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The optimisation of cruciform specimen for the formability evaluation of AA6082 under hot stamping conditions

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Abstract

The hot stamping and cold die quenching process is increasingly adopted to form complex-shaped structures of sheet metals in the automotive industry. However, it is difficult to obtain formability data of sheet metals under hot stamping conditions by using conventional experimental testing methods. In this study, a novel in-plane biaxial testing system, which is attached to a Gleeble materials thermo-mechanical simulator, had been developed for determining forming limit diagrams (FLDs) under hot stamping conditions. However, there is no standard of cruciform specimen geometries available for this type of biaxial tests. In this paper, the features of thickness reduction in the central region and slots in the arms of a type of cruciform specimen of aluminium alloy 6082 were verified first to increase strain uniformity of the biaxial loading zone on a cruciform specimen, based on the selective heating and cooling method. Finite Element (FE) thermo-electrical and thermo-mechanical models with UAMP and VUMAT subroutines were then implemented in ABAQUS 6.12 to optimise specimen dimensions so that fracture occurs in the concerned central region of the specimen during testing. By the use of the optimised specimen for AA6082 in the biaxial testing system, formability tests under the designated strain paths were conducted at specified hot stamping conditions. Strain fields in the gauge region of the cruciform specimens were measured using the digital image correlation (DIC) system and the experimental results were presented and analysed in order to verify the cruciform specimen design.

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1. Introduction

Weight reduction can improve the performance of automobiles and reduce energy consumption directly. Since high strength light alloys have low formability at room temperature, the hot stamping and cold die quenching process [1] is increasingly adopted to form complex-shaped structural panel components in the automotive industry. In a typical hot stamping process, metal sheet is heated to a target temperature for heat treatment, transferred to a press tool, and then stamped and quenched within water-cooled dies under pressure [2]. Stamping conditions, including heating rate, quenching rate, deformation temperature and forming rate, are essential for the success of a process.

Forming limit diagram (FLD) is a conventional tool to characterise the formability of materials under different straining conditions. FLDs for sheet metals are usually determined by the Nakazima test [3] or the Marciniak test [4]. However, both of the conventional methods are not applicable to measure forming limits of alloys under hot stamping conditions because heating rate, cooling rate and deformation rate are very difficult to control precisely. Using universal biaxial testing machine with cruciform specimens is an acceptable method to conduct formability tests [5], but it has not been used for testing at hot stamping conditions.

A Gleeble materials simulator is commonly used for characterising thermo-mechanical behaviour of materials thanks to its capability of accurately controlling heating, cooling and straining rates [6]. However, it cannot be used for biaxial tensile tests. A novel in-plane biaxial testing system with a biaxial mechanism had been designed based on application on Gleeble 3800 [7] for generating FLDs under hot stamping conditions. It was found that choosing two adjacent arms of a cruciform specimen as positive electrodes for resistance heating provides an acceptable uniform temperature field in the gauge zone of the specimen, and using air to envelop the gauge region of the specimen for cooling enables a high quenching rate to be realised prior to deformation at elevated temperature [8].

Although various cruciform samples were proposed and designed for different purposes of biaxial tensile tests [9], they are mainly used for testing at room temperature and no geometry has been standardised. In order to develop a cruciform specimen for formability testing at hot stamping conditions, the uniformity of temperature distribution in the gauge region of the specimen and the location of failure occurrence during testing are needed to be considered as key factors to enable formability data to be measured accurately. Aluminium alloy 6082, which is extensively used in the automotive industry, was adopted to conduct the investigation. The features of cruciform specimens will be validated and the dimensions of cruciform geometries will be optimised using for the formability test under hot stamping conditions.

2. Principles of cruciform specimen design

The objectives of this cruciform specimen geometry optimisation exercise for robust biaxial testing under hot stamping conditions are: 1) Maximisation of strain and stress uniformity in the biaxial loading zone. 2) Minimisation of the global shear strains in the biaxial loading zone. 3) Minimisation of the strain and stress concentration outside the biaxial loading zone. 4) Maximisation of uniformity of temperature distribution in the biaxial loading zone. 5) Maximisation of linearity of strain path. 6) Failure occurs in the biaxial loading zone. 7) Repeatable results. However, it is extremely difficult to develop cruciform specimens that can fulfil all requirements simultaneously.

The first step of the optimisation procedure was to validate main features of a cruciform specimen experimentally using resistant heating and air cooling. The second step contained parameter adjustments based on the results of thermal analysis, which have been obtained and presented in [8]. The final step was to study failure locations, the uniformity of strain distribution and strain path control.

3. Features of cruciform specimen

3.1. The effects of thickness reduction in central region and slots in arms

For a cruciform specimen, the arms undergo uniaxial tension while the central zone is biaxially tensioned. The capacity of load bearing of metal sheets under biaxial tension is larger than that under uniaxial tension, which causes localised necking or fracture usually starts in the arms of a cruciform specimen during a biaxial stretching [10]. In

order to investigate the effects of thickness reduction in the central region and slots in the arms of a cruciform specimen, the preliminary geometries of cruciform specimens, which meet the basic requirements, were designed and shown in Fig. 1.

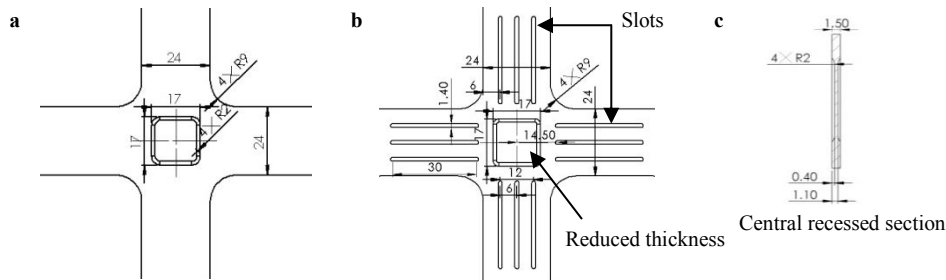


Fig. 1. Dimensions of two cruciform geometries. (a) Geometry A; (b) Geometry B; (c) Central sections of Geometries A and B.

For Geometry A, as shown in Fig. 1(a), fillets of 9 mm are introduced at the intersection of two perpendicular arms of the specimen to decrease stress concentration in the four corners. The thickness of the specimen is 1.5 mm and it is reduced with a depth of 0.4 mm on the two faces of the central region to form a recessed square gauge section with a dimension of 17 mm $\times$ 17 mm and a thickness of 0.7 mm in the middle of the specimen, marked in Fig. 1(c). The radius of the fillet in the recessed zone is 2 mm. This is designed to experience deformation under biaxial stretching. The difference of Geometry B from Geometry A is that slots with a length of 30 mm and a width of 1.4 mm are cut into the arms in order to investigate whether they can distribute the load more uniformly to the central gauge section. Each slot distance is 6 mm and the distance from the end of each slot to the mid-length of the specimen is 14.5 mm, as shown in Fig. 1(b).

Following solution heat treatment at 535 $^{\circ}\text{C}$ for 1 minute and quenching process at a cooling rate of 100 $^{\circ}\text{C/s}$, trial tests of AA6082 were conducted at a temperature of 400 $^{\circ}\text{C}$ and a strain rate of 0.1/s. The digital image correlation (DIC) technique was adopted to determine and record displacement and strain fields at the surface of specimens. Fig. 2 shows the results of the first principal strain and shear strain measurements when the maximum effective true strain in central zone for each test reaches 0.3. The central recessed zone is defined as the gauge region where to fulfill biaxial loading condition. Strain pattern is not symmetric in the central region, which caused by the non-uniformity of temperature distribution in the arms of specimens. It is clear that the strain level of the first principal strain is around 30% higher than that in surrounding regions on Geometries A and B, which indicates that reduced thickness could enable localised necking to occur in the central zone.

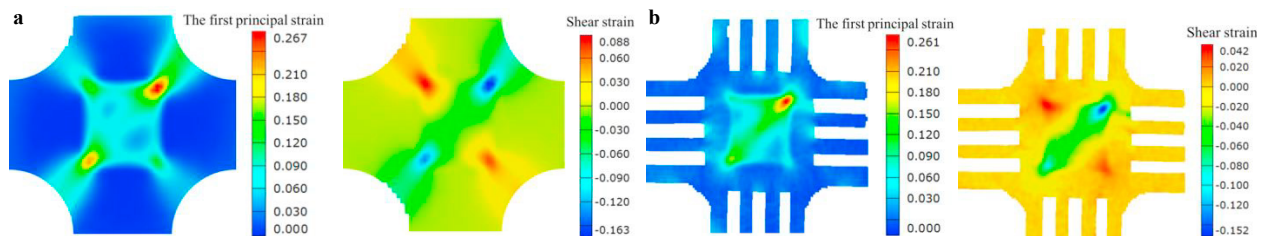


Fig. 2. DIC experimental results of the first principal strain and shear strain distribution for Geometries A and B tested at the temperature of 400 $^{\circ}\text{C}$ and the strain rate of 0.1/s. (a) full-field strains of Geometry A; (b) full-field strains of Geometry B.

According to shear strain distributions for the two tested geometries, the maximum values for Geometry A in the gauge section are over 20% larger than that for Geometry B, and the average values are similar over the milled zone. High strain can be observed for the transition region between the milled surface and the full thickness of the specimen, especially in the corners of the square recess. Therefore, the strain concentration needed to be reduced over the milled surface.

3.2. The effect of recessed shape

Fig. 3(a) shows the dimension of Geometry C altered from Geometry B in order to reduce the strain concentration over the milled zone. The change in Geometry C from Geometry B is the shape of the recess in the biaxial loading zone. A circular region with a diameter of 17 mm and a depth of 0.4 mm was milled away from the front and back sides of the specimen. The dimensions of other regions are the same as those of Geometry B.

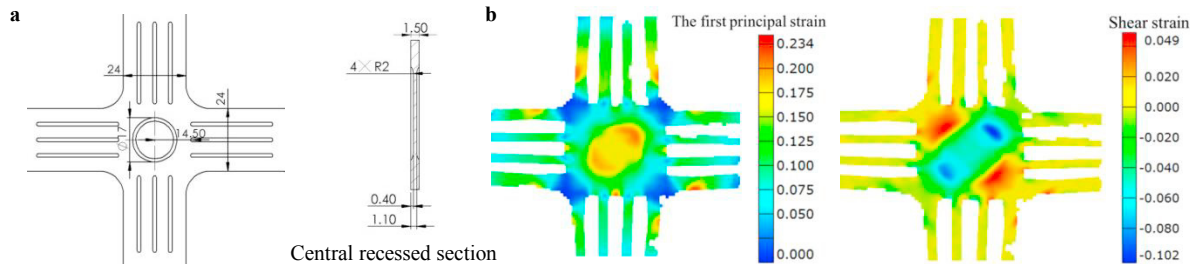


Fig. 3. (a) Dimensions of cruciform Geometry C; (b) DIC results of the first principal strain and shear strain distribution for Geometry C tested at the temperature of 400 °C and strain rate of 0.1/s.

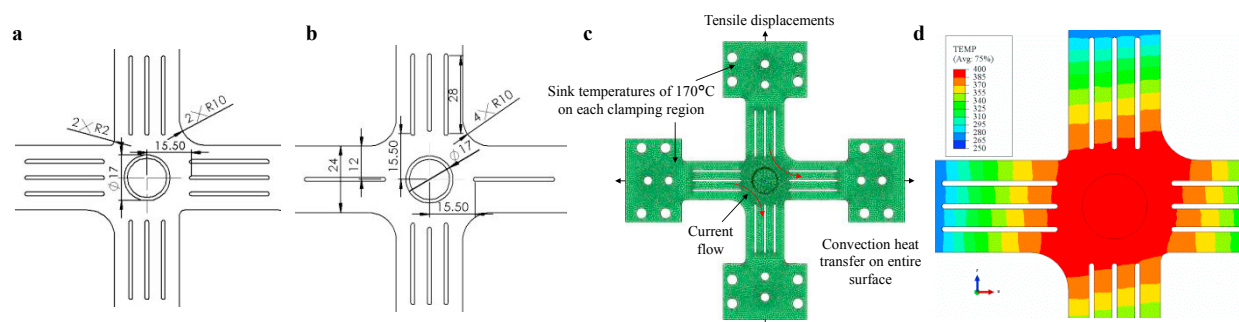
Fig. 3(b) shows the DIC results tested at the same condition as for Geometry B. No severe strain concentration was observed anymore during uniform deformation in the circular miller zone. The uniformity of the first principal strain distribution for Geometry C is better than that for Geometry B, which shows that strain concentration and shear strain level were reduced by introducing a circular reduced thickness so that the uniformity of strain distribution has been improved significantly in the gauge section. However, fracture was observed experimentally on the ends of slots before that occurred in the central zone for Geometry C because of severe stress concentration. This is also due to the fact that the distance 14.5 mm, as shown in Fig. 3 (a), from the slot ends to the mid-length of the specimen is small for Geometry C despite the fact that a smaller distance would be better for improving the uniformity of strain distribution in the central region.

After previous thermal analysis of temperature distribution on the specimen [8], in Geometry D used for equibiaxial testing (Fig. 4(a)), the corner fillet between two arms was modified to 10 mm and it was reduced to 2 mm for two opposite corners in order to balance the temperature difference in the arms of the specimen. The position of the ends of the slots from the mid-length was attempted to increase to 15.5 mm from 14.5 mm in order to retain potentially uniform stressing of the central gauge region while avoiding fracture at the ends of the slots. Other dimensions are the same as for Geometry C. In Geometry E used in plane strain testing for determining an FLD, the middle slot is 1.5 mm shorter than others in two fixed arms and only one slot was introduced in two loaded arms, as shown in Fig. 4(b).

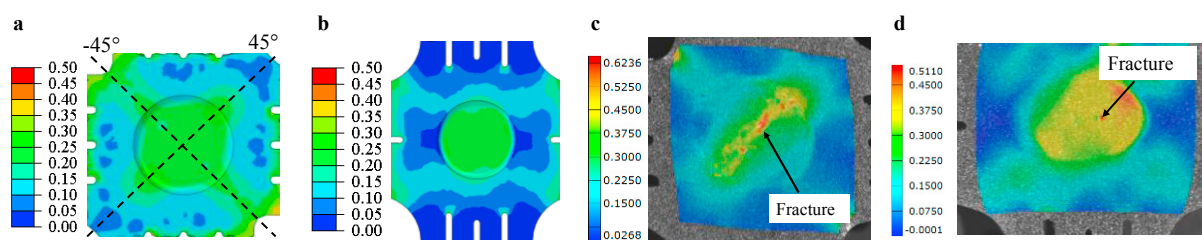
4. Dimensions of cruciform specimens

4.1. Thermo-electrical and thermo-mechanical FE models

An optimum specimen design requires a combination of experimental tests and corresponding FE simulations. A thermo-electrical FE model had been developed in ABAQUS to simulate Joule heating and calculate temperature distribution in a cruciform specimen. A user-defined subroutine UAMP was adopted in ABAQUS/Standard 6.12 to provide temperature feedback control by adjusting the current density input to simulate resistance heating, illustrated in [8]. The boundary conditions are illustrated in Fig. 4(c). Full-field temperature distribution was calculated and agreed with experimental results measured by thermocouples in a Gleeble, as shown in Fig. 4(d). The temperature profile obtained from the first step simulation was imported to the explicit thermo-mechanical FE model, embedded with a user-defined subroutine VUMAT, as a pre-defined temperature field in ABAQUS/Explicit. This analysis was used to simulate deformation of the specimen by using the same geometrical model with the same mesh quality as for the thermo-electrical model. The simulation was performed at a temperature of 400 °C and a strain rate of 0.1/s.



4.2. Dimension optimisation for equi-biaxial and plane strain testing



Strain values were used for the analysis and comparison of simulated and experimental results since stress values in the biaxial loading zone cannot be calculated experimentally due to the ill definition of the load bearing area. Fig. 5 (a) and (b) show the FE results of the first principal strain for both geometries used in equi-biaxial and plane strain testing, respectively. Due to the unsymmetrical distribution of temperature in the arms of specimens, there was a difference of strain level along 45° and -45° directions within the milled zone in Geometry C. When a smaller corner fillet was introduced at the intersection of two perpendicular arms at -45° direction in Geometry D, the difference of strain level within the central zone is reduced. The number of slots is reduced to one in two opposite arms for Geometry E so that the central zone has higher strain values than that in the arms for plane strain testing, in which two opposite clamping regions of a cruciform specimen are fixed to the specimen carriages so that the overall deformation in that direction is close to zero for testing under the strain path of plane strain. It was found that the length of the middle slot reduced for Geometry E in the two unloaded arms can avoid failure to start out of the central zone. The fracture location, as shown in Fig 5(c) and (d), for both of the two geometries occurred in the central zone, which was considered to meet the aim of the optimisation.

Fig. 6(a) shows the DIC results of the normalised value of the first principal strain distribution along the 45° inclined surface over the milled zone for the tested geometries. The uniformity of the first principal strain distribution for Geometry D and E are better than that for Geometry C, which shows that strain concentration was reduced by introducing a circular reduced thickness and by optimising dimensions so that the uniformity of strain distribution has been improved in the gauge section.

The evolution of the ratio values at the central point for Geometries is shown in Fig. 6(b). The strain path is directly controlled by displacements imposed on each axis of the specimen and it can be quantified as the value of the ratio of minor strain to major strain, which should be 1.0 for equi-biaxial strain and 0 for plane strain state. In this study, the values of the ratios are around 0.7 for Geometry D used for equi-biaxial testing and 0.17 for Geometry E used for plane strain testing. The values of the ratios are not ideal because of the absence of shear strain in the central zone, which cannot be avoided for testing with a cruciform specimen, so that the location of the onset of necking in the central zone of the specimen which was not exactly at the central point and the strains measured in the two

loading directions are not the principal strains. If only the fracture occurs in the central gauge region and strain distribution in the central zone is uniform, both of the values are acceptable to determine the FLD of an alloy under different strain paths at elevated temperature.

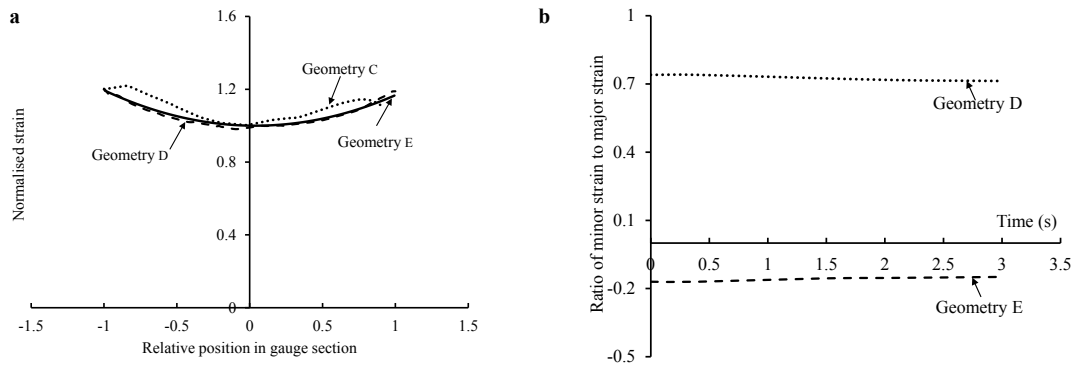


Fig. 6. (a) Variation of normalised the first principal strain over the milled zone for Geometries D and E; (b) Experimental results of the ratio of minor strain to major strain for Geometries D and E.

5. Conclusions

Based on the developed biaxial testing system, it has been observed that reduced thickness within the central biaxial loading zone and slots in the arms of a cruciform specimen are beneficial to improving the uniformity of strain distribution within the gauge region and inducing fracture to occur in the gauge region. By analysing DIC experimental results and FE simulation results at the testing temperature of 400 °C and strain rate of 0.1/s after rapid cooling, dimensions of specimens of AA6082 for formability tests under each strain path were finally determined to fulfil as many of the desired characteristics as possible. This formability testing method using cruciform specimens and the optimisation process of cruciform specimens can be adopted to generate formability data of alloys under complex hot stamping or tailored testing conditions.

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