A type of cruciform specimen applied to evaluate forming limits for boron steel under hot stamping conditions

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A type of cruciform specimen applied to evaluate forming limits for boron steel under hot stamping conditions

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Abstract. The ultra-high strength boron steel has been intensively used in the hot stamping process to produce complex-shaped structural components in transportation industries. Forming limit diagram (FLD) is a fundamental and useful tool to evaluate the formability of metallic materials under various forming conditions. Since the standardized Nakajima test and Marciniak test are not applicable to perform formability tests for hot stamping applications due to the complex heating and cooling processes required, an in-plane testing method, in which cruciform specimens are deformed under hot stamping conditions in a Gleeble materials simulator combined with a multi-axial tensile rig to convert an input force to an output biaxial force, has been successfully applied to assess the formability of aluminium alloys at elevated temperatures. However, it is challenging to apply this in-plane testing method for boron steel due to higher nonuniformity of temperature distribution in gauge region of the cruciform specimen at a higher temperature. In this paper, a new type of cruciform specimen, together with a new specimen heating strategy, has been proposed to improve the temperature distribution in the gauge region. The dimensions of the newly-designed cruciform specimen have been optimised by a thermo-electrical finite element model embedded with a UAMP subroutine in ABAQUS to improve the uniformity of temperature distribution in the gauge region. In order to validate the new design of cruciform specimen, biaxial tensile tests were conducted under hot stamping conditions by using the in-plane testing method.

1. Introduction

Boron steel has been widely used for hot stamping applications to manufacture complex-shaped components with ultra-high strength. Forming limit diagram (FLD), which represents the limit strains for a material deformed under the different strain states from uniaxial tension over plane-strain tension to biaxial tension, is one of the most significant tools to evaluate the formability of a material. An FLD can be usually determined by the standardised Nakajima/Marciniak test at room temperature [1]. Both testing methods have been applied to determine FLDs at high temperatures [2-4]; however, it is difficult to realize the complex temperature profile for testing under hot stamping conditions. Testing by using a multi-axial testing machine and a cruciform specimen is an alternative method to determine FLDs for sheet materials [5, 6]. Given that the advantages, such as linear strain paths and the elimination of friction effect, it has been applied for the formability determination for materials at room temperature [7-10].

To determine the forming limits of sheet metals under hot stamping conditions, a novel in-plane multi-axial apparatus, which can covert an input uniaxial force into an output multi-axial force, was designed and patented to be used on a Gleeble 3800 [11]. This method is the first method available to realize the control of complex heating and cooling history, and it has been successfully applied to

determine forming limits of aluminium alloy 6082 under hot stamping conditions [12]. However, due to the applied direct resistance heating method in Gleeble and the geometry of the designed cruciform specimen of aluminium alloy 6082, the temperature distribution in the gauge region of the cruciform specimen was not absolutely uniform, which leads to the non-uniform strain field in the gauge region during deformation process [13]. The forming temperature for boron steel is much higher than that of AA6082 for hot stamping applications [14, 15], which would aggravate the non-uniformity of temperature distribution and deformation.

In order to improve the temperature distribution within gauge region for formability tests, a new type of cruciform specimen, based on a new specimen heating strategy, has been proposed in this paper. A thermo-electrical finite element (FE) model with a UAMP subroutine in ABAQUS was used to simulate temperature distribution for various geometries. The geometry and dimensions of the newly-designed cruciform specimen have been optimised based on the objective of minimum temperature gradient. The temperature distribution and strain field in the gauge region were measured to validate the new design of cruciform specimen by performing biaxial tensile test under hot stamping conditions.

2. Difficulties to determine forming limits for boron steel

Figure 1 shows the designated temperature profile for boron steel applied to testing to simulate the hot stamping process. The material was heated to an austenitization temperature of 925 °C at a heating rate of 10 °C/s and a following lower heating rate of 5 °C/s to avoid temperature overshooting. After soaking for 60 s to complete austenite transformation, the material was quenched at a quenching rate of 60 °C/s to a specified forming temperature for formability testing. One difficulty to determine forming limits for boron steel under hot stamping conditions is to measure strain fields in boron steel specimens using the digital image correlation (DIC) technique, which has been systemically discussed in [16]. In this paper, the difficulty to obtain homogeneous temperature in gauge region, has been discussed and overcome for evaluating forming limits for boron steel under hot stamping conditions.
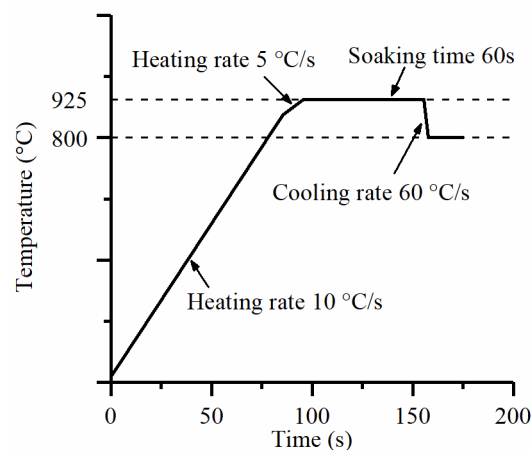

Figure 1. temperature profile for boron steel applied for the hot stamping process.

3. Cruciform specimen design

3.1. Cruciform specimen geometries

The temperature distribution and evolution in a cruciform specimen, during the direct resistance heating in a Gleeble, are able to be simulated precisely by thermo-electrical FE model with a UAMP subroutine in ABAQUS [11]. Under the hot stamping conditions as shown in Figure 1, two different types of cruciform specimen name as Geometry A and Geometry B are presented in Figure 2 (a) and (b) to investigate temperature distribution, respectively. The thickness of the specimens is 1.5 mm. A central circular gauge region with a diameter of 11 mm and thickness of 0.5 mm was made in the specimens to be beneficial to the onset of necking or fracture in this region. Table 1 shows the physical properties of

boron steel. One boundary condition is to control the temperature profile of the centre point in the gauge region of each cruciform specimen to be consistent with Figure 1. The heating strategy with two positive and negative electrodes suggested in [11] was adopted and marked in Figure 2 (a) and (b). Other boundary conditions in the FE model, such as film coefficient and sink temperature, were determined by ensuring the consistency of experimental and simulated temperatures in the cruciform specimen with geometry A. The simulated temperature distributions in the intersection regions of the cruciform specimen Geometry A and Geometry B at the time of 170 s are shown in Figure 2 (c) and (d), respectively. The areas with the temperature of over 800 °C and less than 700 °C have been greyed out. It can be seen that the orthogonal corners of the opposite electrodes are with the highest temperature and the maximum temperature gradient to the centre point in the gauge region is about 100 °C. The current flow route in the adopted heating strategy resulted in this non-uniform temperature distribution.

Table 1. Physical properties of the boron steel.

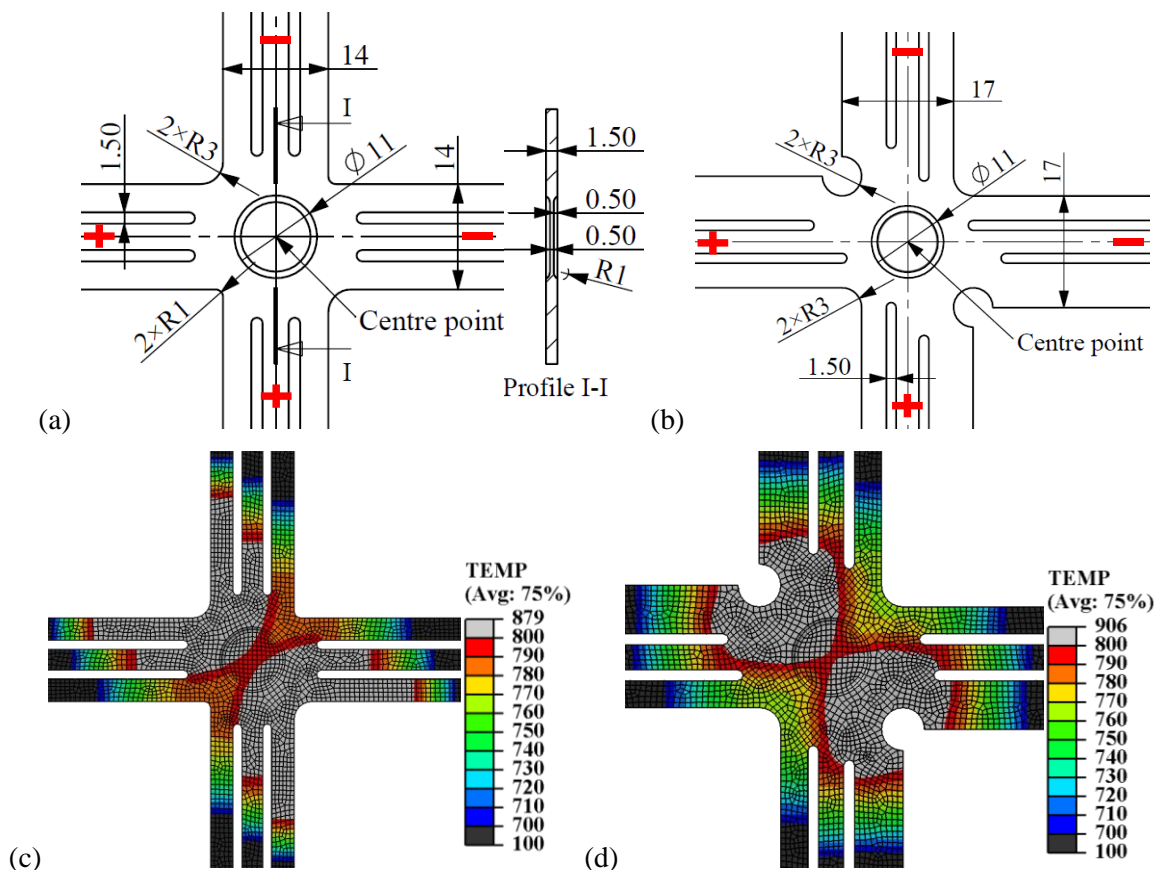| Element	Density /(Kg/m^3)	Young's modulus /(MPa)	Poisson's ratio	Electrical conductivity /(S/m)	Thermal conductivity /(W/m•K)	Specific heat capacity /(J/(Kg•K))
Value	7830	1.00E+005	0.3	6.29E+006	32	712

Figure 2. (a) and (b) are cruciform specimens named as Geometry A and Geometry B, respectively, (c) and (d) show simulated temperature distributions in the interaction regions for Geometry A and Geometry B, respectively.

In order to reduce temperature gradient in the intersection region, a new type of cruciform specimen named as Geometry C is proposed under a new heating strategy, in which two opposite wider arms of Geometry C are attached to the positive and negative electrodes, respectively, as shown in Figure 3 (a).

Both the thickness and central circular gauge region of the Geometry C remain the same as those of the Geometry A and Geometry B. The dimensions of W1 and W2 are equal to 20 mm. The simulated temperature distribution in Geometry C, at the time of 170 s, is shown in Figure 3 (b). It can be seen that although there are grey areas with the temperature of higher than 800 °C, the maximum temperature gradient from those areas to the centre point in the gauge region is only 6 °C. This indicates that the temperature distribution in the intersection region can be improved by using this type of cruciform specimen and the heating strategy.
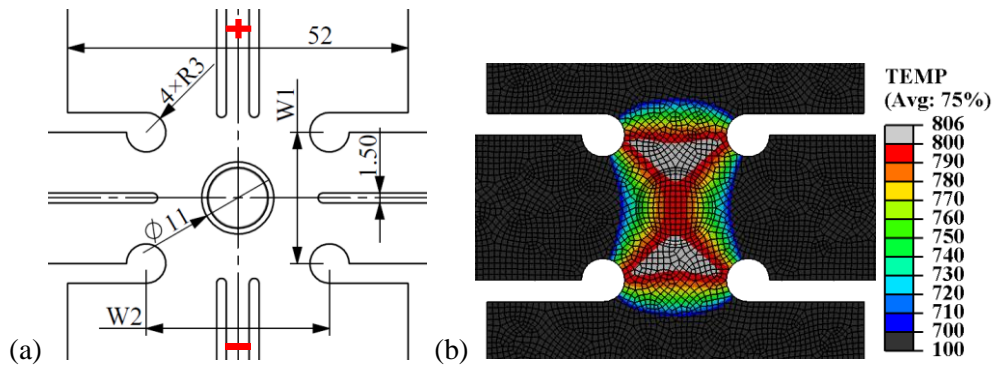

Figure 3. (a) Newly-designed cruciform specimen named as Geometry C, (b) simulated temperature distribution in interaction region for Geometry C.

3.2. Dimension optimisation for Geometry C

The dimensions of Geometry C need to be further optimised since there exists a temperature gradient of higher than 60 °C in the gauge region. To ensure comparable results, the temperature distribution in Geometry C with different dimensions of W2 (i.e. 24 mm, 28mm and 32 mm) when W1 remains at 20 mm were simulated.
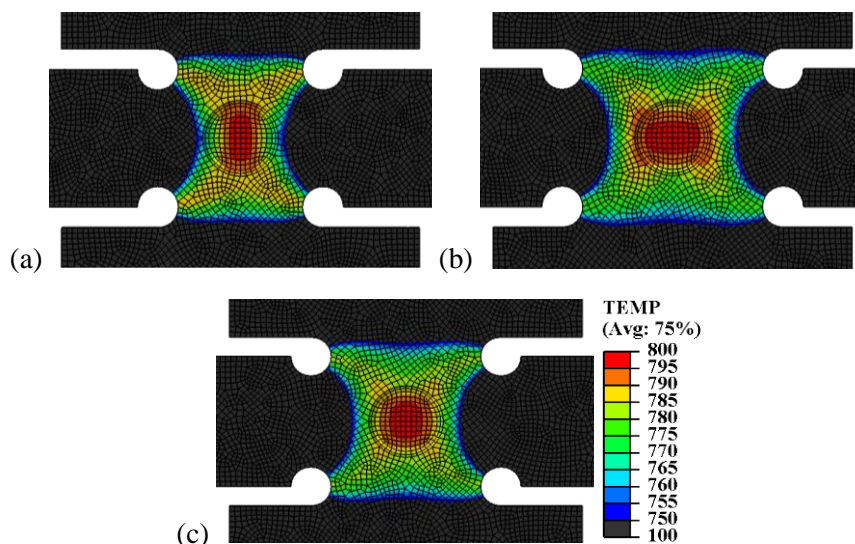

Figure 4. Simulated temperature distribution in gauge region in Geometry C with different dimensions: (a) W1=20 mm, W2=24 mm, (b) W1=20 mm, W2=32 mm and (c) W1=20 mm, W2=28 mm.

Figure 4 shows the simulated results at the time of 170 s and they indicate that the temperature distribution in the cruciform specimen is highly dependent on the ratio of the dimensions of W1 and W2. For Geometry C with W2 of 24 mm, as shown in Figure 4 (a), the centre point is with the highest temperature of 800 °C and the maximum temperature gradient in gauge region is reduced to 40 °C. For

Geometry C with W2 of 32 mm and 28 mm, respectively, in Figure 4 (b) and (c), although the maximum temperature gradients in the gauge region are almost equal to 20 °C, the temperature distribution in Figure 4 (c)is the most uniform in consideration of different directions in the gauge region.

4. Experimental results and discussion

4.1. Temperature distribution in gauge region

The design of cruciform specimen with Geometry C and the strategy of heating specimen were verified by performing biaxial tensile tests for boron steel under hot stamping conditions in Gleeble 3800 and the in-plane multi-axial rig to convert an input uniaxial force into an output biaxial force. Figure 5 shows the experimental set-up for biaxial tensile tests. In order to heat cruciform specimen using the direct resistance heating system in the Gleeble, two opposite wider arms were attached to the electrode and negative electrodes respectively. One pair of thermocouples were welded at the centre in the gauge region to monitor and control temperature. The DIC technique was used to measure strain fields in the gauge region of boron steel specimens. The biaxial tensile tests were conducted at a temperature of 850 °C and a strain rate of 0.02 /s, and three tests were repeated at the same conditions to control experimental error.
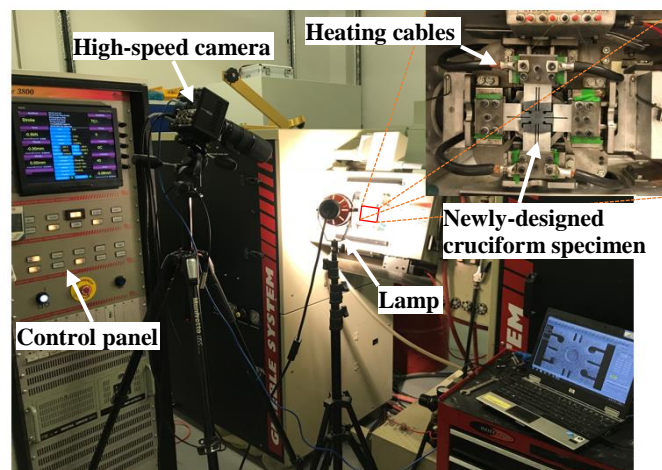

Figure 5. Experimental setup for formability tests under hot stamping conditions.

During the heating and cooling processes under hot stamping conditions, the temperature distribution in the gauge region was measured. Due to the limited space in the gauge region, four different locations around the gauge region, marked as T1, T2, T3 and T4, were selected for temperature measurement, as shown in Figure 6 (a). Figure 6 (b) shows the measured temperature profile at the locations of T1 and T2, compared with that at the centre in the gauge region. It can be seen that, during the heating and cooling processes, the values of temperature at the locations of T1 and T2 are very close to that at the centre within the gauge region.
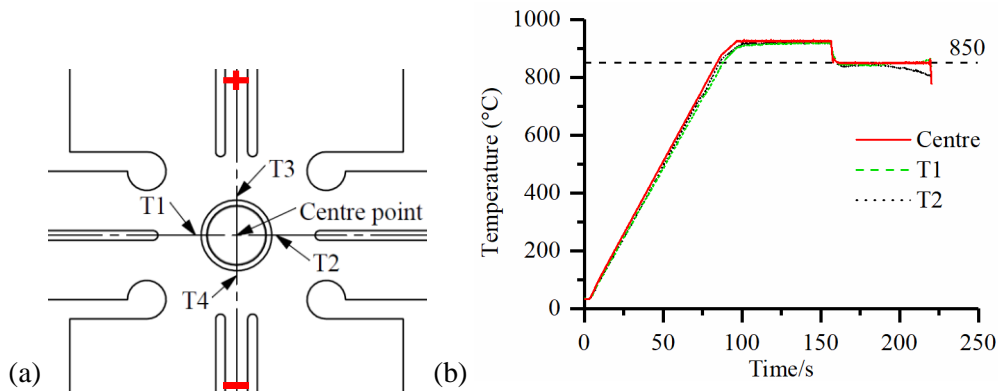
Figure 6. (a) Four different locations for temperature measurement by thermocouples, (b) experimentally measured temperature profile at different locations during the heating and cooling processes.

In order to quantify the temperature gradient in the gauge region, the temperature during the time of 160-175 s was averaged at the different locations, and the results are shown in Table 2. It can be seen that the centre point in gauge region has the highest temperature of 850 °C and the maximum temperature gradient to the surrounded locations is less than 2.5%, which indicates that a uniform temperature distribution in the gauge region can be obtained using the new type of cruciform specimen combined with the strategy of specimen heating in the Gleeble.

Table 2. Experimental temperature distribution in/around the gauge region.

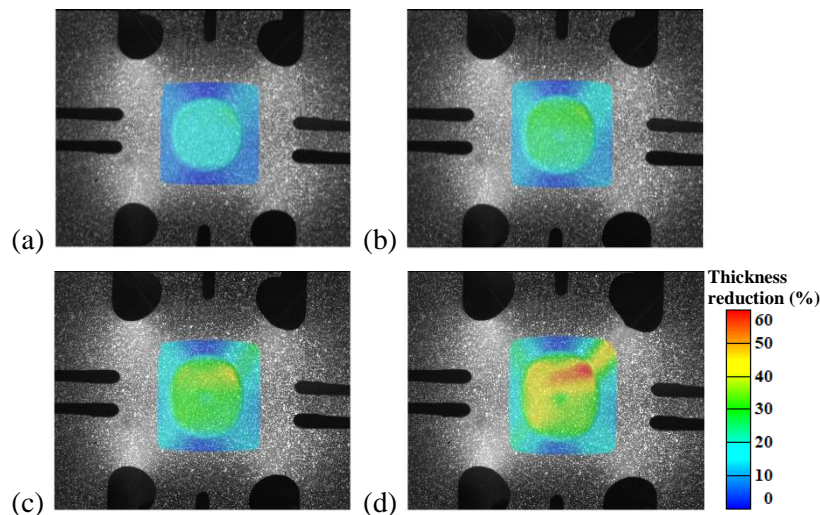| Location	Centre	T1	T2	T3	T4
Averaged temperature (°C)	850.0	830.0	832.9	840.5	845.1

4.2. Strain fields in gauge region

Figure 7. Evolution of the strian field in the gauge region for the newly-designed cruciform specimen in equi-biaxial tensile test at the temperature of 850 °C and the strain rate of 0.02/s, corresponding to (a) 80%, (b) 90%, (c) 95% and (d) 100% of failure.

After the heating and cooling processes under hot stamping conditions, the biaxial tensile tests were conducted at a temperature of 850 °C and a strain rate of 0.02 /s, and the strain fields in boron steel specimens were measured using the DIC technique. Figure 7 shows the strain fields in one deformed

specimen at different stages of deformation, in which Figure 7 (d) represents the stage of the deformed specimen at the final stage before failure and Figure 7 (a), (b) and (c) represent stages at 80 %, 90 % and 95 % of failure, respectively. As can be seen in Figure 7 (a) and (b), a uniform strain field was obtained in the gauge region thanks to the improved temperature distribution. With the increase of deformation, the strain field became localized within the gauge region until the occurrence of fracture, as shown in Figure 7 (c) and (d).

5. Conclusions

A type of cruciform specimen was proposed in this study for the evaluation of forming limits for boron steel tested under hot stamping conditions in a Gleeble equipped with a designed multi-axial tensile rig for biaxial testing. Using the direct resistance heating system in the Gleeble, two opposite wider arms attached to positive and negative electrodes, respectively, were used for heating specimens. Based on numerical optimisation and experimental results, it can be concluded that temperature distribution in the gauge region can be improved to be more uniform by using the new type of cruciform specimen and this heating strategy. It is beneficial for the evaluation of forming limits for boron steel. Formability tests will be performed, for the first time, under hot stamping conditions by using the cruciform specimen to determine forming limit diagrams for boron steel at various conditions.

Acknowledgement

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