The formability and application of hot-rolled dual-phase steel under nonlinear strain paths

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Abstract. The hot-rolled dual-phase steel 700DP was developed to reduce weight and improve safety in automobile industry. However, strain path changes inevitably occur for most of components during sheet forming process. Therefore, it’s valuable to predict the cracking accurately under nonlinear strain paths for the application of 700DP steel with finite element method (FEM). In this paper, the mechanical properties of hot-rolled dual-phase steel 580DP and 700DP were studied with tensile test. Nakazima test and two-step nonlinear loading test were used to establish the modelling with the method of equivalent plastic strain-based FLC (ep-FLC). Furthermore, the ep-FLC was applied to predict the disc forming result of three-stage process, which agreed well with the experimental results for both 580DP and 700DP compared with conventional FLC.

1. Introduction
At the component design stage, numerical simulation has been used popularly to determine the forming process and die structure. Accurate description of the mechanical properties and formability is important for the process design, which indeed has great influence on the effectiveness and cost of project. Forming limit curve (FLC) is most widely used in sheet metal forming. However, it has been pointed out that conventional FLC is difficult to predict the forming failure under multi-stage forming process for the strain path changing [1-3]. Stress based FLC (FLSC) was proposed to evaluate formability during nonlinear loading process [4-6]. Nevertheless, the FLSC data cannot be determined directly from the experiments which mainly limits the application in engineering, the concept of the effective plastic strain-based FLC (ep-FLC) and Polar Equivalent Strain (PEPS) were proposed successively to estimate the failure under nonlinear forming process [7,8].

For low-cost and high property, hot-rolled dual-phase steel 580DP has been used widely for automotive part manufacturers [9,10]. Furthermore, higher strength dual-phase steel 700DP was developed to satisfy the need for further lightweight and higher property. In this page, the mechanical property and formability of 580DP and 700DP were investigated. The modelling of equivalent plastic strain-based FLC (ep-FLC) was established to describe the formability during nonlinear strain process, compared with conventional FLC.
2. Material and experimental procedure

2.1 Material and tensile test
Hot-rolled dual-phase steels usually consist of martensite and ferrite phases. The soft and ductile ferrite matrix provides dual phase steels with low yield strength and good ductility, while the hard martensite phase provides the high tensile strength mainly. Compared with cold rolled DP steel, hot-rolled DP steel has the similar property through controlled rolling and controlled cooling process, which is much more low-cost. 700DP is produced to balance the strength and plasticity, as the middle grade between 580DP and 780DP. The microstructures of 580DP steel and 700DP steel are illustrated in Fig. 1, the volume fraction of 700DP is higher than that of 580DP.

![Microstructures of hot-rolled steels: a)580DP, b)700DP.](image)

The sheet thicknesses of 580DP and 700DP in this investigation are 3.0mm and 2.95mm respectively. Tensile tests had been performed on INSTRON testing machine in various directions, including 0 degree, 45degree and 90 degree along rolling direction, two specimens were measured in each direction to determine the test data. As shown in Figure 2, the yield strength of 700DP is similar to that of 580DP, while the tensile strength is much higher. The material property of 580DP and 700DP are anisotropic, and the tensile strengths of two steels at 90 degree are highest, the elongations at 0 degree are greatest.

![The engineering stress-strain curves of 580DP and 700DP in three directions.](image)

2.2 Formability test under linear and nonlinear strain paths
According to the standard of the ISO 12004, the linear FLC was measured on Interlaken sheet metal testing machine with Nakazima test. And the whole deformation history can be recorded to identify the onset of necking directly with the VIALUX photogrammetric equipment. Friction between sample and punch was minimized by using polyurethane gasket as lubricant. The samples were deformed until

![FLCs of 580DP and 700DP under linear strain paths.](image)
fracture by a hemispherical punch with a diameter of 100 mm. In this method, ten specimens with the same length of 196 mm but different widths were selected to obtain different loading paths, varying from 20 up to 180 mm. The obtained FLCs of 580DP and 700DP under linear strain paths are showed in Figure 3.

The two-step forming method was employed to produce nonlinear strain paths, which was used to check the influence of changing strain paths of 700DP. Four different loading paths were proposed totally in this study. The path of pre-uniaxial to plane strain is defined as UT-PS, while the path of pre-uniaxial to biaxial strain is defined as UT-BS. The path of pre-biaxial strain to plane strain is called BS-PS, and the path of pre-biaxial strain to uniaxial strain is defined as BS-UT. The pre-strains under different loading conditions and limit strain results on the onset of necking were measured through optical method. The experimental results of nonlinear paths were added to the traditional FLC. As shown in Fig. 4(a), it is not unexpected that the limit principle strains of two-step path change were out of the traditional FLC. Therefore, the traditional FLC of 700DP can’t predict the material formability accurately under nonlinear strain path.

![Figure 4](image_url)

**Figure 4.** The two-step nonlinear strain results of 700DP: a) with linear FLC, b) with ep-FLC.

The strains under two-step loading condition could be transformed to equivalent strain form. Hill48 anisotropic yield criterion can be described as Equation (1):

\[
\sigma^2 = (G + H)\sigma_1^2 + (F + H)\sigma_2^2 + 2H\sigma_1\sigma_2 + 2N\sigma_{12}^2
\]

Considering the associated flow, Equation (2-3) can be obtained:

\[
\rho = f(\alpha)
\]

\[
\beta = g(\alpha)
\]

where \(\alpha\) is the ratio of principal stresses:

\[
\alpha = \frac{\sigma_2}{\sigma_1}
\]

the strain path \(\rho\) can be written as:

\[
\rho = \frac{d\varepsilon_2}{d\varepsilon_1}
\]

de the strain parameter \(\beta\) can be written as:

\[
\beta = \frac{d\varepsilon}{d\varepsilon_1}
\]

where F, G and H are the anisotropic coefficient parameters, \(d\varepsilon_1, d\varepsilon_2, d\varepsilon\), \(\sigma_1\) and \(\sigma_2\) are the principal and equivalent strain increments, and the principal stresses. If the limit principal strains and the strain path were given, the equivalent plastic strain can be calculated quickly combined of Equation (1-6). As shown in Figure 4(b), the FLC was transformed to ep-FLC, which was consisted of equivalent limit
strain and strain path ρ as the vertical and horizontal coordinates. The two-step loading path change results can agree with the ep-FLC well.

3. The application of ep-FLC

3.1 The feature of wheel disc and experimental forming results

The 3D model of the wheel disc in this study is presented in Figure 5. The initial blank with the diameter of φ 462 mm was employed to produce the disc with max diameter of φ 364 mm and Max depth of 73mm. It should be difficult to form the approximate square seal seats which are arranged along the circle in the centre area of disc. The radii of the square seal seat are small, just 3mm at the bottom of seat and 5mm at the top of seat.

The wheel disc was designed to form with five stages, and the main deformation occur in the first three forming stages, as shown in Figure 6. Hot-rolled dual-phase steel 580DP and 700DP were attempted to forming the disc with that dimension. The stamping results were given in Figure 7. The wheel disc was formed perfectly with 580DP without cracking, but several cracks were observed at position A, B and C of the wheel disc formed with 700DP.

![Figure 5. 3D model of the wheel disc.](image1)

![Figure 6. The three-stage forming process of disc.](image2)

![Figure 7. Forming results of wheel disc using 580DP and 700DP.](image3)

3.2 The FEM results with traditional FLC and ep-FLC

FEM was used to simulate the three-stage forming process for the disc with Autoform software. The shell element was used in this simulation. The Coulomb friction coefficient between the blank and the die surfaces was set to 0.1 according to the actual lubrication condition. Hill48 anisotropic yield criterion and Swift hardening law were used to describe the yield and hardening behaviour of 580DP and 700DP.

The result of three-stage forming simulation was evaluated with traditional FLC firstly, and the strain path of disc during three-stage forming process is indeed nonlinear, as shown in Figure 8(a) and Figure 9(a). The principle strains of 700DP are almost equivalent to that of 580DP in the critical area of seal seat. The limit principle strains of 700DP still in safe area, though the maximum strain of position C is very close to the FLC. Obviously, the simulating results cannot agree with the experimental forming results using 700DP, the cracking actually occurred at position A, B and C.
The strain paths at position A, B and C of both 580DP and 700DP were respectively extracted to calculate the equivalent strains. From the Figure 8(b), the equivalent strains at position A, B and C are still under ep-FLC for 580DP, however the final equivalent strains of position A, B and C exceeded the ep-FLC for 700DP. Therefore, the high risk of cracking for 700DP at position A, B and C during three-stage forming process can be predicted accurately with ep-FLC, which was well coincident with the experimental results.

![Figure 8. Simulation results of seal seat position for 580DP: a) prediction with linear FLC, b) prediction with ep-FLC.](image)

![Figure 9. Simulation results of seal seat position for 700DP: a) prediction with linear FLC, b) prediction with ep-FLC.](image)

4. Conclusions
The mechanical property and formability under linear and nonlinear strain paths for hot-rolled steel were studied, and the main conclusions can be got:
(1) 580DP and 700DP both consist of martensite and ferrite phase. The yield strength of 700DP is similar to that of 580DP, while the tensile strength is much higher. The conventional FLC of 700DP is much lower than that of 580DP.
(2) The modelling of ep-FLC for 700DP was certified by the two-step strain path changing experimental results.
(3) The ep-FLC was applied to predict the disc forming result of three-stage process, which agreed well with the experimental results for both 580DP and 700DP compared with conventional FLC.

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