Failure Investigation for QP Steel Sheets under uniaxial and Equal-Biaxial Tension Conditions

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Abstract. The Quenching and Partitioning (QP) steel sheet is new generation material to induce phase transformation for plasticity in forming vehicle parts. The phase transformation is strongly stress state dependent behavior in experiments, which should affect the failure timing and limit strain in forming processes. In this paper, Nakajima test with QP980 and DP1000 steel sheets under equal-biaxial loading condition is performed for failure behavior. X-ray diffraction (XRD) is adopted to obtain the volume fraction of retained austenite ($f_A$). Digital Image Correlation (DIC) is used to record the surface strain field and its evolution during equal-biaxial tension deformation. The same level Dual Phase (DP) steel is also employed for the purpose of comparison. The results show that phase transformation in QP steel gives small impact on failure strain under equal biaxial tension condition which is contradicted with our understanding. It suggests that failure behavior under uniaxial tension of QP980 is strongly phase transformation dependent. But it shows almost independent under equal biaxial tension condition.

1 Introductions

The Quenching and Partitioning (QP) steel sheet is new generation material with excellent elongation for forming the vehicle safety part. The austenite-to-martensite phase transformation during material deformation provides excellent ductility for forming processes. The martensitic transformation kinetics has been widely studied with different advanced material characterization methods such as XRD, TEM, SEM and EBSD. The published experimental results show that the phase transformation behaviour depends on the stress state applied on the material. In sheet metal forming process, forming limits are employed as failure criterion for predicting material split in simulation. Nakajima test is performed on sheet metal specimens with different shapes for the purpose of obtaining forming limits under specific strain path. Obviously, certain stress state will be applied on the sheet metal specimen during the Nakajima test with accordingly strain path. The micro structure evolution of the austenite-to-martensite phase transformation is expected to impact the macro mechanical behavior as well as its failure limits consequently.

Due to the length limitation of the paper, we will briefly summarize the research work for austenite-to-martensite phase transformation behaviour. Recently, experimental study [1] indicates that the transformation-induced plasticity (TRIP) effect occurs in QP steel, which enhances the strain hardenability and delays the necking of materials [2-5]. Beese and Mohr [6] produce a comprehensive...
set of data that illustrates the effect of stress state on the martensitic transformation kinetics in an
austenitic stainless steel. They found that the martensitic transformation depends on both stress
triaxiality and Lode angle. Compare to the research of phase transformation kinetics in steel, limited
effort has been made to understand the detailed relationship of austenite-to-martensite phase
transformation and the failure behaviour of sheet steels.

In this paper, Nakajima test with QP980 and DP1000 steel sheets under equal-biaxial loading
condition is performed for failure behavior. X-ray diffraction (XRD) is adopted to obtain the volume
fraction of retained austenite ($f_A$). Digital Image Correlation (DIC) is used to record the surface strain
field and its evolution during equal-biaxial tension deformation. Different micro structures but similar
strength level steels (QP980 and DP1000) are compared with each other. Interesting results are obtained
and discussed in detail.

2 Mechanical Experiments

2.1 Test materials

The cold-rolled QP980 steel sheets provided by the Baosteel Group Corp. in Shanghai China with the
thickness of 1.2mm are adopted in experiments. The provided QP980 has a multi-phase microstructure
of retained austenite (RA), martensite (M) and ferrite (F) as shown in Fig.1. For the comparison purpose,
the commercial DP980 sheets steels are employed for comparative study. The microstructure of DP980
(1.0mm) used in this study is martensite and ferrite.

2.2 Uniaxial tension tests

Uniaxial tension tests for QP980 and DP1000 under static deformation condition are performed with
Zwick Roell tensile testing machine at room temperature. The engineering stress and strain curves of
these two materials are presented in Fig. 1. The elongation between these two different materials is very
different due to the phase transformation-induced plasticity (TRIP) effect from the austenite-to-
martensite transformation. The failure limit strain between the QP980 and DP1000 is about 12% to 17%
under uniaxial stress state condition (or uniaxial strain path condition). The retained austenite gives
significant impact on sheet metals failure under uniaxial tension. Micro structures of these two materials
are critical factors for the discrepant ductility. Based on this phenomenon, it suggests that TRIP effect
enhances failure limit strain for QP steel and also provides similar strength.

2.3 Equal biaxial tension tests

The Nakajima test is performed for equal biaxial tension test of both QP980 and DP1000 sheets. The
Zwick Roell BUP400 forming limit testing equipment with regular radius 50mm punch is adopted to
tension the sheet metal as shown in Fig.2.
Digital Image Correlation (DIC) is set up for strain computing and evolution recording. When testing with the complete disk to obtain balanced-biaxial deformation, rectangular shaped Teflon plastic about 1 mm thick was used. Viscous oil is painted uniformly on the Teflon which provides as close to a frictionless condition as is possible. We tested all specimens using a fixed punch velocity of 4.5 mm/s, irrespective of the different material samples. The binder force is fixed as 350kN for all tests. The 12Hz sampling frequency is employed to take speckle pictures of tests due to the limitation of used DIC. The tested samples are presented in Fig.2.

The fracture occurs at the center area of the tested sample for both QP980 and DP1000 which suggest that the friction is almost zero and the material on the punch top is almost deformed under equal biaxial tension state. The arbitrary material point can be selected on strain calculating image for strain evolution and strain field of the top surface.

The strain evolution of the punch top surface material at top point is shown in Fig.3 for both QP980 (1.2mm) and DP1000 (1.0mm). Similar strain evolution can be achieved for both sheets even with different thickness.

In Fig.3, the end point is the last frame before the material split which can be calculated the surface strain of the top material. A little lower limit strain of DP980 than QP980 can be obtained in this figure. If consider the factor that QP980 steel sheet (1.2mm) is a little thicker than DP980 steel sheet (1.0mm), then it may conclude that almost equal formability of these two material under equal biaxial tension loading can be achieved. The experimental results show that TRIP effect gives no impact on sheet metal’s formability under equal biaxial tension loading. The material’s mechanical behavior shows insensitive phenomenon to its micro stricture which is inconsistent with our understanding. This phenomenon suggests failure limits of QP steel material shows very different dependent phenomenon on the austenite-to-martensite phase transformation behaviour.

### 3 Deformation induced martensitic transformation

To further studied the micro structure evolution of the QP steel and explain discrepant phenomenon between failure behaviour under uniaxial and equal biaxial tension, XRD method is used to determine the volume fraction of retained austenite during different deformation stages. The similar deformation process is applied on the QP980 sheet metal.

The XRD experiment was performed at the Thin-walled Structures Laboratory of Shanghai Jiao Tong University. Fig. 4 shows the experimental setup used for the experiments. The detailed volume fraction of retained austenite has been obtained through the XRD method. A size of 10×10 mm area material has been detected in this equipment. The previous study [7] results show that the initial volume fraction of retained austenite is very stable and insensitive to the environmental temperature conditions.

The volume fraction of retained austenite under incremental uniaxial tension and equal biaxial tension are shown in Fig.4. The M.Radu model [8] has been used to fit the experimental results. The detailed expression is:

\[
f_A = 0.1061 * \exp(-3.43 * \eta + 1.05) * (e_\sigma^p)^{0.78}
\]  

(1)
Where \( f_A \) is the volume fraction of retained austenite, \( \eta \) is stress triaxiality and \( \varepsilon_{eq}^p \) is equivalent plastic strain.

Based on the experimental results of retained austenite during incremental deformation, obvious difference is observed between the loading process of uniaxial and equal biaxial tension on QP980 sheet metals. The volume fraction of retained austenite keeps reducing in deformation process which is consistent with our expectation. Moreover, under biaxial tensile tests, the retained austenite transformed to martensite faster than that of uniaxial tensile tests. Therefore, the further question is proposed: if deformation induced martensitic deformation is promoted under equal biaxial tension than uniaxial tension for this QP980 steel sheet, why the QP980 steel sheet show higher failure limit strain under uniaxial tension but almost identical failure limit strain under equal-biaxial tension when compared with the dual-phase DP1000 steel?

**4 CONCLUSIONS**

Both QP980 and DP1000 are tested with uniaxial and equal biaxial tension loading. XRD method has been used to obtain the volume fraction of retained austenite during different incremental deformation stages. The top surface strain field and its evolution were recorded by the DIC system. Experimental results show that the austenite-to-martensite phase transformation induced TRIP effect impacts materials ductility under uniaxial but has little effect on its formability under equal biaxial tension. It suggests that the failure limit of QP980 sheet metals shows obviously TRIP effect (or phase transformation effect) dependent phenomenon under uniaxial tension loading. But the failure strain under equal biaxial tension shows almost TRIP effect independent phenomenon. It is still elusive to answer the contradictory phenomenon of failure behaviour of QP980 sheet metal in this paper. The physical explanation should be continuously searched in future.

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