.60	0.00	0.92	0.90

The part forming adopts a two-step method. Firstly, the tube blank is preforming. The approximate shape of the workpiece section is formed by the method of mechanical pressing, and the material strain in each area is reasonably distributed. Then the preforming part undergoes hot metal gas forming. High-pressure gas is introduced into the tube blank to make the preforming part completely fit with the final forming die and obtain the final part.

3. Forming numerical Simulation

The hot gas metal forming process for the torsion beam includes the steps of tube production, cold preforming, heating, rapid transfer, mold closing, sealing, gas pressure injection, Pressure maintaining, Release gas pressure and, in-mold cooling and quenching. In this study, Autoform simulation software is used to conduct finite element simulation analysis of the preforming and hot gas expansion forming, as shown in Figure 5. The finite element simulation analysis model for preforming and hot gas expansion forming consists of three parts, including the upper die, the lower died, and the tube blank. The friction coefficient is set as 0.45.

Fig.5. Finite element simulation model of preforming and hot metal gas forming

3.1. *Preforming Simulation Results*

In the preforming process, the intermediate section has a V-shaped cross-section [11], and the width of the section shrinks to be completely placed in the final forming die. The minimum wall thickness is 2.352 mm, and the thinning rate is only 1.6%. The position of the minimum wall thickness is located at section B. The preforming quality is good and meets the requirements of the final hot metal gas forming.

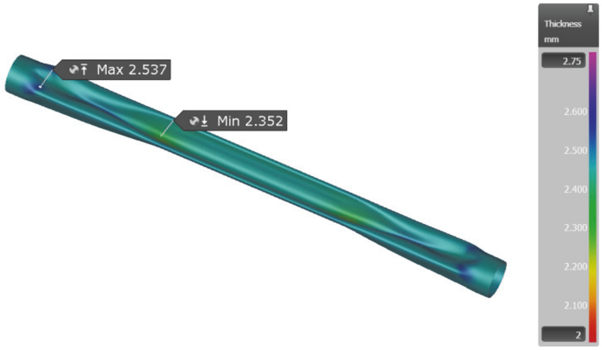


Fig.6. Finite element analysis results of preforming

3.2. *Final forming simulation results*

In this paper, numerical simulations of various process parameters in hot metal gas forming process are conducted, including the influence laws of forming temperature, gas bulging pressure and pressurization rate on the wall thickness uniformity and dimensional accuracy of the formed parts. The heating temperatures are set at 750°C, 800°C and 850°C, the gas bulging pressures are set at 30 MPa, 50 MPa and 70 MPa, the gas pressurization rate are 3.5 MPa/s, 5 MPa/s and 7 MPa/s.

With the increase of the heating temperature, the thinning rate of the part increases. Mainly, the material is more likely to expand at high temperatures. When the initial temperature of the specimen changes from 750°C to 850°C, the minimum wall thickness changes from 2.233mm to 2.184 mm, and the dimensional accuracy improves from 0.752mm to 0.509 mm. As the bulging pressure and pressurization rate increase, the minimum wall thickness decreases, and the dimensional accuracy improves. When the bulging pressure exceeds 50 MPa and pressurization rate exceeds 5 MPa/s, the thinning trend of the part becomes less pronounced. From the slope of the curves in Figure 7, it can be observed that, the heating temperature has a more significant impact on the on the minimum wall thickness and dimensional accuracy than bulging pressure.

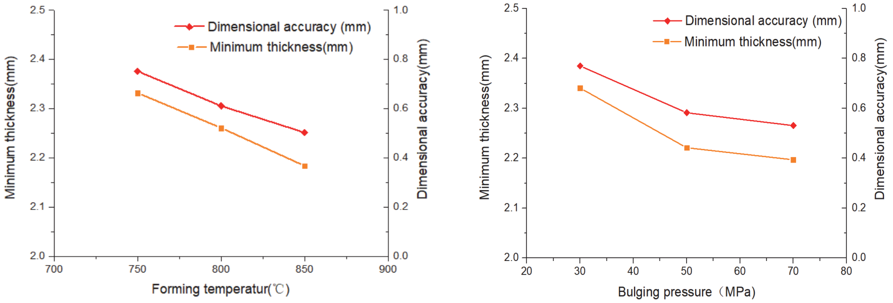


Fig.7. Effect of temperature and bulging pressure on the minimum wall thickness and dimensional accuracy

Through comparative analysis, an optimal hot gas inflation forming process has been determined. The forming temperature is set as 850°C, with an bulging pressure 50 MPa and pressurization rate of 5 MPa/s. Under these conditions, the maximum wall thickness of the part is 2.685 mm, the minimum wall thickness is 2.182 mm, and the dimensional accuracy is 0.509 mm. Additionally, the martensite content is 100%. The results indicate that the tubular beam exhibits good formability and manufacturability.

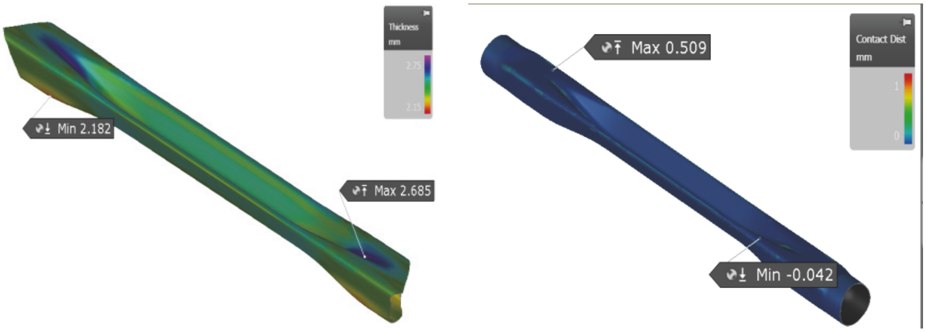


Fig. 8. The minimum wall thickness and dimensional accuracy

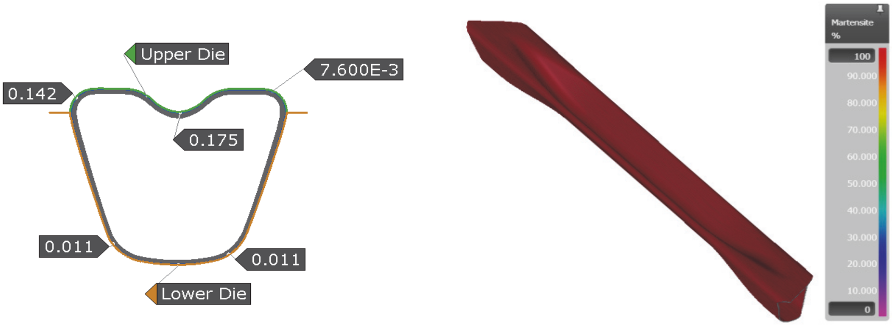


Fig. 9. Dimensional accuracy along circumferential wall and Martensitic phase content

3. 3. *Finite element analysis of fatigue life*

Fatigue cracking is the most common failure mode of the torsion beam. Based on the final formed parts, finite element simulation methods are used to analyze the torsional strength and torsional loading fatigue life [12] . The body connection points of the torsion beam rear axle are fixed to the bench through articulation. The loading point is located at the intersection of the wheel axis and the wheel installation end face on the longitudinal arm. The loading direction is along the z-axis, and the loading stroke is 46.2 mm. The maximum torsional stress is 961.06 MPa, with the safety factor of 1.25. The fatigue life is 36.75 ten thousand times, which meets the requirement of fatigue life > 30 ten thous-and times. The final part reduces the weight by 2.83 kg, resulting in a lightweighting rate of 28.86%. The comparison between the two processes is shown in the table 2. The analysis of torsion beam strength and fatigue life meets the design requirements of the component.

Fig. 10. Torsional fatigue simulation model

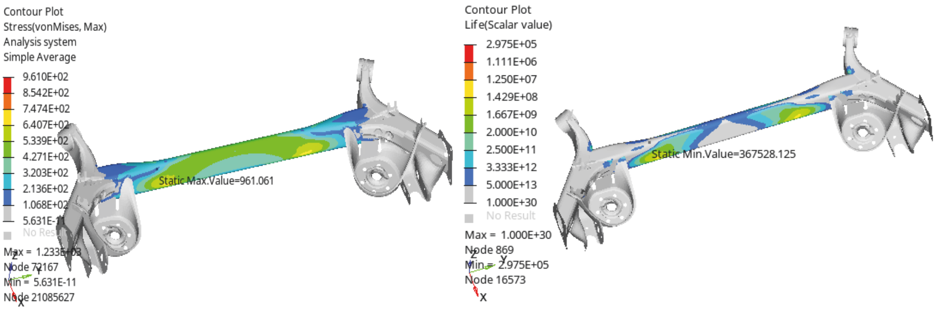


Fig. 11. Torsional strength stress distribution (left) and fatigue life analysis(right)

Table 2. Comparison of Performance of Torsion Beams with different Forming Methods

Material	Thickness/mm	Mass/kg	Torsional stress/Map	Safety factor	Fatigue life/N
SAPH440	3.5mm	9.821	398.971	1.25	430942
CR950/1300HS	2.5mm	6.986	961.061	1.25	367528

4. Conclusions

1) Under high temperature conditions, the flow stress of CR1000/1500HS decreases as the temperature rises, and increases as the strain rate rises. The influence of temperature is greater than the strain rate.

2） With the increase in forming temperature, bulging pressure and pressurization rate, the minimum wall thickness of the part decreases, and forming dimensional impro-ves. The influence of forming temperature is greater than bulging pressure and pressu-rization rate.

3)Through optimization of the hot metal gas forming process, manufacturability meets the required specifications. The minimum wall thickness is 2.182 mm, and the dimensional accuracy is 0.509 mm. Additionally, the martensite content is 100%.

4) By using the hot metal gas forming process instead of the hydroforming, the maximum torsional stress of torsion beam is 961.06 MPa. The fatigue life is 36.75 ten thousand times, which meets the requirement of fatigue life > 30 ten thousand times. The torsion beam achieves a weight reduction of 28.9%.

References

1. L. Y. Bian, Application of multi target positioning in low-speed collision avoidance system, Science & Technology Information 5, 41 (2011).
2. P. Li, Research on the Application of HSS in Automobile Lightweight, Special Purpose Vehicle 11, 61 (2022).
3. S. L. Zheng, S. Lin, Weight-reduction Design of Auto Structures Based on Strength Features, Chinese Journal of Mechanical Engineering 44, 129 (2008).
4. Q. N. Zhong, Discussion on Lightweight Design of Automobile Structural Design, Automobile Applied Technology 15, 153(2019).
5. B. T, Hot metal gas forming-the next generation process for manufacturing vehicle structure components, SAE Paper 1, 3229(1999).
6. G. Q. Wang and J. P. Li, Development of thermoforming equipment with inner high atmospheric pressure for ultra-strength steel pipe, Journal of Northeastern Unive-rsity 38, 234(2017).
7. C. Cheng, F. Han and L. Shi, Hot metal gas forming characteristics of ultra-high strength steel tube and development of A-pillar specimens, Forging Stamping Technology 5, 95(2003).

8. X. F. Chen and Z. Y. Chen, Study on the effects of different forming processes on the performance of torsion beam, Forging Stamping Technology 39, 112(2014).
9. W. W. Zhang, C. Han and S. J. Yuan, Effect of loading paths on thickness distribution and precision of a hydroformed torsion beam, Materials Science and Technology 20,1 (2012).
10. X. L. Li and H. Li, Development and performance evaluation on 1500 MPa anti-fatigue torsion tubular beam based on numerical simulation, Forging Stamping Technology 10, 108(2023).
11. C. Han, W. W. Zhang and S. J. Yuan. The effect of preform shape on hydroforming of a V-type hollow component. Materials Science and Technology 19, 1(2011).
12. H. Li, F. Yu and N. Liu, Research on key technology of forward development of torsion beam based on numerical simulation, Modern Manufacturing Engineer-ing 4,94(2024).