

Crack initiation observation and local stress analysis in shear fracture tests of ultra-high strength steels

Ninshu Ma¹, Kenji Takada² and Nao Sugimoto²

¹ JSOL Corporation, 2-2-4, Tosabori, Nishiku, Osaka, 550-0001, Japan

² Honda R&D Co. Ltd., 4630, Shimo-Takanezawa, Hagamachi, Haga-gun, Tochigi-ken, 321-3393, Japan

Abstract. To investigate the local strain and stress at the crack initiation position in shear fracture test pieces of ultra-high strength steels, a butterfly shear fracture specimen was employed. The crack initiation position and propagation direction were observed during shear fracture tests by high speed cameras and investigated through analysing the fracture surface by scanning electron microscope. Further, the finite element method was employed and the stress-triaxiality at the crack initiation position was investigated. It can be obtained that the crack initiated at the position where the stress state is close to uniaxial tensile state or plane strain state more than pure shear stress state.

1. Introduction

To make light and strong automotive bodies, ultra-high strength steels and their structure components have been increasingly employed. However, with increasing the strength of steels, the elongation and ductility become worse. These will increase the difficulties in the metal forming. In addition, these make the prediction of the crack occurrence and its propagation become more difficult. To reduce the injury to humans due to transportation accidents, the prediction accuracy on the cracking position and deformation behaviours of automotive structures under various impact loading conditions must be investigated and improved.

There have been several criteria for the prediction of cracks due to sheet metal forming which include thinning [1], forming limit diagram based on principal strains [2] and stress forming limit diagram based on principal stresses [3]. However these criteria have difficulties when loading paths and three dimensional stress states become complicated. Recent researches indicated that the fracture strain of automotive steel sheets under different stress states is not a constant and it strongly depends on the stress-triaxiality [4-8]. The fracture strain under high stress-triaxiality states has been investigated using the standard uniaxial tensile test piece or the tensile test pieces with a centre hole or notches at edges [7-8]. To measure the fracture strain under low stress-triaxiality states such as the pure shearing stress state, several shear fracture specimens were designed and their test methods were proposed [4-8]. Most researchers observed the macro shear fracture mode in these shear fracture tests and found that the macro stress state in the shear fracture tests is close to the pure stress state. They concluded that the fracture strain is smaller than the uniaxial tensile stress state [5-7]. However, the local strain and the local stress at the crack initiation position were not exactly identified. In this article, we focused the research on the local fracture strain and local stress state at the crack initiation position in the shear fracture specimens. We selected a widely used shear fracture specimen with “Butterfly” shape [5] and conducted the shear fracture tests for three strength grades of 590MPa, 980MPa and 1500MPa of steel sheets. The crack initiation position during shear fracture testing was observed using high speed



camera and also identified by observing fracture surface using scanning electron microscope (SEM). The local fracture strain and the stress-triaxiality at the crack initiation position of shear fracture specimens were analysed by the finite element method (FEM).

2. Butterfly shear specimen of high strength steels

The butterfly specimen for shear fracture tests is shown in Fig. 1, which was proposed by Bai and Wierzbicki [5]. The thickness in the shear zone of the butterfly specimen is 0.5mm which is much thinner than the specimen thickness (1.6mm) in other zones. The width of the shear zone varies along the length direction of the butterfly specimen to produce the shear stress state. The load in the shearing direction is applied by displacement and the vertical displacement is controlled. The three strength grades of 590MPa, 980MPa and 1500MPa steels for shear fracture tests were employed. The 590MPa and 980MPa shear specimens were made from rolled steel sheets. The 1500MPa shear specimen was cut off from a piece of the rolled sheet to which the hot stamping thermal cycle has been applied. To ensure the reliability of shear fracture tests, three pieces of specimens for each strength grade of steels were prepared and experiments were repeatedly conducted.

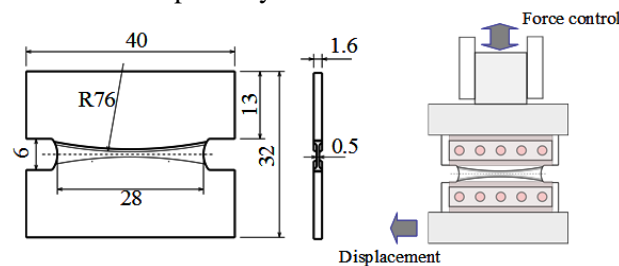


Fig. 1 Butterfly specimen and setup for shear fracture test [5].

3. Crack initiation position and propagation direction in butterfly specimen during shear tests

The crack initiation position during shear fracture tests was observed by a high speed camera and analysed using SEM photos along the fracture surface for three strength grades of steels. Fig. 2 shows macro photos of the butterfly specimen of the 1500MPa steel when the stroke is 0.0mm, 1.8mm and large enough for the final fracture, respectively. The crack initiation position is almost the same for three strength grades of steel sheets. The crack initiated at the stroke of 3.7mm, 2.5mm and 1.8mm for 590MPa, 980MPa and 1500MPa steels, respectively.

Fig. 3 shows the SEM photos along the fracture surface for the 1500MPa steel. Generally, it looks like a quasi-clearage fracture. From the photo shown in Fig. 3(b), the crack initiation position can be obviously seen around the edge of the butterfly specimen. From the river-like fracture patterns shown in Fig.3 (c), the crack propagation direction indicated by arrows in these figures.

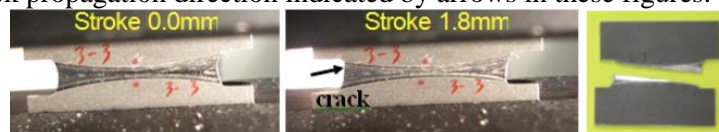


Fig.2 Macro-photos of butterfly shear specimen of 1500MPa steel at crack initiation and fracture states.

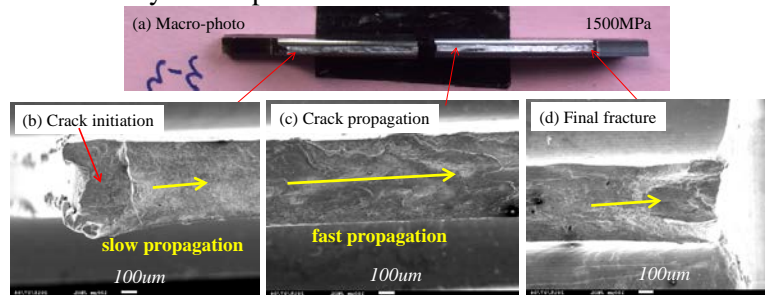


Fig.3 SEM-photos of 1500MPa shear specimen along fracture surface: (a) macro-photo, (b) around crack initiation position, (c) crack propagation zone, (d) final fracture.

4. FE analysis of fracture strain and stress-triaxiality

4.1. Mechanical properties of high strength steels

The Young's modulus and Poisson's ratio of advanced high strength steels 590MPa, 980MPa and 1500MPa are 206GPa and 0.3 respectively. The nonlinear stress and strain curves for 590MPa, 980MPa and 1500MPa materials are measured through uniaxial tensile tests [8]. The results are shown in Fig. 4 which accurately reproduced force-stroke historical curves of uniaxial tensile tests [8]. The strength coefficient A following swift hardening law for steels 590MPa, 980MPa and 1500MPa is 1012.7MPa, 1368.3MPa and 1896.2MPa, respectively. The exponential hardening coefficient n is 0.175, 0.086 and 0.058, respectively.

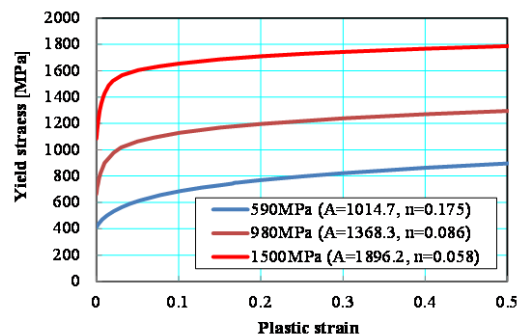


Fig. 4 Measured stress-strain curves [8].

4.2. Finite element model for butterfly shear specimens

To investigate the local stress and the local fracture strain, the nonlinear FEM software LS-DYNA was employed. Since the geometry of the butterfly shear specimen is symmetric in the thickness direction, only a half size through the specimen thickness is modelled by solid elements as shown in Fig. 5. Three elements were divided in the thickness direction of the finite element model and the minimum size of elements is about 0.1mm. The nodal displacements on the bottom surface are fixed. The vertical nodal displacement on upper surface is constrained. The horizontal nodal displacement on the upper surface is applied following the experimental data.

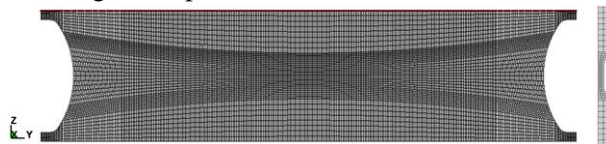


Fig. 5 Butterfly specimen and setup for shear fracture test.

4.3. Local fracture strain and stress-triaxiality in shear fracture tests

With the aid of FEM, the local strain and local stress were computed. The distribution of the equivalent plastic strain and the distribution of the stress-triaxiality in the shear fracture test at the crack initiated stroke (1.8mm) for the 1500MPa steel are shown in Figs. 6(a) and 6(b), respectively. The distribution of the equivalent plastic strain and the distribution of the stress-triaxiality are similar for 590MPa and 980MPa steels at the stroke 3.7mm and 2.5mm, respectively. For all shear fracture tests of three strength grades of 590MPa, 980MP and 1500MPa steels, the local plastic strain and stress-triaxiality are both largest around the edge point-A where the crack occurred.

Using the computed results during shear fracture testing, the historical changes of the plastic strain and the stress-triaxiality at the edge point-A and the inside point-B for all three strength grades of steels are plotted in Fig.7. The changing characteristics of stress-triaxiality at the edge point-A are complicated and those at the inside point-B have almost a same value of 0.05 which is close to the pure shear stress state. At the edge point-A, the stress-triaxiality is about -0.4 or -0.5 when the plastic strain is small. When the plastic strain becomes large, the stress-triaxiality increases to about 0.2~0.4. The local fracture strain for three strength grades of 590MPa, 980MPa and 1500MPa steels is 1.55, 0.88, 0.41, with the stress-triaxiality of 0.38, 0.24, 0.21, respectively. Although the plastic strain at the

edge point-A is smaller than that at the inside point-B, the crack occurred at the edge point-A. This is because the stress-triaxiality at the edge point-A is larger than that at the inside point-B. From above results, we can know that the crack initiated at the position where there is higher stress-triaxiality and the crack did not initiate at the pure shear stress state even the local plastic strain is larger.

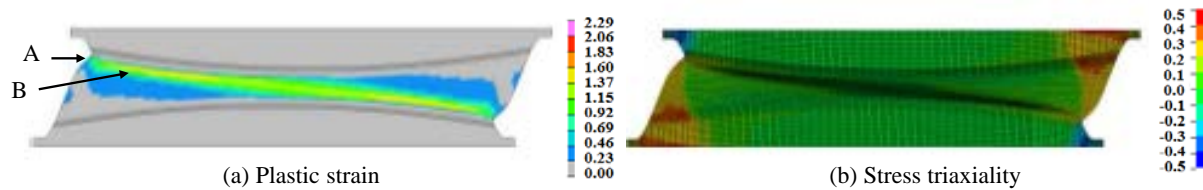


Fig. 6 Computed results of 1500MPa steel at stroke=1.8mm: (a) plastic strain, (b) stress-triaxiality.

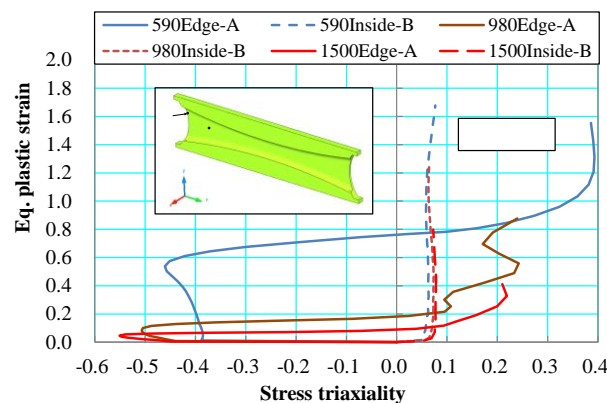


Fig.7 Local fracture strain and stress-triaxiality estimated by FEM.

5. Conclusions

- (1) Shear fracture tests using butterfly specimen for three strength grades of 590MPa, 980MPa and 1500MPa steel sheets were conducted.
- (2) The crack initiation position, the edge of the butterfly specimen, was observed by the high speed camera and also identified from analysis of fracture surface using scanning electric microscope.
- (3) The stress-triaxiality at the crack initiation position is much higher than the pure shear stress state.
- (4) Although the plastic strain at the position with the pure shear stress state is larger than the plastic strain at the edge of the butterfly specimen, the crack did not occur at the position with the shear stress state.
- (5) The local fracture strain at the crack initiation position is 1.55, 0.88, 0.41 with the higher stress-triaxiality of 0.38, 0.24, 0.21 for three strength grades of 590MPa, 980MPa and 1500MPa steels, respectively.
- (6) It looks that the crack propagation is along the pure shear stress zone in the butterfly specimen and detail research is necessary.

References

- [1] Ma N 2013 *Sokeizai*, v54n4, pp 21-26 (in Japanese).
- [2] Marciniak Z and Kuczynski K 1967 *Int. Journal of Mechanical Science*, v9, pp 609–620.
- [3] Kuwabara T 2005, *Proc. NUMISHEET2005*, pp 20-39.
- [4] Isik K, Soyarslan C, Richter H and Tekkaya A E 2011 *Proc. 8th European LS-DYNA Users Conf.*, Strasbourg, May, 2011.
- [5] Bai Y and Wierzbicki T 2010 *Int. J. Fracture*, 161, pp 1-20.
- [6] Cesar de Sa J M A 2014 *Proc. Numisheet2014*, pp 344-349.
- [7] Dunand M and DirkMohr 2011 *J. Mechanics and Physics of Solids*, v59, pp1374–1394.
- [8] Sato K et al. 2014 *Trans JASE*, 45-6, pp 1099-1104.
- [9] Ma N et al. 2016 *Trans JASE*, 46-2, pp 603-608.