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Prediction of forming limit curve for pure titanium sheet

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Abstract: Commercially pure titanium (CP Ti) has been actively used in the plate heat exchanger due to its light weight, high specific strength, and excellent corrosion resistance. However, researches for the plastic deformation characteristics and press formability of the CP Ti sheet are not much in comparison with automotive steels and aluminum alloys. The mechanical properties and hardening behavior evaluated in stress−strain relation of the CP Ti sheet are clarified in relation with press formability. The flow curve denoting true stress−true strain relation for CP Ti sheet is fitted well by the Kim−Tuan hardening equation rather than Voce and Swift models. The forming limit curve (FLC) of CP Ti sheet as a criterion for press formability was experimentally evaluated by punch stretching test and analytically predicted via Hora's modified maximum force criterion. The predicted FLC by adopting Kim−Tuan hardening model and appropriate yield function shows good correlation with the experimental results of punch stretching test.

Key words: Kim−Tuan hardening equation; Hora modified maximum force criterion; pure titanium sheet; forming limit curve

1 Introduction

Heat exchangers are devices that perform heat exchange between two heat transfer fluids separated by solid walls (tubes or plates) at different temperatures. There are various types of heat exchangers. Among them, plate heat exchanger (PHE) has been widely applied to almost all industrial fields such as food industry, chemical industry, power generation facility, and general industry. Titanium heat transfer plates, which are frequently used in PHE, are manufactured by hydraulic presses with various patterns of ridge and corrugation (washboard pattern, herringbone pattern, etc) in order to maximize the heat exchange area and to increase the strength and rigidity of the plate. Figure 1 shows a representative form of titanium PHE, where red arrow indicates the direction of high-temperature medium flow, and blue one indicates low-temperature medium flow direction.

As a PHE material, a stainless steel sheet is mainly used. However, Grade 1 commercially pure titanium (CP Ti), which is excellent in non-strength, corrosion resistance and high temperature strength and has no toxicity, is used in the corrosive environment. The CP TI is known to have high ductility and low strength due to its low carbon and iron content. Recently, efforts have been made to improve the press formability and processing technology while Grade 2 and 3 titanium sheets with high strength are adopted to improve the heat exchange efficiency [1].

The pure titanium sheet is an allotropic metal with a hexagonal closed packed (HCP) crystal structure at low temperature and a body-centered cubic (BCC) structure at 800 °C or higher. On the other hand, the CP Ti has a very limited plastic sag system, a low elastic modulus and strong in-plane anisotropy. Compared with ordinary steel, it is a material hard to press forming. It is also known that the plastic deformation of the titanium plate is mainly caused by twin deformation, and there is a strength differential (SD) effect that has a distinctly different stress−strain curve in tension and compression in the direction parallel to the rolling direction [2].

The purpose of this work is to obtain basic data on the press formability of pure titanium sheet, which is relatively few compared with automotive steel sheet or aluminum sheet. For this purpose, forming limit curve (FLC) was evaluated by tensile test and punch stretching

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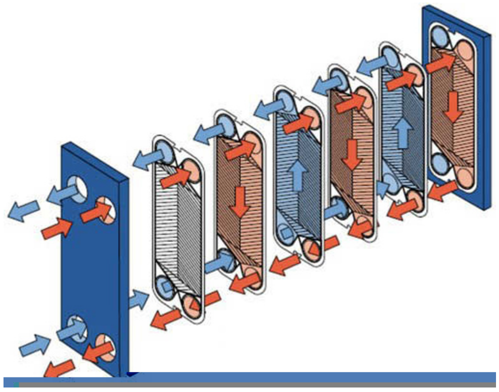

Fig. 1 Shape of titanium plate heat exchanger showing various pattern shapes

test using spherical punch for pure titanium sheet. The accurate modeling of the true stress−strain relationship obtained from the tensile test results is the most basic data for the PHE press forming and the design of the forming tool using CAE (computer aided analysis). In this work, we proposed a work hardening model that can best fit the tensile test results of pure titanium sheet, and predicted the forming limit curve analytically using the proposed flow curve model and compared it with the punch stretching test results.

2 Experimental

2.1 Tensile test

Tensile specimens of ASTM E8 (equivalent to KS 0801 13B) were taken to evaluate the mechanical properties of pure titanium sheet for PHE with a thickness of 0.5 mm. This tensile specimen was subjected to a tensile test at a tensile rate of 1 mm/min according to the KS B 0802: 2003 test method. Table 1 gives the major chemical components, and Table 2 gives the tensile properties for the tensile tests along the 0°, 45° and 90° respected to the rolling direction. Figure 2 shows the tensile test specimens taken in transverse direction (TD) with tensile strains of 2.5%, 5%, 10%, 15% and 20%, respectively. Figure 3 shows the strain−engineering strain curve for each direction.

As known from Table 2 and Fig. 3, the pure titanium sheet has strong in-plane anisotropy. In other words, the yield stress (σ_y) and the anisotropy coefficient (R) of the pure titanium sheet increase significantly as the tensile axis rotates from the rolling direction to the transverse direction, whereas the elongation (δ) to the fracture decreases relatively.

On the other hand, as can be seen from the engineering stress−engineering strain diagram of Fig. 3, it can be seen that the nominal stress increases as the material is stretched in the 0° direction. However, in the case of the 45° and 90° direction, the stress gradually decreases with the deformation of the material after reaching the maximum load point. In the 0° direction, the occurrence of the local neck (marked as inverse triangular position in Fig. 3) begins at positions slightly past the maximum load point (strain of 0.37) and at 0.25 and 0.23 far beyond the maximum load point in the 45° and 90° directions, respectively.

Table 1 Main chemical components (mass fraction, %)

Oxygen	Hydrogen	Nitrogen	Carbon	Iron	Residual (max)
0.18	0.015	0.03	0.08	0.2	0.1 (0.4)

Table 2 Mechanical properties of pure titanium sheet

Tensile direction/(°)	Yield strength, σ_y/MPa	Tensile strength, σ_s/MPa	Total elongation, δ/%	Anisotropic coefficient, R
0	162.94	288.2	42.9	1.83
45	185.14	235.3	42.3	3.77
90	211.16	258.8	34.2	5.69

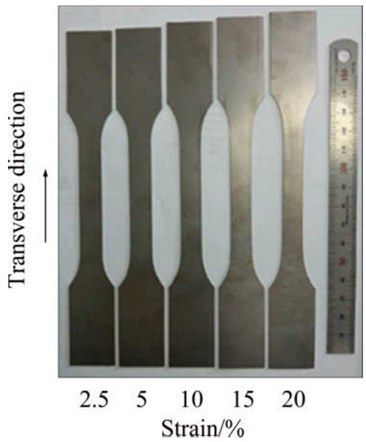

Fig. 2 Deformed shapes of TD specimens after various levels of tensile strain

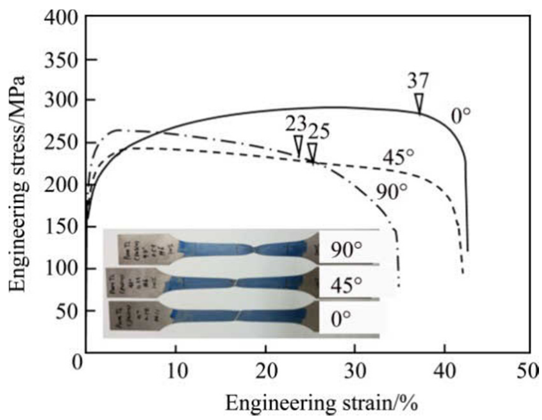

Fig. 3 Engineering stress−engineering strain curves of titanium sheet obtained from tensile tests