

Manuscript Number: PROTEC-D-14-01135R1

Title: Experimental investigation of boron steel at hot stamping conditions

Article Type: SI: Hot Stamping

Keywords: Boron steel; Hot stamping; Correction method; Fracture; Hardening; Viscoplastic constitutive model

Corresponding Author: Dr. Chaoyang Sun, Ph.D.

Corresponding Author's Institution: University of science & Technology of Beijing

First Author: Nan Li, PH.D.

Order of Authors: Nan Li, PH.D.; Chaoyang Sun, Ph.D.; Ning Guo; Momhamed Mohamed, Ph.D.; Jianguo Lin, Ph.D.; Takeki Matsumoto; Chao Liu

Manuscript Region of Origin:

Abstract: The effect of deformation temperature and strain rate on the fracture and strain hardening of boron steel was investigated through the analysis of large amount of experimental data tested using a Gleeble (3800) materials simulator. These features were further modelled by using a set of unified viscoplastic damage constitutive equations. To study the deformation behavior, isothermal uniaxial tension tests of 1500 MPa boron steel at different strain rates of 0.01-5.0 s⁻¹ and different deformation temperatures of 550-850 °C were performed on a Gleeble 3800 materials simulator. Considering the difference between the deformation of the necking cross section and the centre measuring cross section of specimen at necking stage, a correction method of measuring strain at the necking cross section was developed. In addition, by taking temperature rise during deformation into account, a correction method of measuring stress was proposed. The true stress-strain curves were obtained based on the two corrections methods. The influence of deformation temperature and strain rate on the fracture and hardening was analyzed. A set of unified constitutive equations was adopted and determined from experimental data. The correlation between the numerical-computed and experimental true stress-strain data is presented. The average relative error is within the range of allowable experimental conditions and the predicted and experimental values can almost be consistent.

Professor Julian Allwood
Editor-in-Chief of
Journal of Materials Processing Technology

Dear Professor Allwood,

Experimental investigation of boron steel at hot stamping conditions
(PROTEC-D-14-01135)

By

Nan Li, Chaoyang Sun, Ning Guo, Mohamed Mohamed, Jianguo Lin, Takeki Matsumoto, Chao Liu

Thank you so much for your and reviewers' comments for the paper, which are very valuable.

The manuscript has been modified according to reviewers' comments, which have been detailed in the "Response to reviewers' comments". Especially, we have asked an English native speaker, Professor Trevor Dean of Birmingham University, to check/modify English in the paper and we have made corresponding changes to improve the quality of English.

I would very much appreciate if you could consider the original work presented in the paper to be published in your journal.

Yours Sincerely

Professor Chaoyang SUN

Tel.: +86 10 62334197, Fax: +86 10 62329145;

E-mail: suncy@ustb.edu.cn.

Detailed response to referee's comments

Manuscript title:

Experimental investigation of boron steel at hot stamping conditions

All the comments are very constructive and valuable for improving the quality of our paper. We have studied the comments carefully and made appropriate revision of the manuscript. The revised parts are highlighted in the new version of the manuscript. The main corrections in the manuscript and the detailed responses to the reviewers' comments are as summarized in the following:

The comments from Reviewer #3:

1. The statements "Further it could be seen the degree of the change of hardening rate was not obvious for the different strain rates at the temperature of 700C during the whole deformation stage from the beginning to the end. Thus it could be regarded that strain rate has less impact on formability at the tested temperature." are based on the results from Figure 12. The reviewer's view is that the fitting for strain rate of $0.01s^{-1}$ could be brought down where it will be seen that the hardening rate is larger for $1s^{-1}$ at strains larger than 0.1.

✓ *Thanks for this comment. The curve of strain rate gradient at the strain rate of $0.01s^{-1}$ has been properly fitted. Indeed, the hardening gradient for $1s^{-1}$ is higher than that for $0.01s^{-1}$. Fig 12 has been updated; the confusing statements in the previous version have been removed and the paragraph has been modified in section 4.2.2. (Page 18)*

2. It would be beneficial to see how the proposed constitutive material model compares with other temperatures as well (e.g. temperatures in the range 550-850).

✓ *Thanks for this valuable suggestion. Yes, it would be beneficial to add the comparisons between simulations predicted by the proposed model and experiments at other temperatures. Thus in Section 5.7 of the revised version, a new Fig. 15(b) has been given to show the comparison of experimental (symbols) and computed (solid curves) stress strain curves at strain rate $1s^{-1}$ in the range of 650-800 °C (Page 27).*

The comments from Reviewer #4:

This manuscript presents an experimental study about "The isothermal uniaxial tension tests of 1500 MPa boron steel under different strain rates of 0.01-5.0 s⁻¹ and different deformation temperatures of 550-850 Celcius degree using Gleeble 3800 simulator".

A correction method of measuring strain and temperature at necking cross was proposed. Although it is stated that "a set of unified visco-plastic damage constitutive equations based on dislocation" is proposed, there is no new model on the study but models of other researchers were presented.

In addition, the influence of deformation temperature and strain rate on the fracture and hardening were investigated in the study.

In general I believe that the work presented in the paper is suitable for publishing in the present journal. But it can't be published in the present form unless the below comments are dealt with.

1. The language of the manuscript should be reviewed by a native or professional editing service. Inverted sentence are extensively used throughout the text which makes the content difficult to understand. This should be corrected since this is a manuscript for scientific publication

✓ *The whole paper have been read and corrected by a native speaker, Professor Trevor Dean of Birmingham University, UK.*

2. The aim of the study is not clearly given in the abstract. Generally, the aim of the study is given in the first sentence of the abstract.

✓ *The abstract has been modified to highlight the issue (Page1).*

3. The study is about high temperature deformation characteristic of metallic material and the deformation temperature of the material is around from 0.4T_m to 0.5 T_m. The deformation is accepted superplastic deformation if the materials are deformed at around 0.5 T_m. Thus if it is not considered as superplastic deformation, the reason should be explained very clearly.

✓ *A new paragraph and a few more references are given in Page 4 to address this issue.*

4. The assumptions should be presented before going into details of the study. (Size of the grains, the stress vs strain rate curve in log-log scale, the meld point of material should be presented)

✓ Further information of the material and explanation are given in Page 7. A new figure (Fig. 13) is added in Page 19 showing the relationship of “the stress vs strain rate curve in log-log scale”. Further discussions are given in Page 19.

5. In Fig. 1 a, the dimensions of the test pieces should be written in engineering way. It is aligned from left. This is confusing. (arrows etc. be drawn better)

✓ The dimensions of the test pieces have been corrected, Page 6.

6. It is written that "Fig.1 (a) Scheme of the test sample showing the gauge length, effective gauge length and width". This is not about 3 parameters but it is the dimensions of the test piece. This is a scientific paper and the captions should be well and correctly defined.

✓ Thanks for the comments. The figure caption has been changed to address this issue, Page 6.

7. The type of the thermocouple is not given. (K, J type?, Inconel or other type?) All experimental system should be well defined and explained part by part since the study is based on experiments.

What is the usage of merit of the Gleeble test system over conventional tensile test to define the high temperature deformation properties of the material?

✓ Thanks for this suggestions. The K-type thermocouples were used in this study (given in Page 6). Further explanation for the use of Gleeble has been given in Page 6.

8. All over the text, strain rate was one of the important parameter and many data was based on it. But no strain rate sensitivity index consideration was given in the study. No stress-strain rate curve was included in the study. At least a strong explanation of why superplasticity is not considered in the study should be clearly explained.

✓ A new Figure (Fig 13) is given to show the effect of strain rate on the flow stresses and the strain rate sensitivity features. Further discussions are given in a new paragraph in Page 19.

9. On Page 8, "Regarding equation (3)" is written. Should it be equation (2)?

✓ Many thanks. Corrected.

10. On Page 12, it is written that "Fig. 8 (a) shows the increase of strain rate leads to appreciable decrease of ductility for boron steel at 800 °C; however, in Fig. 8 (b), the ductility for boron steel at 700 °C is almost constant at different strain rates.". The (a) and (b) and the temperatures should be checked whether they are correct?

✓ *Many thanks. This is a mistake. The temperatures have been checked. It has been corrected that Fig. 8 (a) (b) corresponds to 700 °C and 800 °C, respectively.*

11. In Fig. 8, the horizontal axis unit should be presented. (Strain rate s-1)

✓ *Many thanks. It has been added.*

Experimental investigation of boron steel at hot stamping conditions

Nan Li¹⁾, Chaoyang Sun^{2*)}, Ning Guo²⁾, Mohamed Mohamed¹⁾, Jianguo Lin^{1,2)}, Takeki Matsumoto³⁾, Chao Liu²⁾

¹ Department of Mechanical Engineering, Imperial College London, London, SW7 2AZ, UK;

² School of mechanical engineering, University of Science and Technology Beijing, Beijing, 100083, China;

³ IMRA Europe S.A.S. U.K. Research Centre, The University of Sussex, Brighton BN1 9RS, UK

ABSTRACT

The effect of deformation temperature and strain rate on the fracture and strain hardening of boron steel was investigated through the analysis of large amount of experimental data tested using a Gleeble (3800) materials simulator. These features were further modelled by using a set of unified viscoplastic damage constitutive equations. To study the deformation behavior, isothermal uniaxial tension tests of 1500 MPa boron steel at different strain rates of $0.01\text{-}5.0\text{ s}^{-1}$ and different deformation temperatures of $550\text{-}850\text{ }^{\circ}\text{C}$ were performed on a Gleeble 3800 materials simulator. Considering the difference between the deformation of the necking cross section and the centre measuring cross section of specimen at necking stage, a correction method of measuring strain at the necking cross section was developed. In addition, by taking temperature rise during deformation into account, a correction method of measuring stress was proposed. The true stress-strain curves were obtained based on the two corrections methods. The influence of deformation temperature and strain rate on the fracture and hardening was analyzed. A set of unified constitutive equations was adopted and determined from experimental data. The correlation between the numerical-computed and experimental true stress-strain data is presented. The average relative error is within the range of allowable experimental conditions and the predicted and experimental values can almost be consistent.

Keywords: Boron steel; Hot stamping; Correction method; Fracture; Hardening; Viscoplastic constitutive model

*The Corresponding author: SUN Chaoyang;

Tel.: +86 10 62334197, Fax: +86 10 62329145;

E-mail: suncy@ustb.edu.cn.

1. Introduction

The growing effort to reduce vehicle weight and improve passenger safety in the automotive industry has drastically increased the demand for ultra-high strength steel components. Hot stamping is one of the most successful processes used to produce complex components with superior mechanical properties (Karbasian and Tekkaya, 2010). Boron steel after hot stamping is a typical ultra-high strength steel. With a uniform martensitic structure, it can have a yield stress of 1200MPa and a tensile stress of 1500MPa (Adamczyk et al, 1997), which is three to four times the strength of the standard deep drawing steel (George et al, 2012). Much research has been undertaken to determine thermal transformation aspects such as, temperature-time transformation curves (Barcellona et al, 2009), austenitizing temperature as well as soaking time (Merklein et al, 2006), and thermoforming properties (Xing et al, 2009) of boron steel alloys, but to enable processes to be made more efficient, much needs to be learned about the mechanics of boron steel under hot stamping press hardening conditions. For instance, knowing fundamental material characteristics could enable damage, which is related to stress state, strain rate and the microstructure of the work-piece (Lin et al, 2005), to be delayed and greater formability and more uniform product thickness to be achieved. Quality assurance demands require materials to be processed with known mechanical properties and this can be achieved only through an understanding of damage evolution and hardening laws during hot stamping. Such data characterising an alloy can be mathematically described using viscoplastic constitutive equations.

Conventionally, data for sheet materials is usually generated through tensile tests; and in view of the effect on data accuracy due to temperature change and necking, it is necessary to adopt special experimental measures. Zhou et al. (2013) established unified viscoplastic constitutive equations for 22MnB5 steel in which a correction factor dealt with the apparent decrease in strength as fracture was approached associated with the sudden downward slope of the stress-strain curve obtained from experiments. Li et al. (2012) acknowledged the role of thermal activation deformation behaviour in austenitization of B1500HS boron steel. However, in both work, the temperature rise during deformation was not considered and effect of on flow stress was not corrected. Luo et al. (2000) proposed a correction method for temperature rise

considering deformation heat effect in GH4169 alloy during a constant strain rate extrusion process. This method indicated that the flow stress at high strain rates must be corrected for the temperature rise induced by plastic deformation. Luan et al. (2014) also adopted a similar correction approach in studying the constant temperature extrusion of AZ31 magnesium alloy. In this paper, deformation heat effect and necking played an important role in the analysis of experimental results, so it is necessary to improve on experimental technology. Lin et al. (2005) summed up damage evolution mechanisms, damage modeling and its calibration for several kinds of process conditions such as creep, superplastic forming and hot stamping. This study assumed the main agents of damage in hot deformation are microvoids and cracks created at second phase particles and/or around grain boundaries. The relative importance of the two agents for damage changes according to the strain rate, temperature and grain size. The micro voids and micro cracks merge to form the macroscopic cracks.

The deformation temperature for hot stamping is similar to superplastic forming, apart from that the deformation rate is about 10^3 higher than that of superplastic forming (Lin and Dunne, 2001). In addition, fine grain size materials are normally used for superplastic forming, which facilitates grain boundary sliding and grain rotation deformation mechanisms during the slow forming process. Strain rate hardening is the main hardening mechanism for achieving uniform deformation of materials under superplastic forming conditions (Cheong et al. 2000). Even if there are many differences, such as deformation mechanisms, hardening mechanisms, between hot stamping and superplastic forming processes, they both belong to viscoplastic deformation (Lin and Dean, 2005) and thus the general modelling framework for viscoplasticity can be used for both processes (Lin, 2003).

Mechanism-based constitutive models, with dislocation density evolution taken into account, for predicting deformation and fracture patterns in hot sheet deformation, have been under development. To model hardening, Mohamed et al. (2012) developed a constitutive model based on the dislocation density evolution in AA6082 alloy during hot stamping; Cai (2011), Li et al. (2011), and Zhou et al. (2013) adopted

a similar model to that of Mohamed to predict the hardening law of boron steel. In the dislocation density evolution, the softening effect of recovery leading to reducing of dislocation density was considered. Engaging in another aspect of ductile fracture, Bariani et al. (2012) reported on a method using continuum damage mechanics to replace the traditional forming limit curve to analyze hot stamping of high strength steel, which reflected the dynamic progression of material damage. The model considering temperature and strain rate had a great effect on numerical modeling and the formulation of process plans for hot sheet stamping (Li et al, 2012). Li et al. (2011) employed a damage evolution model for boron steel and Al alloy based on continuum damage mechanics and simulated the formability of different metal during hot stamping.

The work in this paper utilises the above models to develop an advanced material and process model to extend the understanding of the behaviour of B1500HS boron steel during hot stamping processes. The results of quasi-isothermal tensile tests of B1500HS, carried out at different temperatures and strain rates, are described. True stress-strain curves corrected for temperature rise and necking have been obtained and the variation of hardening and softening characteristics and strain to failure, with temperature and strain rate, has been characterised. Using this information, a set of unified viscoplastic damage constitutive equations has been established based on dislocation density and damage evolution mechanisms, and calibrated from experimental results, which can provide a theoretical basis for predicting the deformation limits of boron steel when press hardening complex parts.

2. Experimental programme

2.1 Material and equipment

The material used in this study was boron steel B1500HS. Quasi-isothermal tensile tests were conducted using a Gleeble 3800 materials simulator. The chemical composition of materials is listed in table 1. The dimensions of the tensile specimens are shown in Fig.1. All specimen used for the experiment were machined from the same batch of as-delivered, 1.58 mm thick, boron steel sheet.

Table1. Chemical composition of B1500HS boron steel (wt. %).

C	Si	Mn	P	S	Cu	Cr	Ni	Al	Ti	B
0.20	0.19	1.24	0.016	0.0027	0.02	0.19	0.02	0.044	0.021	

Experiments were carried out using a Gleeble (3800) materials simulator. Equipped with resistant heating, air, gas and water cooling, the test machine is commonly used for the characterisation of thermo-mechanical properties of metals in various practical thermal mechanical processing conditions. It has accurate feed-back systems, which enables the defined temperature profiles and deformation rates to be accurately controlled for the measured regions.

In order to control the heating rate and achieve the target deformation temperature, a pair of K-type thermocouples was welded to the centre of the test piece surface to provide measured temperature feedback to the controller. A C-Gauge was clamped in the middle of the specimen to measure the width strain associated with deformation. They are schematically shown in Fig.1. In order to apply a high cooling rates (higher than 50 °C/s), two compressed-air nozzles were integrated.

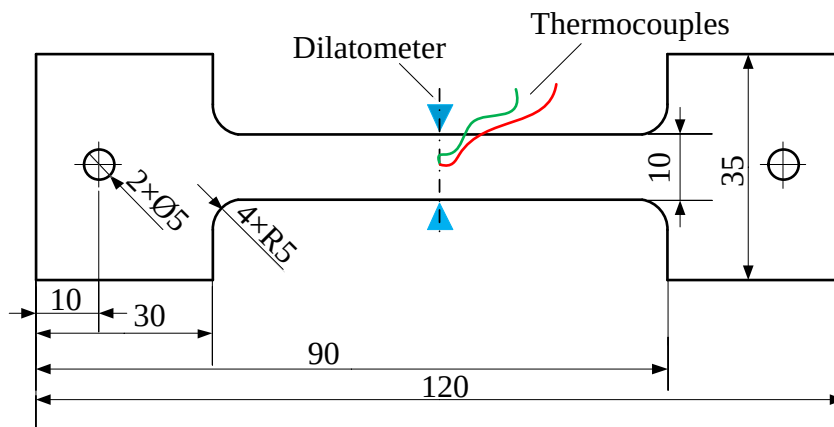


Fig.1 Specimen design (dimensions are in mm) with schematic dilatometer and a pair of K-type thermocouples attached.

2.2 Experimental programme

Under hot stamping conditions, boron steel is deformed in the austenitic phase. Although the nominal forming temperature in industry is 700 °C, temperature will change during forming due to heat transfer between the blank and the dies. Therefore, testing conditions have to be defined over a range of forming temperatures. In this work, uniaxial hot tensile tests were performed to determine the thermo-mechanical characteristics of B1500HS within the strain rate range of 0.01-5 s⁻¹ and temperature range of 550-850 °C. The selected strain rate range is sufficient to cover the range experienced in industrial practice.

Fig. 2 shows the designed heating route to simulate the thermal history profile for industrial hot stamping processes. The heating process was divided into two steps: the first step was to heat the specimens to 730 °C with a heating rate of 8 °C/s; the second step was to 900 °C with a slower heating rate of 3 °C/s. This particular austenisation temperature (900 °C) was chosen ($T/T_m = 0.53$, where $T_m = 1700$ K is the melting temperature of the material) to ensure that (i) the temperature enables the virgin phase of the material to be completely transformed to austenite and (ii) no obvious grain growth (Cai, 2011). Thus the grain size would be fairly stable at the heat treatment and deformation processes. To simplify the studies, the effect of grain size on the deformation is not considered. After heating, test-pieces were cooled to testing temperatures at a cooling rate of 50 °C/s, which is similar to that experienced in transporting the blank to the press, in the industrial process (Cai, 2011). Then, tensile tests were carried out under isothermal conditions.

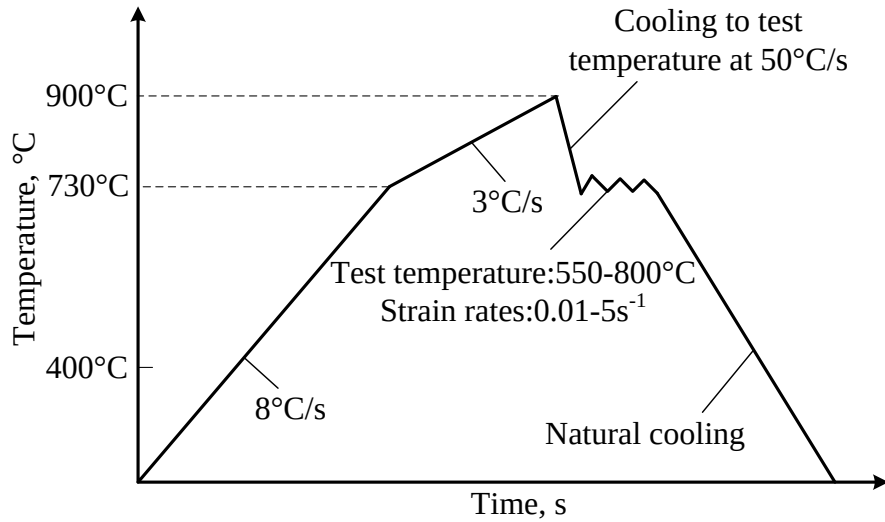


Fig.2 Temperature profile for the experimentation.

3. Corrections for accurate strain and stress records

3.1 Strain correction at necking stage

For tensile testing, when failure doesn't occur at the specimen centre section where the dilatometer is clamped, the strain obtained from dilatometer measurement cannot accurately present the deformation behaviour of specimen after onset of necking. Therefore, a method has been defined to correct measured strain data to represent that at the necking position.

Fig. 3 schematically shows the longitudinal area of interest between the centre section and failure section of a tensioned specimen. At the time just before onset of necking (at the peak load), the area of interest is shown as a light grey rectangle. The specimen width and the distance between centre section and failure section are W_{c0} and l_0 , respectively. When localised deformation takes place, the shape of the area deviates from rectangular, and in this method, it is simplified as a trapezium: the trapezium drawn in dashed lines represents an instantaneous shape during necking, where the widths of centre section and failure section are W_{ci} and W_{fi} , respectively, and the distance between centre section and failure section is l_i ; the trapezium in dark grey represents the final shape of the longitudinal section when the specimen fails, where the corresponding dimensions are W_{cn} , W_{fn} , and l_n . The angle α represents the deviation of specimen edge from

its original direction. It equals zero in the beginning, and for a constant strain rate, it is assumed to increase proportionally with time during necking.

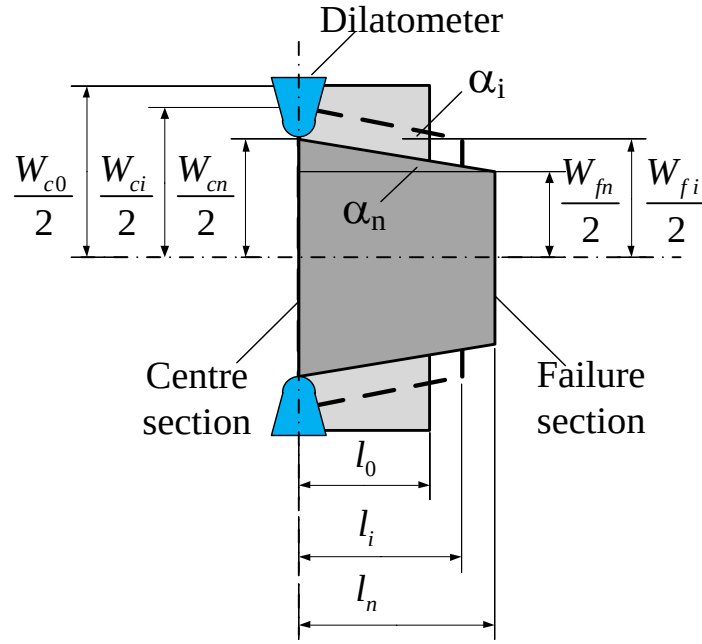


Fig.3 Strain correction method at necking stage.

The target is to map the evolution of W_{ci} to W_{fi} , thus the corrected true strain at necking stage can be given by:

$$\varepsilon_T = -2 \ln \left(\frac{W_{fi}}{W_0} \right) \quad (1)$$

where W_0 is the initial width of specimen. The calculation of W_{fi} is given in detail as follows:

The instantaneous width of the failure section W_{fi} can be formulated as:

$$W_{fi} = W_{ci} - 2l_i \tan \alpha_i \quad (2)$$

where W_{ci} is obtained from dilatometer measurement, and

$$l_i = l_0 + \frac{i}{n}(l_n - l_0) \quad (3)$$

$$\alpha_i = \frac{i}{n} \alpha_n \quad (4)$$

where n is the total number of time intervals for the necking stage in data acquisition, i represents an instantaneous time interval.

Regarding equation (3), l_0 is given by:

$$l_0 = l_n \frac{S_0}{S_n} \quad (5)$$

where S_0 and S_n correspond to the strokes (data from Gleeble data acquisition) at the onset of necking and failure, respectively. The value of l_n can be manually measured from the fractured specimen.

Regarding equation (4), the final angle α_n can be calculated by:

$$\alpha_n = \arctan \frac{W_{cn} - W_{fn}}{2l_n} \quad (6)$$

where W_{cn} is read from dilatometer measurement, W_{fn} and l_n are manually measured from the fractured specimen.

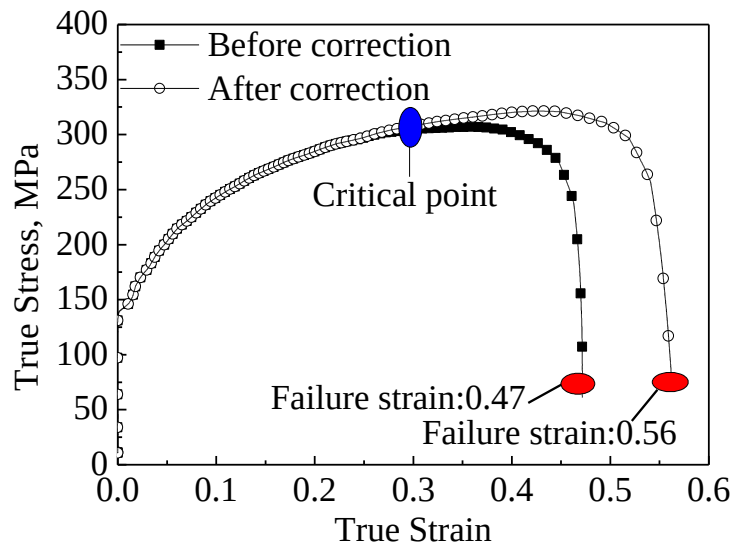


Fig.4 An example true stress-strain curve, at the temperature of 700 °C and strain rate of 1 s⁻¹, before and after correction (red points show failure; blue point shows criticality for necking).

Fig.4 shows the true stress-strain curve, tested at temperature 700 °C and strain rate 1 s⁻¹, before and after correction at necking stage. It can be seen that, beyond the strain value of 0.3, the uncorrected and corrected

true stress-strain curves deviate considerably and the failure strain for the corrected curve is significantly higher.

3.2 Stress correction

Flow softening is a common characteristic of stress-strain curves at elevated temperatures. This is typical of most metals, and is commonly a result of higher dislocation mobility (by increased thermal vibration of the lattice, lower relative strength of obstacles to dislocation motion, etc.), higher activation of diffusion controlled processes such as grain boundary sliding and rotation and dislocation climb, as well as generally more active recovery mechanism, all of which are thermally activated processes (Mohamed et al, 2012). It is generally understood that, during workability testing such as hot stamping, about 95% of the energy of plastic deformation is converted to heat to raise the temperature of the specimen, while the rest 5% stays in the material as stored energy. In the tensile tests, the temperature is measured and controlled by thermocouple and computer, but the response time of thermocouple is often too long for good measurement accuracy. When strain rate is high, it is not possible to control the instantaneous heat generation to maintain a constant temperature. So the deformation process is not completely isothermal (Li et al, 2002). As a result, during a test, the specimen temperature is increased due to plastic deformation and the resulting flow stress will be lower than the flow stress at the desired test temperature under isothermal conditions.

Fig.5 (a) and (b) show the measured temperature changes during tensile tests at a range of strain rates of 0.01-5 s⁻¹ at the present temperatures of 700 °C and 800 °C, respectively. It can be seen that, at a strain rate of 0.01 s⁻¹, the maximum temperature rise is about 2 °C; however, at a strain rate of 5 s⁻¹, the maximum temperature rise is 25 °C. Therefore, the flow stress at high strain rates (1 s⁻¹ and 5 s⁻¹) must be corrected to account for the temperature rise induced by plastic deformation. The changes of stress caused by temperature rise can be calculated by the following equation (Luan et al, 2014):

$$\Delta\sigma = \left[\frac{\partial\sigma}{\partial(1/T)} \right]_{\dot{\epsilon}} \cdot \left(\frac{1}{T_n + \Delta T} - \frac{1}{T_n} \right) \quad (7)$$

Where σ is the flow stress (MPa), T_n is the present temperature (°C) and ΔT is the difference between T_n (°C) and the specimen temperatures measured by thermocouples.

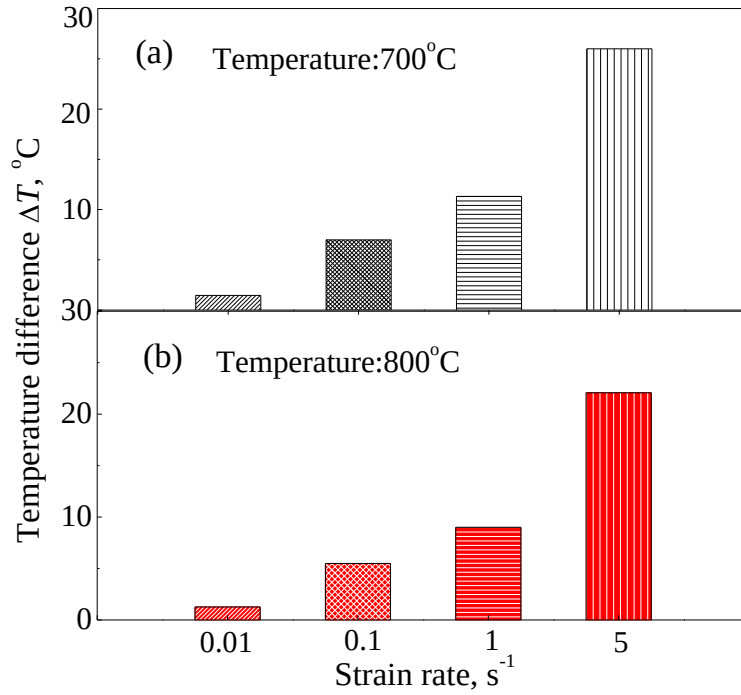


Fig.5 Temperature rise (ΔT) during hot deformation of boron steel, at different strain rates (0.01-5 s⁻¹), at the pre-set temperature of (a) 700 °C and (b) 800 °C.

Fig.6 shows the comparisons of the flow stress curves of B1500HS boron steel before and after correction. It can be seen that the thermal effect on flow stress becomes larger at a lower temperature and a higher strain rate.

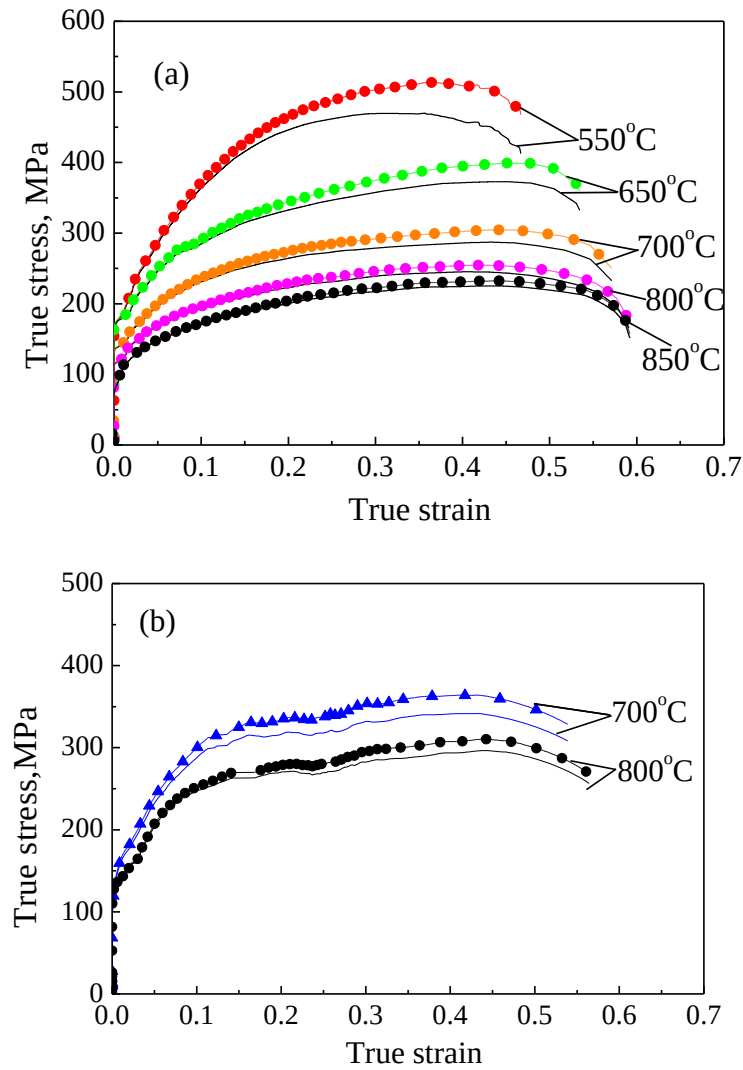


Fig.6 Comparison of flow stress before (solid curves) and after (symbols) correction at the strain rate of (a) 1 s^{-1} (temperature range: 550-850 °C) and (b) 5 s^{-1} (temperature: 700 °C and 850 °C).

4. Test results and discussion

4.1. Ductility

4.1.1 Effect of Temperature on ductility

The symbols in Fig.7 show the strain to failure for B1500HS tested at different deformation temperatures (550-850 °C) at a strain rate of 1 s^{-1} . The measured strain to failure increases with increasing temperature although the results seem scattered due to experiment error. In general, greater ductility can be obtained

with increased temperature. Increased ductility implies that the formability can be increased by forming at a higher temperature, hence more complex shapes in terms of larges depth, sharp corners and multi-part assemblies can be produced.

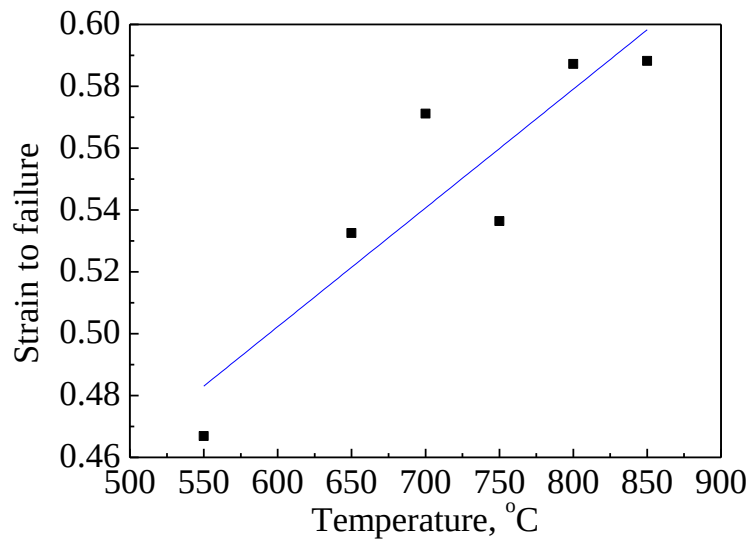


Fig.7 Strain to failure at different temperatures at a strain rate of 1 s^{-1} .

4.1.2 Effect of Strain rate on ductility

As a general rule, ductile fracture during tensile deformation results from the nucleation, growth and coalescence of damage (Nicolaou et al, 2000). The dependency of tensile behaviour of the boron steel on strain rate has been investigated at different strain rates (0.01 to 5 s^{-1}). Fig. 8 (a) and (b) show the strain to failure of the boron steel tested at $700\text{ }^{\circ}\text{C}$ and $800\text{ }^{\circ}\text{C}$, respectively. The minor changes of the values reflect low sensitivity of ductility with strain rate at the typical hot stamping temperature range, which would benefit forming of complex parts at a high forming speed for the increase of productivity and reducing heat loss.

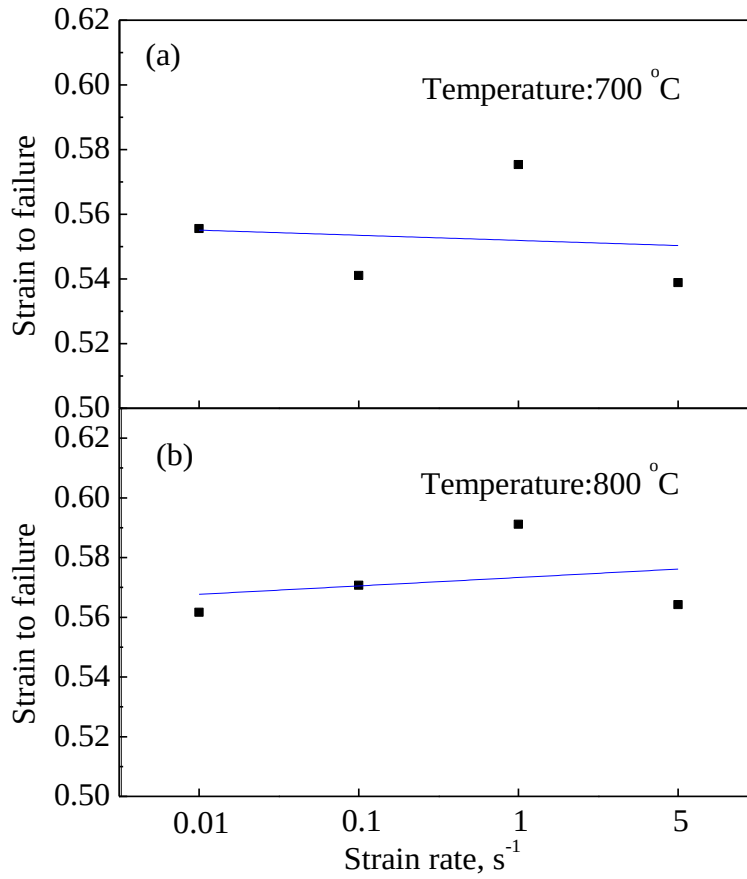


Fig.8 Strain to failure at different strain rates at the temperature of (a) 700 °C and (b) 800 °C.

4.2. Flow stress

4.2.1 Effect of Temperature on flow stress

The influence of temperature on the flow stress of the tested material B1500HS has been investigated for a range of temperatures (550-850 °C) in the austenitic state after rapid cooling. Exemplarily for a test at the temperature of 850 °C (with a strain rate of 1 s⁻¹), an interpretation for the tendency of the shapes of the true stress-strain curve and strain hardening gradient ($\partial\sigma/\partial\epsilon$) curve is shown in Fig.9 (a). The strain hardening gradient ($\partial\sigma/\partial\epsilon$) decreases while strain increases, which indicates that the effect of recovery balances the strain hardening and the dislocation net-work reaches saturation state for further plastic deformation. Before strain reaches 0.2, the test piece is deformed in uniform deformation zone (light yellow area in Fig.

9 (a)) with strong strain hardening. Then, the curve asymptotically becomes stable. While true stress reaches the peak value, the strain hardening gradient drops to zero.

Fig. 9 (b) shows the strain hardening gradient ($\partial\sigma/\partial\epsilon$) curves at different temperatures (550°C, 700°C and 850°C) for the strain rate of 1 s⁻¹. Due to temperature dependency, the level of strain hardening gradient is lower and the variation of strain hardening is less apparent at a higher temperature. As deformation proceeds, there is a tendency for strain hardening gradient to be steady due to dynamic and static recoveries, at all the tested temperatures.

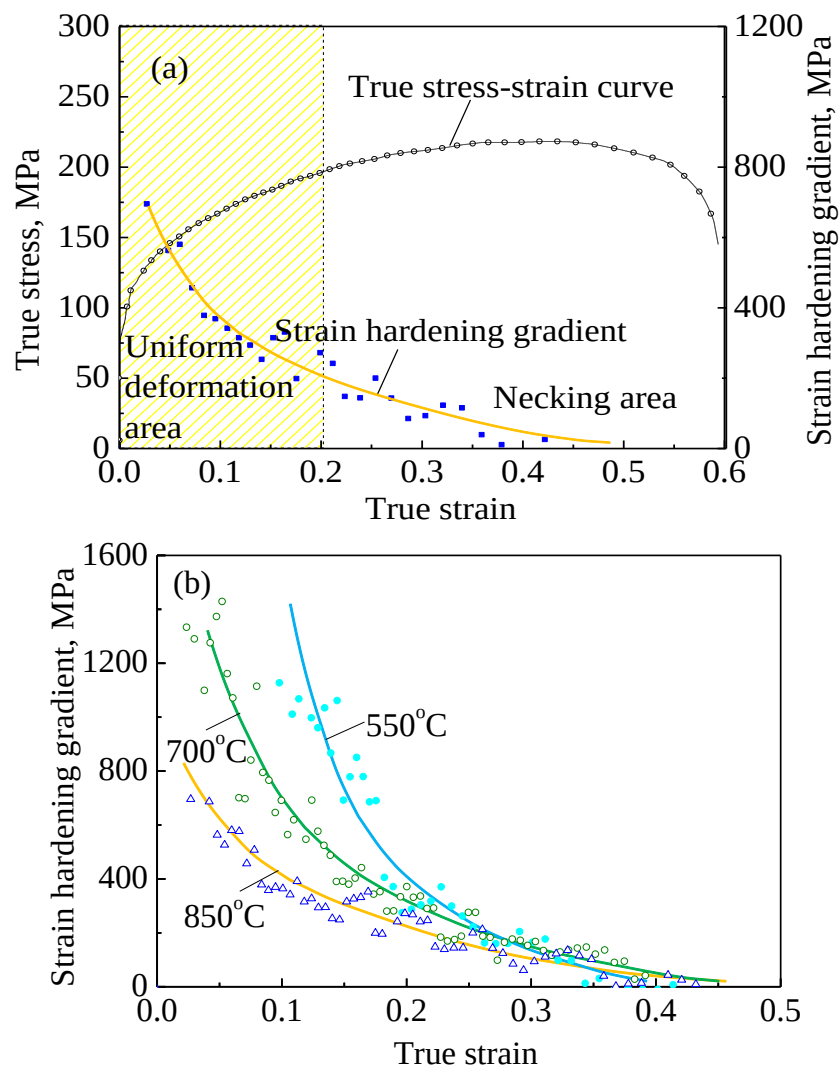


Fig.9 (a) Curves of true stress-strain and strain hardening gradient (for temperature: 850 °C, strain rate: 1 s⁻¹); (b) Comparison of strain hardening gradient at different temperatures, at a strain rate of 1 s⁻¹.

Fig. 10 shows the effect of temperature on the maximum true stress. It can be seen that the maximum true stress decreases with increasing temperature. This is a result of greater active dislocation mobility at a higher temperature. More sliding systems promote plastic deformation of metals and thus the strength of the alloy reduces.

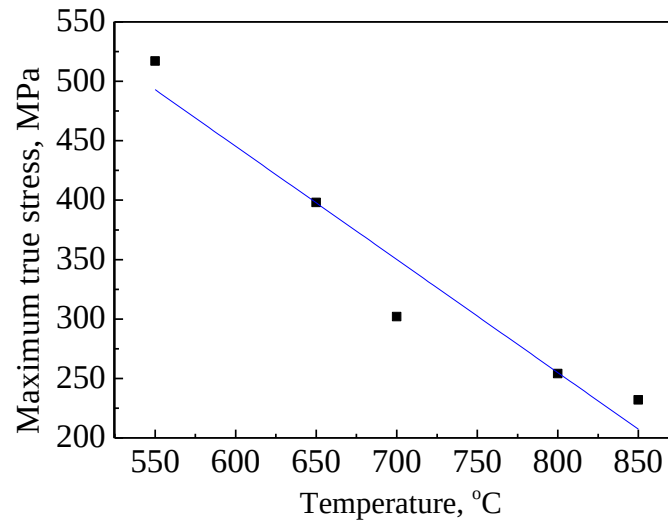


Fig.10 The maximum true stresses for different temperatures at a strain rate of 1 s^{-1} .

4.2.2 Effect of strain rate on flow stress

The dependency of the material tensile behavior on the strain rate has been investigated at a range of strain rates ($0.01\text{-}5 \text{ s}^{-1}$). Fig. 11 shows that increasing strain rate leads to appreciable increase of the stress level when the boron steel is deformed at $700 \text{ }^{\circ}\text{C}$. Inner stress of material could be generated during a tensile test, which would make the metal crystal slip. Insufficient crystal rotation occurs and slip saturates at a higher strain rate so that flow stress increases at the macro level; furthermore, deformation would be hindered due to strain hardening. For a higher strain rate, the viscous stress is higher; at the same time, there is less time for static recovery which is normally the main softening mechanism for deformation at elevated temperatures. Therefore, the external force has to be increased to maintain deformation, which explains the increasing resistance to deformation and enhanced strength.

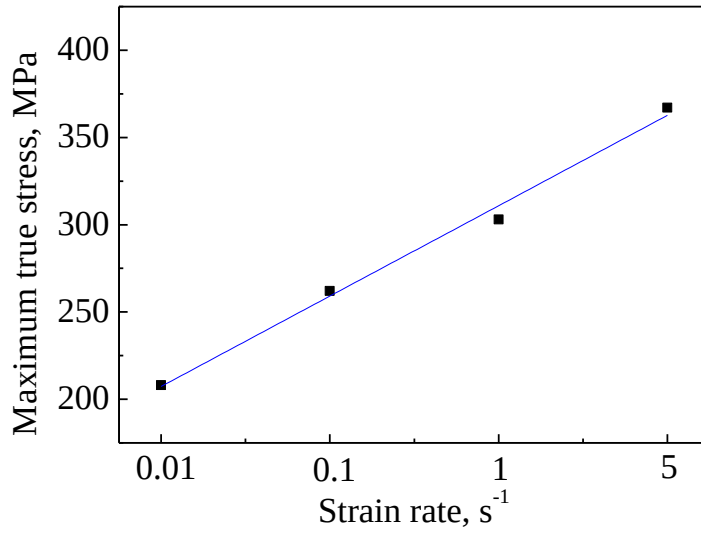


Fig.11 The maximum true stresses for different strain rates at a temperature of 700 °C.

Fig. 12 shows that the strain hardening gradient at a strain rate of $1 s^{-1}$ is larger than that of $0.01 s^{-1}$ during the whole deformation processes. This is mainly due to less static recovery occurs during a higher strain rate deformation at the same temperature. High strain hardening increases the drawability of the material in hot stamping processes.

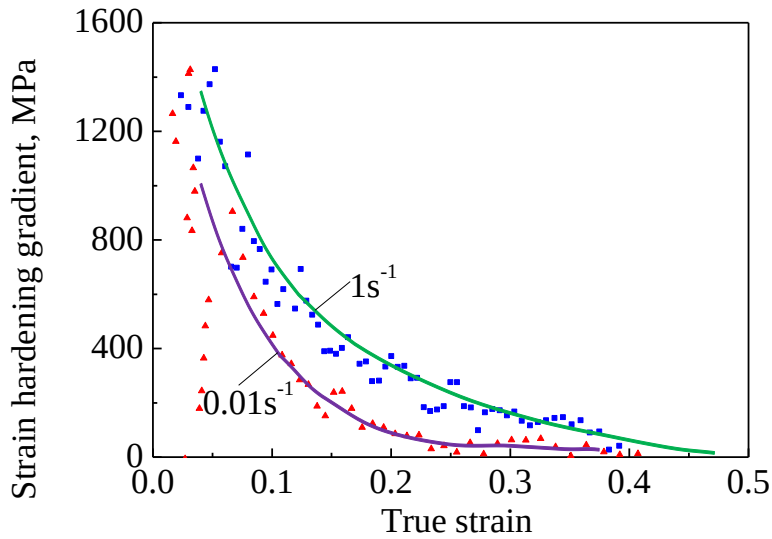


Fig.12 Comparison of strain hardening gradient at different strain rates at a temperature of 700 °C.

Fig. 13 shows the effect of strain rate on the flow stress for the boron steel at a strain level of 0.2 deformed at the temperature of 700 °C and 800 °C. By plotting true stress again strain rate in a log-ling scale, linear fits have been obtained for both temperatures, which suggests the power law viscoplastic response of the material. The increase of flow stress with increasing strain rate exhibits the strain rate hardening characteristics. The strain rate hardening exponent is represented by the slope of trend lines, ‘ m ’, and corresponds to the power exponent in the equations. It is a critical factor influencing the uniformity of deformation during hot stamping processes. Generally, a larger m value indicates a higher tendency to reduce the strain rate gradient within the material flow. The m value for 800 °C is slightly larger than that for 700 °C for the boron steel. The effect of temperature within the hot stamping temperature range on the strain rate hardening is small.

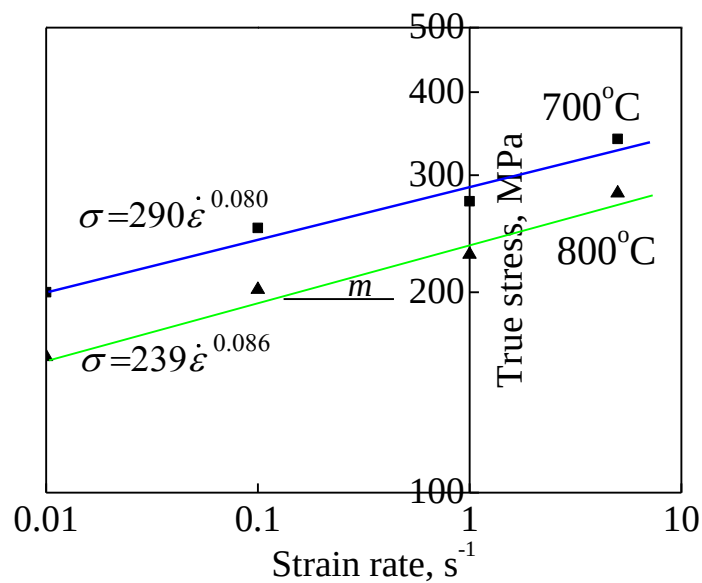


Fig 13. Variation of stress at a strain level of 0.2 with different strain rates (0.01-5 s^{-1}) for the material deformed at the temperature of 700 °C and 800 °C.

5. Determination of a constitutive model

5.1. Flow rule

Constitutive equations for viscoplasticity have been developed for many types of metals. The equations enable a wide range of time-dependent phenomena to be modelled, such as strain hardening and stress relaxation, and allow finite element model implementations of the equations to accurately reproduce time-dependent plastic deformation in forming simulation, including strain rate effects and recovery. Lin et al. (2005) made further contributions to model viscoplastic behaviour under hot forming conditions by developing a set of dislocation-based, coupled viscoplastic constitutive equations for general multiaxial stress and strain states, which are able to account for the effect of interdependent aspects of microstructure evolution, such as recrystallization, grain growth and dislocation behaviour, on viscoplastic flow.

For ductile metals and alloys at temperatures less than $0.4T_m$, at which plastic deformation occurs by dislocation motion, the hardening relationship is conventionally described by a power-law (Mohamed et al, 2012)

$$\sigma = K \cdot \varepsilon_p^N \quad (8)$$

where K is a stress constant and N is the strain-hardening exponent. When the temperature rises above $0.5T_m$, thermally activated processes become significant and the flow stress depends on strain rate:

$$\sigma = K \cdot \varepsilon_p^N \cdot \dot{\varepsilon}_p^m \quad (9)$$

where $\dot{\varepsilon}_p$ is the plastic strain rate and m is the strain rate hardening exponent.

In practice, most metals and alloys show plastic yield and work hardening during straining. The material has an initial yield stress k . After sufficient plastic strain occurs, dislocation entanglement, pile-ups, etc., harden

the material by an amount H (Nes, 1997); the stress that leads to viscoplastic flow is reduced to $\langle \sigma - H - k \rangle$ (Mohamed et al, 2012). Thus the flow rule can be modified to depend directly on the isotropic hardening and initial yield stress. Eq. (9) is replaced by

$$\dot{\epsilon}_p = \left(\frac{\sigma - H - k}{K} \right)^{n_c} \quad (10)$$

which is the traditional power-law viscoplastic flow formulation and K and n_c are material constants.

5.2 Modeling of dislocation density

Dislocations are accumulated when mobile dislocations are trapped and halted at discontinuities, such as grain boundaries, or inclusions, or when mobile dislocations interact with other dislocations during the plastic deformation (Cai, 2011). With increasing density, the stored energy of dislocations provides the driving force for static recovery which is time dependent. Static recovery occurs faster when dislocation density is higher.

It can be seen from the results of this work that softening predominates after reaching a critical strain from the hardening rate curve in this paper, which can be explained by the start of recovery with increasing strain. However, recrystallization should not be considered because the stress-strain curves have not expressed a obvious stable tendency along with increasing strain. Therefore, in consideration of high temperature deformation mechanisms, static and dynamic recovery, a constitutive equation for normalized dislocation density evolution is proposed by Cai (2011):

$$\dot{\bar{\rho}} = A \cdot (1 - \bar{\rho}) \cdot |\dot{\epsilon}^p| - C \cdot \bar{\rho}^{\gamma_2} \quad (11)$$

where A and γ_2 are material constants, and C is a temperature dependent parameter:

$$C = C_0 \cdot e^{\left(p - \frac{Q_c}{RT} \right)} \quad (12)$$

where C_0 is a material constant, Q_c is the activation energy for static recovery.

The normalized dislocation density varies from 0 (the initial state) to 1 (the saturated state of a dislocation networks). The first term in Eq. (12) represents the development of dislocation density due to plastic strain and dynamic recovery; the second term gives the effect of static recovery on the evolution of dislocation density.

5.3. Modeling of damage

Under a hot metal forming condition when the forming temperature is normally half T_m or greater, and strain rates are higher than 1 s^{-1} , plasticity induced damage may occur around inclusions and hard particles. The grain boundary diffusion at high temperatures which facilitates grain rotation and grain boundary sliding tend to be inhibited, due to the high strain rates (Lin et al, 2005). The damage dominating in hot stamping conditions can be schematically illustrated, as shown in Fig. 14.

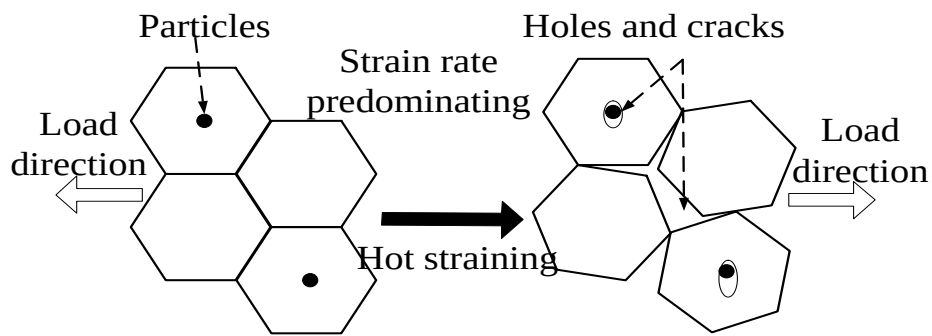


Fig.14 Schematic illustration of damage mechanism under hot metal forming condition (Lin et al. 2005).

Theoretically, in hot deformation, higher strain rates and consequent higher flow stresses result in more microcracks; thus damage is a function of flow stress and plastic strain rate, given by:

$$\dot{D} = f(T, \sigma_e, \dot{\epsilon}_p) \quad (13)$$

where $\dot{D}$ is the damage evolution rate, T is the absolute temperature. Odquist and Hult (1961) have further demonstrated that the damage rate can be a separable function of σ , T and D , therefore the above equation was present as:

$$\dot{D} = f(D) \cdot \beta_d \cdot \sigma_e \cdot \dot{\epsilon} \quad (14)$$

where β_d is a material constant to represent the temperature effects on damage evolution.

A new damage model suitable for hot deformation comprehensively includes equivalent stress, plastic strain rate and damage was established based on damage mechanism, high temperature creep damage model (Lin et al, 2005) and the existing damage model (Cai, 2011) proposed by scholars, which highlighted the importance of strain rate on damage.

$$\dot{D} = \beta_d \cdot \frac{\sigma_e \cdot \dot{\epsilon}_p^{d_2}}{(1-D)^{\gamma_3}} \quad (15)$$

The value of D lies in a range from 0 to 1. When $D=0$, the material is undamaged. A value of $D=1$ would represent a completely disintegrated material, which is practically impossible, as metals fail at damage levels lower than $D=1$. d_2 and γ_3 are material constants. The temperature dependent parameter β_d can be given as:

$$\beta_d = \beta_0 \cdot \exp\left(\frac{Q_D}{RT}\right) \quad (16)$$

where β_0 is a material constant, and Q_D is the activation energy associated with damage.

5.4. Formulation of unified viscoplastic damage constitutive equations

Unified constitutive equations for viscoplasticity damage have been developed for many metal materials (Lin et al, 2002). This work intends to develop a set of unified viscoplastic damage constitutive equations to model the evolution of recovery, dislocation density, hardening and damage to rationalize their inter-relationships and effects on viscoplastic flow of metal alloys. **It is noted that the influence of grain size is neglected for simplification.** The mechanism-based unified viscoplastic damage constitutive equations for hot stamping may take the form:

$$\begin{aligned}\dot{\varepsilon}^p &= \dot{\varepsilon}^o \cdot \left(\frac{\frac{\sigma}{1-D} - H - k}{K} \right)_+^{n_c} \cdot \frac{1}{(1-D)^{\gamma_1}} \\ \dot{\varepsilon}^o &= \begin{cases} 1, & \text{when } \sigma > 0 \\ -1, & \text{when } \sigma < 0 \end{cases} \\ \dot{\bar{\rho}} &= A \cdot (1 - \bar{\rho}) \cdot |\dot{\varepsilon}^p| - C \cdot \bar{\rho}^{\gamma_2} \\ H &= B \cdot \bar{\rho}^{0.4} \\ \dot{D} &= \beta_d \cdot \frac{\sigma_e \cdot \dot{\varepsilon}_p^{d_2}}{(1-D)^{\gamma_3}} \\ \sigma &= E \cdot (1-D) \cdot (\varepsilon^t - \varepsilon^p)\end{aligned}\tag{17}$$

Relevant temperature dependent parameters are given by:

$$\begin{aligned}k &= k_0 \cdot \exp\left(\frac{Q}{RT}\right) \\ K &= K_0 \cdot \exp\left(\frac{Q}{RT}\right) \\ n_c &= n_0 \cdot \exp\left(\frac{Q_n}{RT}\right)\end{aligned}$$

$$C = C_0 \cdot \exp\left(-\frac{Q_C}{RT}\right) \quad (18)$$

$$B = B_0 \cdot \exp\left(\frac{Q}{RT}\right)$$

$$E = E_0 \cdot \exp\left(\frac{Q_E}{RT}\right)$$

$$\beta_d = \beta_0 \cdot \exp\left(\frac{Q_D}{RT}\right)$$

where T is the absolute temperature, R is the gas constant, Q , Q_n , Q_C , Q_E , and Q_D are activation energy associated constants.

5.5. Determination of the equations via optimization

The equation set has a total of 17 material constants that must be determined. These are: k_0 , K_0 , n_0 , C_0 , B_0 , E_0 , β_0 , Q , Q_n , Q_C , Q_E , Q_D , γ_1 , γ_2 , γ_3 , A , d_2 . They are calibrated by fitting computed and experimental true stress-strain curves for different strain rates and deformation temperatures. The values of the material constants were determined by the optimization techniques (Li et al, 2002), and are listed in Table 2.

Table 2 Determined material constants of boron steel for viscoplastic damage constitutive model

Q	Q_c	Q_D	k_0	B_0	C_0	K_0
(J/mol)	(J/mol)	(J/mol)	(MPa)	(MPa)	(-)	(MPa)
8400	99900	10650	12.4	80	13000	30
n_0	γ_1	A	γ_2	γ_3	d_2	E_0
(-)	(-)	(-)	(-)	(-)	(-)	(MPa)
0.0068	0.1	3.666	1.54	16.3	0.9178	1100
Q_E	β_0	Q_n	R			
(J/mol)	(-)	(J/mol)	(J/mol·K)			
17500	1.09e-4	50000	8.314			

5.6. Verification for the constitutive model

The determined constants in Table 2 were used to make the model predictions (solid curves) of true stress versus true strain shown in Fig.15. Subfigures (a) and (b) show the true stress-strain curves of B1500HS boron steel at different strain rates (temperature: 700 °C) and different temperatures (strain rate: 1 s⁻¹), respectively. Good agreements between computed and experimental results have been obtained for both groups of curves.

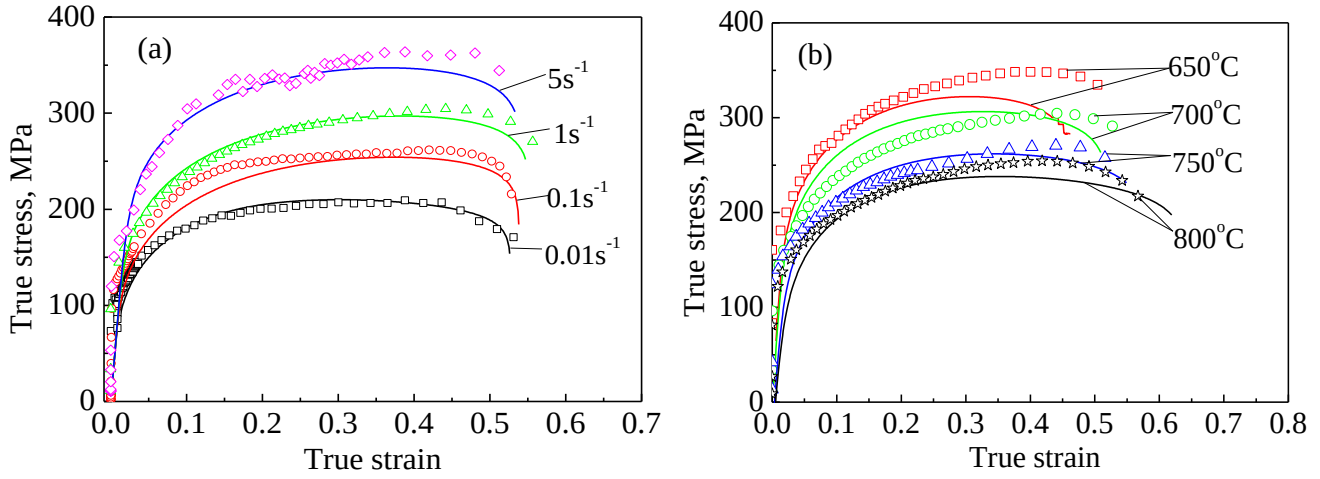


Fig.15 Comparison of experimental (symbols) and predicted (solid curves) true stress-strain curves at (a) different strain rates (temperature: 700 °C) and (b) different temperatures (strain rate: 1 s⁻¹).

To further explore the model calibration, the predicted true stress values for deformation temperature of 700 °C are plotted against the experimental ones in Fig. 16. As is evident, most of the data points lie close to the best regression line, and the correlation coefficient R_c for the predicted constitutive model is 0.969, which shows that a good correlation between the predicted and experimental data has been achieved. For further demonstrating the accuracy of the constitutive model, the absolute average relative error δ has been used as an unbiased statistical parameter to evaluate the deviation of the predicted values (Ismael et al, 2009). This error is expressed as:

$$\delta = \frac{1}{N} \sum_{i=1}^N \left| \frac{E_i - P_i}{E_i} \right| \quad (19)$$

where E_i is the experimental stress (MPa), P_i is the predicted stress (MPa) calculated using the obtained model and N is the number of data employed in this present investigation (this contains 212 data). The calculated value of average relative error δ was 3.73%, which indicates that the material model can give an accurate estimate of the hardening and fracture for B1500HS boron steel and can be used to numerically analyse the hot stamping process of this material.

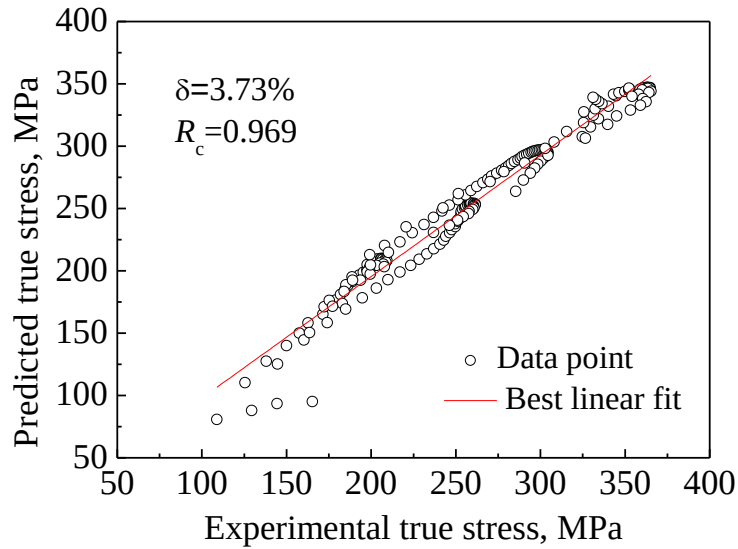


Fig.16 Correlation between the experimental and predicted true stress data at 700 °C.

From Fig. 16, some discrepancy can be observed. Possible sources for the errors may come from: (1) constitutive model: the employed model should be improved by further understanding of physical mechanism of boron steel in order to predict deformation behaviour in greater detail; (2) experimental data: the data has been generated at high temperatures, where inhomogeneity of deformation due to uneven temperature distribution of the specimen, is most likely to adversely affect results; (3) experimental facilities: the location of thermocouples and C-Gauge may have deviated from the centre line of some samples and have not been precisely in the highest temperature region.

6. Conclusions

(1) In elevated temperature tensile tests of B1500HS boron steel, flow stress was corrected by taking temperature rise due to deformation energy into consideration and strain at necking stage was corrected to minimize measurement errors. The maximum value of stress correction is 50 MPa and the maximum value of strain correction is 0.1. It is verified that experimental accuracy is improved by promoting data processing techniques.

(2) In the aspect of hardening for B1500HS boron steel: increasing strain rate, in the range $0.01-5 \text{ s}^{-1}$, leads to appreciable increase of the flow stress level and strain hardening gradient; increasing temperature, in the range $550-850 \text{ }^{\circ}\text{C}$, leads to a significant reduction of the flow stress level and strain hardening gradient.

(3) In the aspect of fracture for B1500HS boron steel: the measured strain to failure increases with increasing temperature for a particular strain rate 1 s^{-1} ; the strain rate sensitivity for ductility at studied temperatures $700 \text{ }^{\circ}\text{C}$ and $800 \text{ }^{\circ}\text{C}$ is low.

(4) Constitutive equations were formulated to predict the hardening and damage of B1500HS boron steel accurately. The results show that the constitutive equations give a precise estimation as the correlation coefficient is 0.969, and the absolute average relative error is 3.73 % in the range of allowable experimental conditions.

Acknowledgements

The authors thank IMRA Europe S.A.S.U.K. Research Centre for financial support.

References

- Adamczyk, J., Ozgowicz, W., Wusatowski, R., Kalinowska-Ozgowicz, E., Grzyb, R., 1997. Boron-treated microalloyed quenched and tempered plates, their structure and properties. *Journal of Materials Processing Technology*, 64, 1-8.
- Barcellona, A., Palmeri, D. 2009. Effect of plastic hot deformation on the hardness and continuous cooling transformations of 22MnB5 micro alloyed boron steel. *Metallurgical and Materials Transactions A*, 40, 1160-1174.
- Bariani, P., Bruschi, S., Ghiotti, A., 2012. Advances in predicting damage evolution and fracture occurrence in metal forming operations. *Journal of Manufacturing Processes*, 14, 495-500.
- Cai, J., 2011. Modelling of phase transformation in hot stamping of boron steel. Imperial College London.
- Cheong, B. H., Lin, J. and Ball, A. A., 2000. Modelling of the hardening characteristics for superplastic materials, *Journal of Strain Analysis*, 35, 149-157.
- George, R., Bardelcik, A., Worswick, M.J., 2012. Hot forming of boron steels using heated and cooled tooling for tailored properties. *Journal of Materials Processing Technology*, 212, 2386-2399.
- Ismael, A.M., Ahmed, H., Johannes, R., 2009. Investigation of the effect of strain rate and temperature on the deformability and microstructure evolution of AZ31 magnesium alloy. *Materials Science and Engineering: A*, 504, 40-48.
- Karbasian, H., Tekkaya, A. E., 2010. A review on hot stamping. *Journal of Materials Processing Technology*, 210, 2103-2118.
- Li, B., Lin, J., Yao, X., 2002. A novel evolutionary algorithm for determining unified creep damage constitutive equations. *International Journal of Mechanical Sciences*, 44, 987-1002.
- Li, L., Lou, Y., Yang, L., Peng, D., Rao, K., 2002. Flow stress behaviour and deformation characteristics of Ti-3Al-5V-5Mo compressed at elevated temperatures. *Materials & Design*, 23, 451-457.
- Li, N., Mohamed, M. S., Cai, J., Lin, J., Balint, D., Dean, T. A., 2011. Experimental and numerical studies on the formability of materials in hot stamping and cold die quenching processes. *AIP Conference Proceedings*, 1353, 1555-1561.
- Lin, J., 2003. Selection of material models for predicting necking in superplastic forming. *International Journal of Plasticity*, 19, 469-481.

- Lin, J., Cheong, B., Yao, X., 2002. Universal multi-objective function for optimising superplastic-damage constitutive equations. *Journal of Materials Processing Technology*, 125, 199-205.
- Lin, J. and Dean, T.A., 2005. Modelling of microstructure evolution in hot forming using unified constitutive equations. *Journal of Materials Processing Technology*, 167, 354-362.
- Lin, J. and Dunne, F. P. E., 2001. Modelling grain growth evolution and necking in superplastic blow-forming. *International Journal of Mechanical Sciences*, 43, 595-609.
- Lin, J., Liu, Y., Farrugia, D. C. J., Zhou, M., 2005. Development of dislocation-based unified material model for simulating microstructure evolution in multipass hot rolling. *Philosophical Magazine* 85, 1967-1987.
- Luan, J., Sun, C., Li, X., Zhang, Q., 2014. Constitutive model for AZ31 magnesium alloy based on isothermal compression test. *Materials Science and Technology*, 30, 211-219.
- Luo, Z.J., Yang, Q., Ji, W.H., 2000. New method to establish constitutive relationship considering effect of deformation heating. *Chinese Journal of Nonferrous Metals*, 10, 804-808.
- Merklein, M., Lechler, J., 2006. Investigation of the thermo-mechanical properties of hot stamping steels. *Journal of Materials Processing Technology*, 177, 452-455.
- Xing, Z.W., Bao, J., Yang, Y.Y., 2009. Numerical simulation of hot stamping of quenchable boron steel. *Materials Science and Engineering A*, 499, 28-31.
- Mohamed, M. S., Foster, A. D., Lin, J., Balint, D. S., Dean, T. A., 2012. Investigation of deformation and failure features in hot stamping of AA6082: Experimentation and modelling. *International Journal of Machine Tools & Manufacture*, 53, 27-38.
- Nes, E., 1997. Modelling of work hardening and stress saturation in FCC metals. *Progress in Materials Science*, 41, 129-193.
- Nicolaou, P. D., Semiatin, S. L., Ghosh, A. K., 2000. An analysis of the effect of cavity nucleation rate and cavity coalescence on the tensile behaviour of superplastic materials. *Metallurgical and Materials Transactions A*, 31, 1425-1434.
- Odqvist, F., Hult, J., 1961. Some aspects of creep rupture. *Arkiv for fysik*, 19, 379-382.
- Zhou, J., Wang, B., Xu, W., Huang, M., Yi, S., Jiao, W., 2013. Damage-coupled constitutive model of 22MnB5 steel in hot deformation. *Journal of University of Science and Technology Beijing*, 35, 1450-1457.

Figure Captions

Fig.1 Specimen design (dimensions are in mm) with schematic dilatometer and a pair of K-type thermocouples attached.

Fig.2 Temperature profile for the experimentation.

Fig.3 Strain correction method at necking stage.

Fig.4 An example true stress-strain curve, at the temperature of 700 °C and strain rate of 1 s⁻¹, before and after correction (red points show failure; blue point shows criticality for necking).

Fig.5 Temperature rise (ΔT) during hot deformation of boron steel, at different strain rates (0.01-5 s⁻¹), at the pre-set temperature of (a) 700 °C and (b) 800 °C.

Fig.6 Comparison of flow stress before (solid curves) and after (symbols) correction at the strain rate of (a) 1 s⁻¹ (temperature range: 550-850 °C) and (b) 5 s⁻¹ (temperature: 700 °C and 850 °C).

Fig.7 Strain to failure at different temperatures at a strain rate of 1 s⁻¹.

Fig.8 Strain to failure at different strain rates at the temperature of (a) 700 °C and (b) 800 °C.

Fig.9 (a) Curves of true stress-strain and strain hardening gradient (for temperature: 850 °C, strain rate: 1 s⁻¹); (b) Comparison of strain hardening gradient at different temperatures, at a strain rate of 1 s⁻¹.

Fig.10 The maximum true stresses for different temperatures at a strain rate of 1 s⁻¹.

Fig.11 The maximum true stresses for different strain rates at a temperature of 700 °C.

Fig.12 Comparison of strain hardening gradient at different strain rates at a temperature of 700 °C.

Fig 13. Variation of stress at a strain level of 0.2 with different strain rates (0.01-5 s⁻¹) for the material deformed at the temperature of 700 °C and 800 °C.

Fig.14 Schematic illustration of damage mechanism under hot metal forming condition (Lin et al. 2005).

Fig.15 Comparison of experimental (symbols) and predicted (solid curves) true stress-strain curves at (a) different strain rates (temperature: 700 °C) and (b) different temperatures (strain rate: 1 s⁻¹).

Fig.16 Correlation between the experimental and predicted true stress data at 700 °C.

Table Captions

Table1. Chemical composition of B1500HS boron steel (wt. %).

Table 2 Determined material constants of boron steel for viscoplastic damage constitutive model

Figures

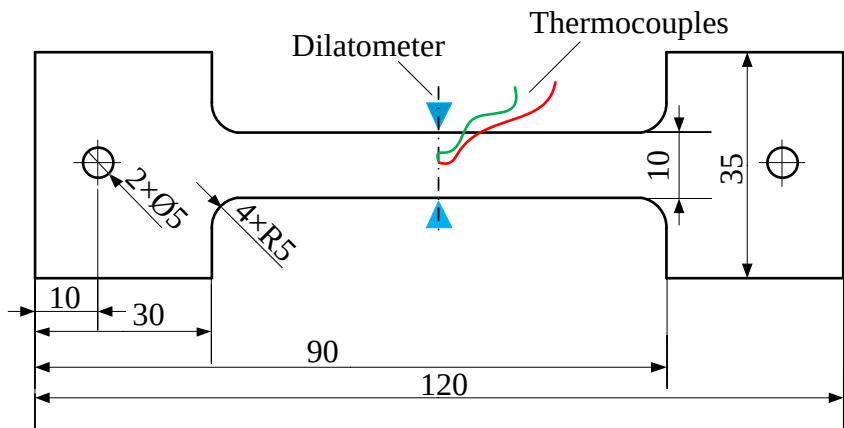


Fig.1 Specimen design (dimensions are in mm) with schematic dilatometer and a pair of K-type thermocouples attached.

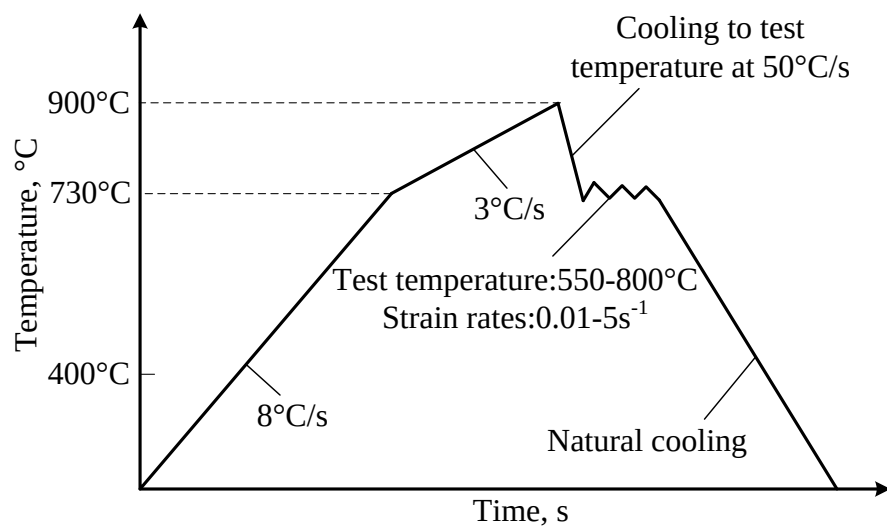


Fig.2 Temperature profile for the experimentation.

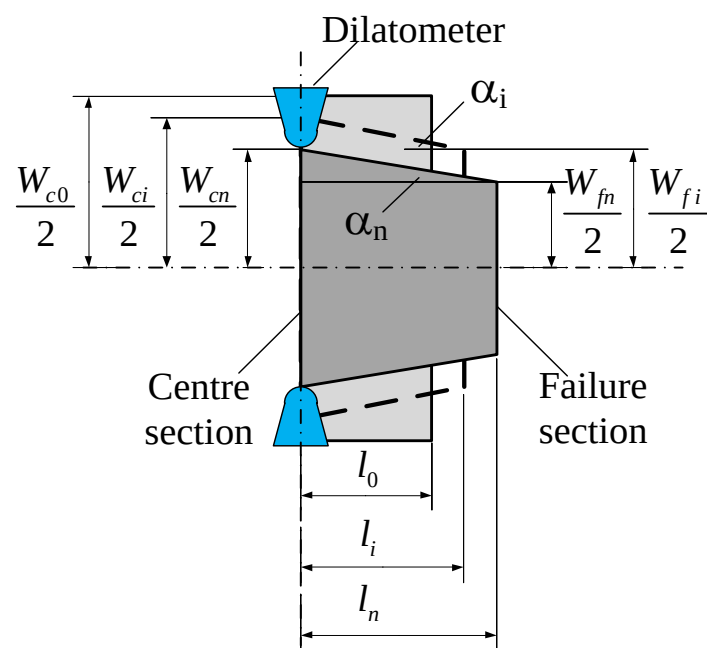


Fig.3 Strain correction method at necking stage.

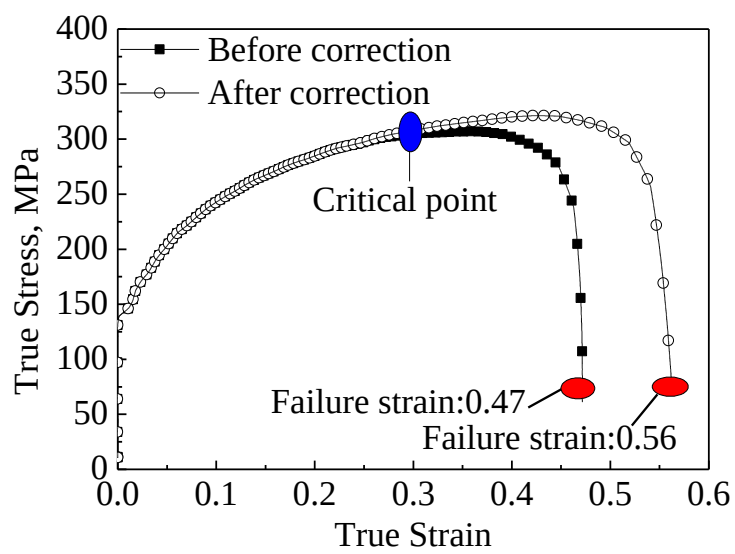


Fig.4 An example true stress-strain curve, at the temperature of 700 °C and strain rate of 1 s^{-1} , before and after correction (red points show failure; blue point shows criticality for necking).

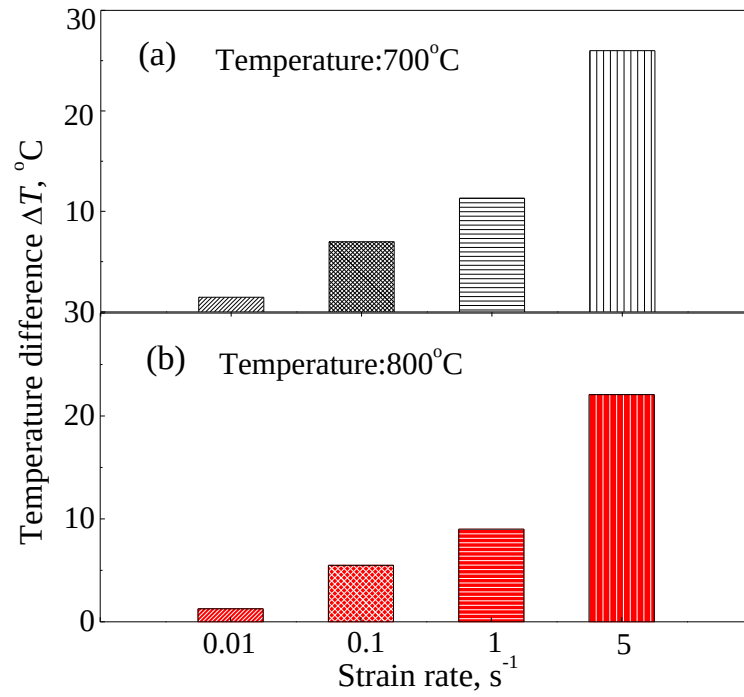


Fig.5 Temperature rise (ΔT) during hot deformation of boron steel, at different strain rates ($0.01\text{-}5\text{ s}^{-1}$), at the pre-set temperature of (a) 700°C and (b) 800°C .

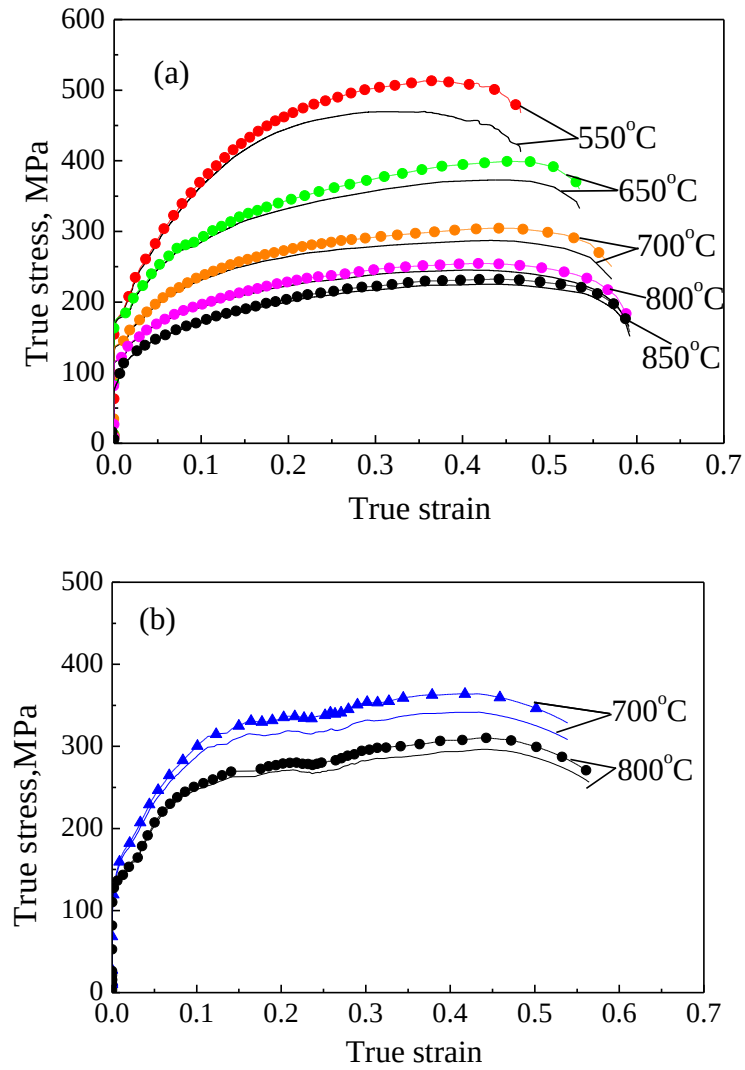


Fig.6 Comparison of flow stress before (solid curves) and after (symbols) correction at the strain rate of (a) 1 s^{-1} (temperature range: 550-850 °C) and (b) 5 s^{-1} (temperature: 700 °C and 850 °C).

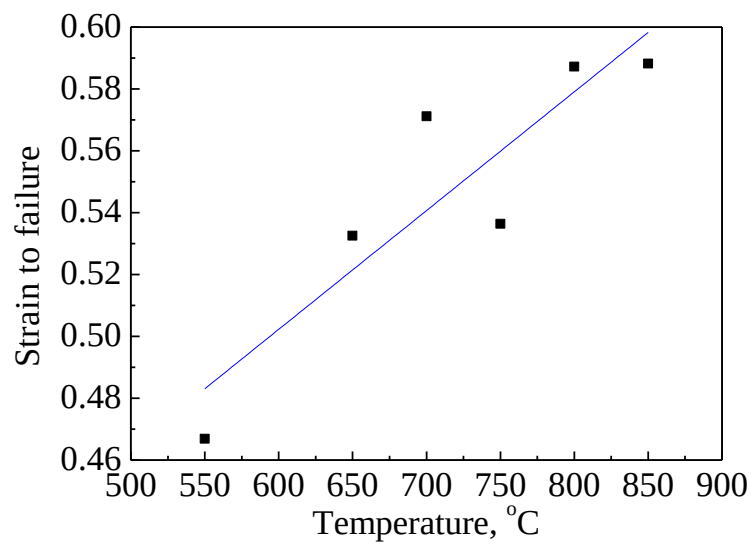


Fig.7 Strain to failure at different temperatures at a strain rate of 1 s^{-1} .

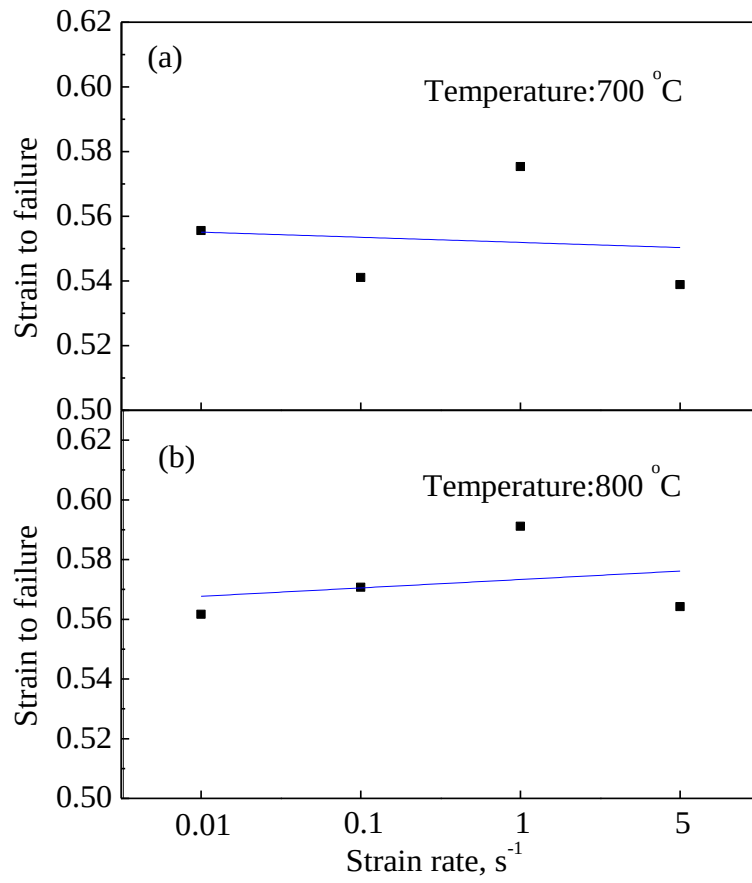


Fig.8 Strain to failure at different strain rates at the temperature of (a) 700 °C and (b) 800 °C.

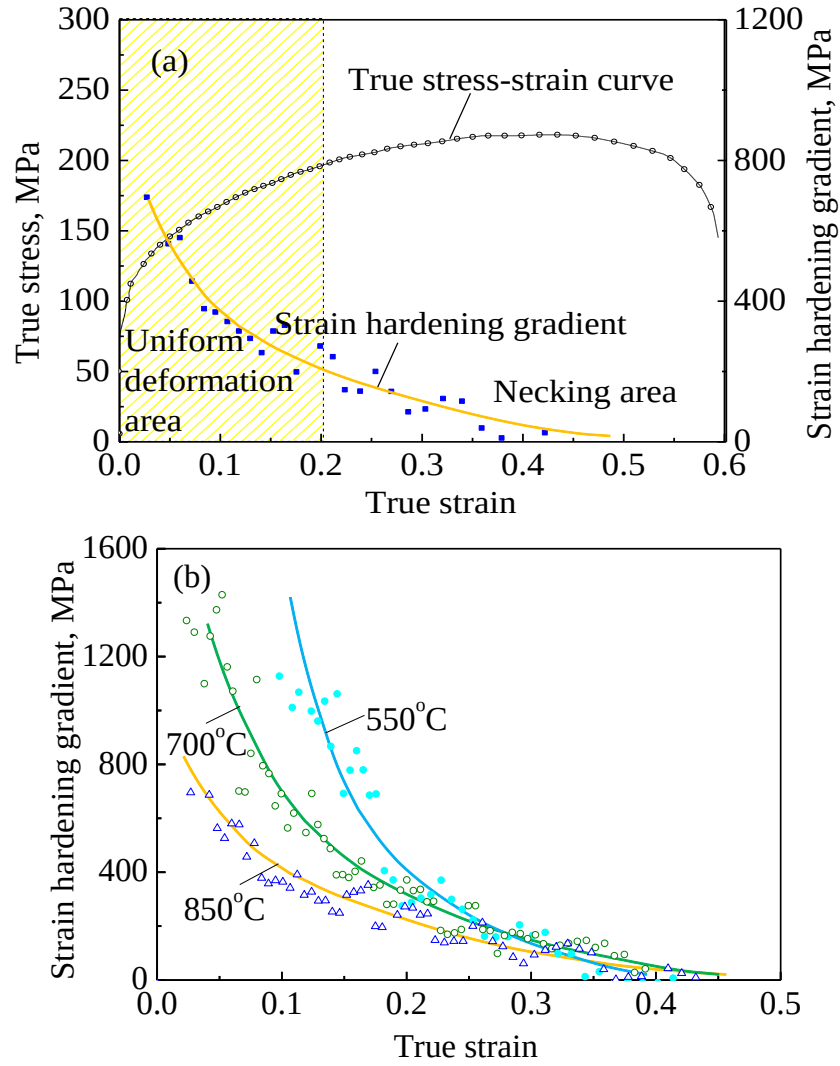


Fig.9 (a) Curves of true stress-strain and strain hardening gradient (for temperature: 850 °C, strain rate: 1 s⁻¹);
 (b) Comparison of strain hardening gradient at different temperatures, at a strain rate of 1 s⁻¹.

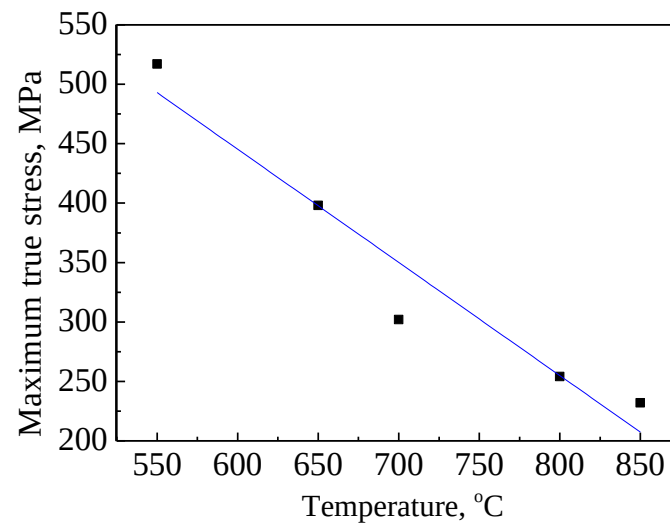


Fig.10 The maximum true stresses for different temperatures at a strain rate of 1 s^{-1} .

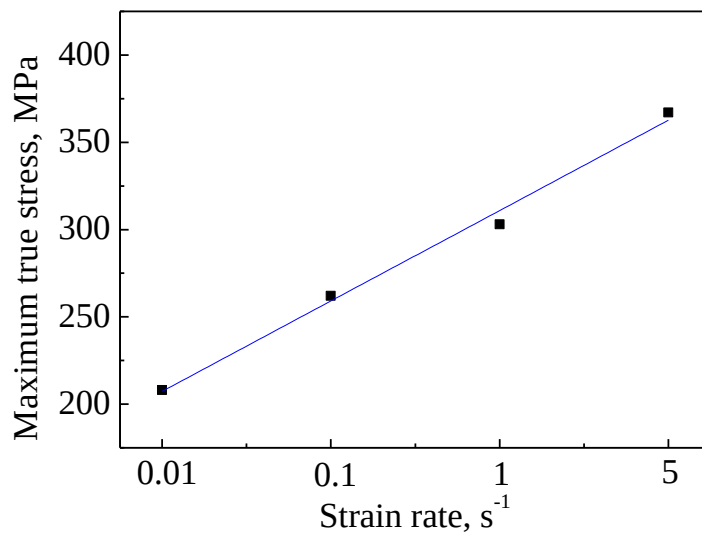


Fig.11 The maximum true stresses for different strain rates at a temperature of 700 °C.

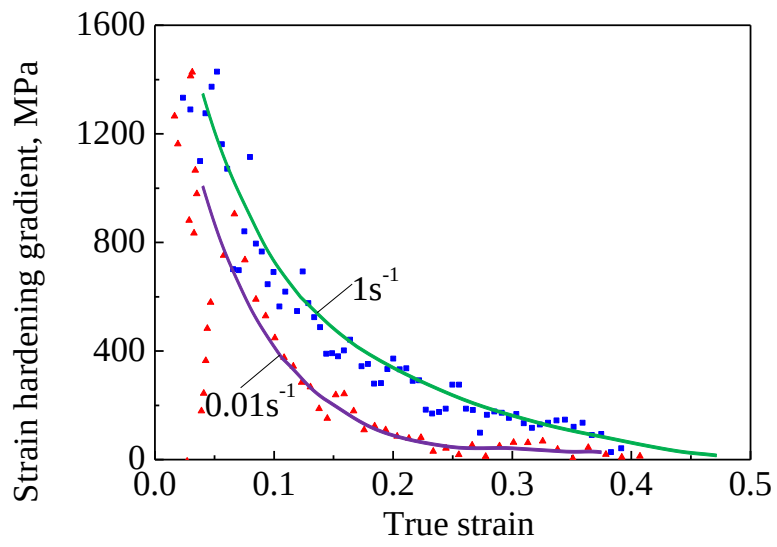


Fig.12 Comparison of strain hardening gradient at different strain rates at a temperature of 700 °C.

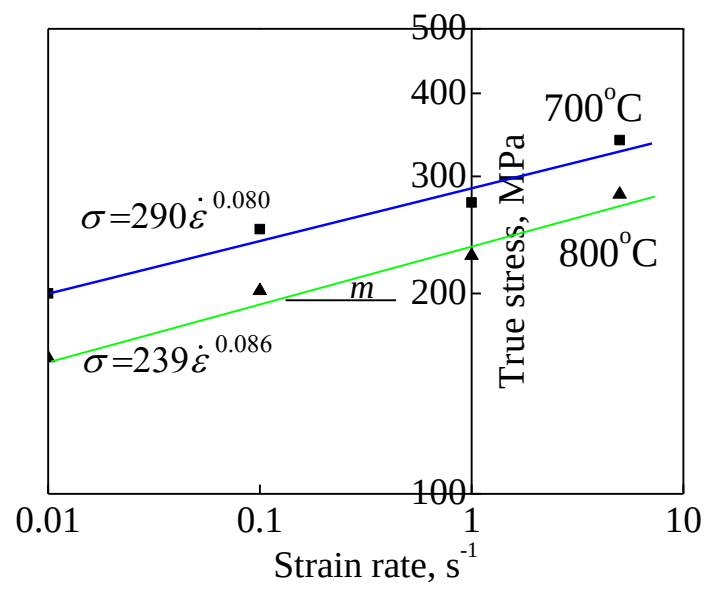


Fig 13. Variation of stress at a strain level of 0.2 with different strain rates (0.01-5 s⁻¹) for the material deformed at the temperature of 700 °C and 800 °C.

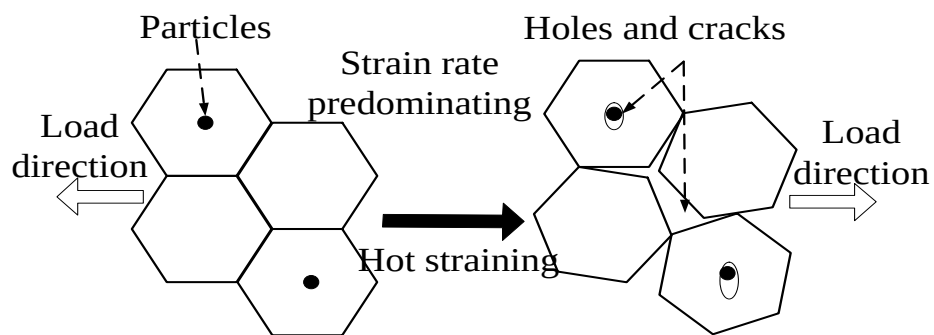


Fig.14 Schematic illustration of damage mechanism under hot metal forming condition (Lin et al. 2005).

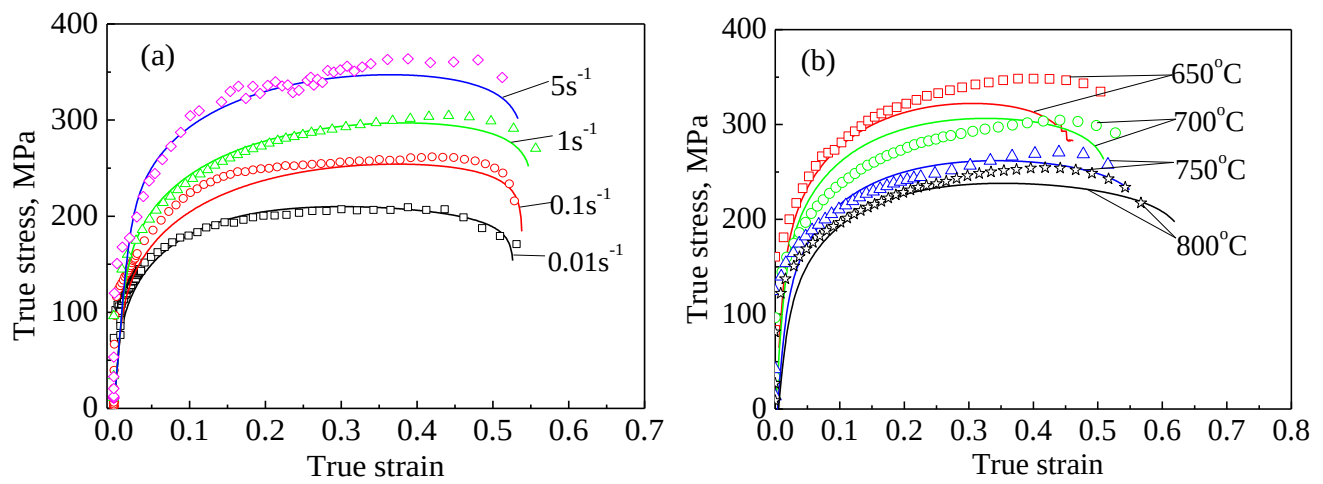


Fig.15 Comparison of experimental (symbols) and predicted (solid curves) true stress-strain curves at (a) different strain rates (temperature: 700 °C) and (b) different temperatures (strain rate: 1 s⁻¹).

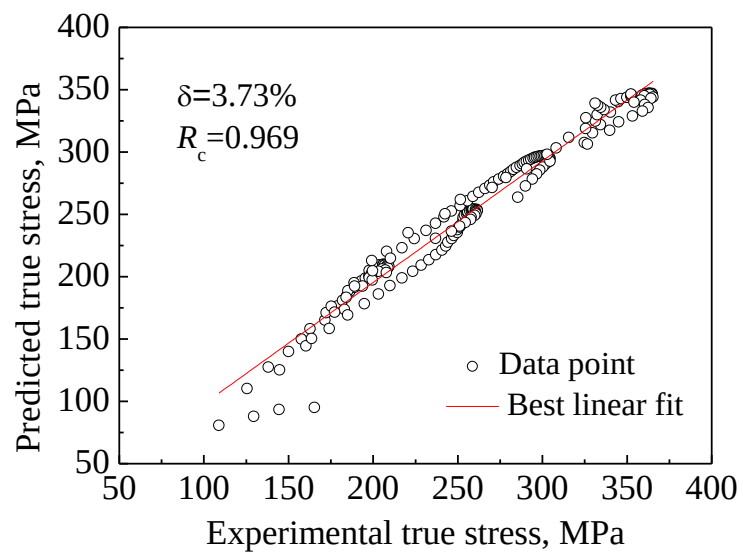


Fig.16 Correlation between the experimental and predicted true stress data at 700 °C.

Tables

Table1. Chemical composition of B1500HS boron steel (wt. %).

C	Si	Mn	P	S	Cu	Cr	Ni	Al	Ti	B
0.20	0.19	1.24	0.016	0.0027	0.02	0.19	0.02	0.044	0.021	

Table 2 Determined material constants of boron steel for viscoplastic damage constitutive model

Q	Q_C	Q_D	k_0	B_0	C_0	K_0
(J/mol)	(J/mol)	(J/mol)	(MPa)	(MPa)	(-)	(MPa)
8400	99900	10650	12.4	80	13000	30
n_0	γ_1	A	γ_2	γ_3	d_2	E_0
(-)	(-)	(-)	(-)	(-)	(-)	(MPa)
0.0068	0.1	3.666	1.54	16.3	0.9178	1100
Q_E	β_0	Q_n	R			
(J/mol)	(-)	(J/mol)	(J/mol·K)			
17500	1.09e-4	50000	8.314			