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Prediction and Experimental Validation of Forming Limit Curve of a Quenched and Partitioned Steel

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Abstract: Forming limit curve (FLC) is an effective tool to evaluate the formability of sheet metals. An accurate FLC prediction for a sheet metal is beneficial to its engineering application. A quenched and partitioned steel, known as QP980, is one of the 3rd generation advanced high strength steels and is composed of martensite, ferrite and a considerable amount of retained austenite (RA). Martensite transformation from RA induced by deformation, namely, transformation induced plasticity (TRIP), promotes the capability of work hardening and consequently formability. Nakazima tests were carried out to obtain the experimental forming limit strains with the aid of digital image correlation techniques. Scanning electron microscopy (SEM) was employed to examine the fracture morphologies of Nakazima specimens of the QP980 steel. The observed dimple pattern indicated that tensile stress was the predominant factor which led to failure of QP980 specimens. Therefore, maximum tensile stress criterion (MTSC) was adopted as the forming limit criterion. To predict the FLC of QP980 steel, Von-Mises yield criterion and power hardening law were adopted according to the tested mechanical properties of QP980 steel. Results were compared with those derived from other three representative instability theories, e. g. Hill criterion, Storen-Rice vertex theory and Bressan-Williams model, which shows that the MTSC based FLC is in better agreement with the experimental results.

Key words: forming limit curve; fracture morphology; maximum tensile stress criterion; quenched and partitioned steel; high strength

QP980 steel is a 3rd generation advanced high strength steel (AHSS), where Q and P indicate quenching and partitioning[1], respectively. It consists of martensite, ferrite and carbon-enriched retained austenite (RA). The presence of hard martensite phase promises the high strength, while soft ferrite and retained austenite, which induces transformation induced plasticity (TRIP)[2], promise good ductility. This combination of excellent strength and good ductility makes QP980 steel become one of the most potential vehicle lightweight material. The mechanical properties at room temperature[3] and necking phenomenon under uniaxial tension[4] of quenched and partitioned steel (Q&P steel) were studied. Accurate evaluation of the formability of QP980 steel is of utmost importance for its application into auto-body parts.

Forming limit curve (FLC), which was first introduced by Keeler and Backofen[5], is an effective tool to evaluate the formability of sheet metals. The FLCs can be obtained from Nakazima tests[6] and Marciniak tests[7]. However, the experiments are highly cost and time consuming. Furthermore, due to the fact that for some AHSS, the samples tend to fail at the radius of the punch (for Marciniak tests) or die (for Nakazima tests) earlier, it can be very difficult to acquire the whole FLCs experimentally. Therefore, predictive models for FLC are necessary.

The accuracy of the predictive models for FLC greatly depends on the instability criteria. Several lo-

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calized instability theories have been developed, such as Hill criterion[8], Marciniak-Kuczynski (M-K) grove theory[7], Storen-Rice (S-R) vertex theory[9], Bressan-Williams (B-W) model[10] and so on. It is experimentally found that, for QP980 steel, the predicted FLCs based on existing instability theories are not in accordance with the experimental FLC. New instability criteria, which are suitable for AHSS, should be proposed. Studies[11,12] suggested that the criteria commonly used in brittle materials may be suitable for AHSS. Wierzbicki et al. [11] showed that maximum shear stress (MSS) criterion can successfully predict the failure of 2024-T351 aluminum alloy in a wide range of tests. Bai and Wierzbicki[12] proposed a new criterion (referred as MMC) by modifying Mohr-Column criterion, which is used to evaluate the strength of soil and rock, and showed that MMC can be successfully applied to predict the formability of 2024-T351 aluminum alloy and TRIP690 steel sheet.

In this work, in order to find out the predominant factor that leads to the instability of QP980 steel, Nakajima tests with the aid of digital image correlation (DIC) techniques[13] were conducted, and scanning electron microscopy (SEM) was employed to examine the fracture morphologies of QP980 specimens after Nakazima testing. Based on the SEM observation, a suitable instability criterion was proposed and the FLC of QP980 steel was predicted. By comparing with the experimental FLC, the instability criterion and the consequent predictive model for FLC are validated.

1 Experimental

The microstructure of QP980 steel studied in this work is composed of martensite (58.4 at.%), ferrite (30 at.%) and austenite (11.6 at.%). The gauge thickness is 1.6 mm. The mechanical properties of QP980 steel are listed in Table 1. Nakazima tests[6] with the aid of DIC techniques were conducted on Interlaken servo-controlled hydraulic press to get strain paths from uniaxial tension to balanced biaxial tension, by varying the specimen width from 20 mm to 180 mm. Here, the width direction of specimens is along the rolling direction (RD). The detail dimensions of all used Nakazima specimens are shown in Fig. 1 and Table 2. The diameter of the spherical punch is 100 mm.

Table 1 Mechanical properties of QP980 at room temperature

Degree to RD/(°)	Yield strength/ MPa	Tensile strength/ MPa	Uniform elongation/ %	Elongation at fracture/%	Lankford parameters (R_0, R_{45}, R_{90})
0	828±18	1015±6	10.9±0.5	15.8±0.4	0.985±0.068
45	823±15	1007±2	10.2±0.7	15.3±0.8	1.032±0.105
90	843±21	1011±2	10.5±0.4	15.1±0.5	0.950±0.068

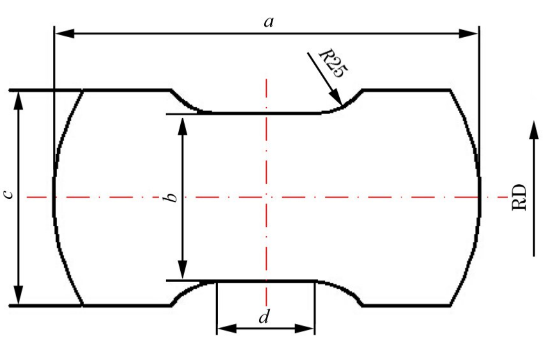

Fig. 1 Illustration for geometries of Nakazima specimens

Table 2 Dimensions of Nakazima specimens mm

Specimen number	1	2	3	4	5	6	7	8	9
a	180	180	180	180	180	180	180	180	180
b	20	40	60	80	100	120	140	160	180
c	30	55	80	100	120	140	140	160	180
d	100	80	60	40	20	0	0	0	0

Before performing Nakazima tests, the specimen surfaces were cleaned with alcohol, and then speckle patterns, composed of one layer of white paint and black paint dots with size of about 0.5 mm on the white paint layer, were applied on the cleaned specimen surfaces. A Teflon sheet with a thickness of 0.1 mm as a lubricant was placed between the spherical punch and Nakazima specimen.

During all Nakazima tests, a clamping force of 2000 kN was applied, and the punch speed was set to 1 mm/s. The framing rate of the DIC cameras was 14 frame/s.

DIC-Grid method, which was proposed by Zhang et al. [14], was employed to acquire the experimental FLC.

It is important to understand the failure mechanism of QP980 steel before formability prediction. Observation of the fracture morphology is an important method to investigate the failure mechanism. SEM