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Influence of different rolling routes on mechanical anisotropy and formability of commercially pure titanium sheet

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Abstract: Influence of three different rolling routes on mechanical anisotropy and formability of commercially pure titanium sheet was investigated. Route A and Route B are unidirectional rolling (UR) where the rolling direction is along initial rolling direction (RD) and transverse direction (TD), respectively. Route C is cross rolling (CR) where the rolling direction is changed by 90° after each rolling pass. The microstructure and texture, tensile mechanical properties including strength and elongation, and also the anisotropy of the UR and CR sheets were investigated at room temperature. The XRD results indicate that the texture intensity of rolled samples gradually weakens from Route A to Route C. Compared with Route A and Route B rolled samples, the Route C rolled samples show a smaller planar anisotropy. The deep drawing tests reveal that cross rolling can avoid the occurrence of earing. Erichsen tests indicate that rolling routes have an effect on stretch formability of pure titanium sheet.

Key words: CP-Ti; cross rolling; anisotropy; texture; deep drawing

1 Introduction

Titanium and titanium-based alloys have been widely used in various engineering and medical fields due to their high elastic limit-to-density ratio, high resistance to corrosion and good biocompatibility [1−3]. Consequently, many researches on pure titanium or CP-Ti have been done in the past decades due to its complex deformation mechanisms [4−6]. CP-Ti has a hexagonal close-packed (hereafter referred to as HCP) structure with a c/a ratio of 1.587, which is lower than the ideal c/a ratio (1.633). Consequently, compared with other HCP metals, the most favorable slip system in CP-Ti is prismatic $\langle a\rangle$ slip rather than basal $\langle a\rangle$ slip at room temperature. Though basal $\langle a\rangle$ slip and pyramidal $\langle a\rangle$ slip are potential slip systems [1,7,8], the $\langle a\rangle$ slip systems can only provide four independent slip systems. According to the von Mises criterion, at least five independent slip systems are necessary to accommodate arbitrary plastic strains, so $\langle c+a\rangle$ slip on pyramidal plane or deformation twinning are required to compensate for the insufficient slip systems [9,10−12]. Pure titanium, like most HCP metals, is characterized by highly anisotropic mechanical behavior at ambient temperatures [13,14]. The strong anisotropy in CP-Ti sheets is due to the strong crystal anisotropy of the HCP structure and the strong basal texture with c-axis tilted between 20° and 40° from the normal direction (ND) to the TD [15−17]. ROTH et al [18] discussed the possible mechanisms of mechanical anisotropy of α-titanium in tension conditions. Through compression tests, WON et al [19,20] revealed that deformation characteristics of high purity α-Ti with rolling texture were significantly dependent on the loading direction, i.e., deformation anisotropy.

It is well known that deep drawing is an important and popular process in sheet metal forming. Apart from

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its employment in electronics products, it is applied widely in the automotive industry for the manufacturing of car body parts [2,21,22]. The deep-drawn products of CP-Ti sheets are always accompanied with earing defects. The occurrence of earing, during the deep drawn process, is undesirable since extra processing is required to trim it, which will improve the costs of productions. Therefore, it is significant to make efforts to reduce earing during the deep drawing of CP-Ti sheets.

It is well established that the earing defect, during the deep drawing process, is primarily caused by the planar anisotropy of sheet metal. OHWUE and KOBAYASHI [23] found that the earing always occurs in 45° direction by experiment and simulation and the correlation between $\Delta R/R_{\text{ave}}$ and the average earring height is not always true.

It is common for CP-Ti to develop texture during the sheet rolling process, in which most grains exhibit their *c*-axis titling at about ±35° in the TD [15,16]. This is called preferred grain orientation, which will result in strong anisotropy in CP-Ti. Accordingly, the earing defect can be reduced by weakening the texture of the rolled CP-Ti sheets. It has been demonstrated by ZHANG et al [24,25] that CR is quite effective in reducing the mechanical anisotropy of magnesium alloy markedly by weakening the basal texture. TANG et al [22] have investigated the effect of UR and CR on mechanical anisotropy and deep drawing behavior of AZ31 magnesium alloy sheets. The experiment result on Mg−0.6%Zr (mass fraction) of XIONG et al [26] showed that compared with the UR sheets, the CR sheets exhibited a more uniform microstructure, larger grain size and weaker texture intensity. Above studies indicate that the anisotropy of the CP-Ti sheets might be also reduced by the CR. However, the literatures about CR applied on CP-Ti are rather limited. Therefore, the present work aims to systematically investigate the influence of three different rolling routes on the mechanical anisotropy and formability of CP-Ti sheets.

2 Experimental

As-rolled CP-Ti sheets with a thickness of 3 mm were cut into square samples with dimensions of 80 mm × 80 mm, then the square samples were subjected to annealing at 650 °C for 2 h before rolling. Three different rolling routes were conducted at a rolling reduction per pass of 0.15 mm. A schematic view of the applied rolling routes is presented in Fig. 1. Route A and Route B are UR where the rolling direction is along initial RD and TD, respectively. Route C is CR where the rolling direction is changed by 90° after each rolling pass. All samples were rolled from 3 mm to 0.9 mm in thickness. After the final pass, all specimens were annealed at 650 °C for 30 min.

The tensile specimens with 25 mm in gage length, 6 mm in gage width and 0.9 mm in gage thickness were machined from the annealed sheets with the longitudinal axis along RD of the sheets, 45° to rolling direction and TD in the sheet plane. Tensile tests were conducted using a CMT6305−300kN electronic universal testing machine, at room temperature with an initial strain rate of 3×10^{-3} s^{-1}.

In order to examine the influence of different rolling routes on the formability, deep drawing test and Erichsen test were performed. The circular blanks with diameter of 80 mm were machined from rolled sheets for the deep drawing test. Deep drawing tests were conducted at a punch speed of 5 mm/min. The blank holder force was 4.0 kN. Anti-wear hydraulic oil was used as the lubricant for deep drawing tests. The main dimensions of tools used for the deep drawing tests are as follows: punch diameter 50.0 mm; punch shoulder radius 5.0 mm; die hole diameter 51.8 mm, die shoulder radius 6.4 mm. The samples with dimensions of 50 mm × 50 mm were cut from rolled sheets for Erichsen tests. The Erichsen tests were conducted using a hemispherical punch with a diameter of 20 mm at room temperature. The punch speed was set to be 5 mm/min and the blank holder force was 10 kN. Anti-wear hydraulic oil was used as the lubricant. The Erichsen value was measured when the samples started to fracture.

The optical microscopy samples were treated by mechanical polishing and electro-polishing. The electro-polishing was performed under a controlled temperature of −40 °C using a voltage of 30 V for 60−90 s, and the

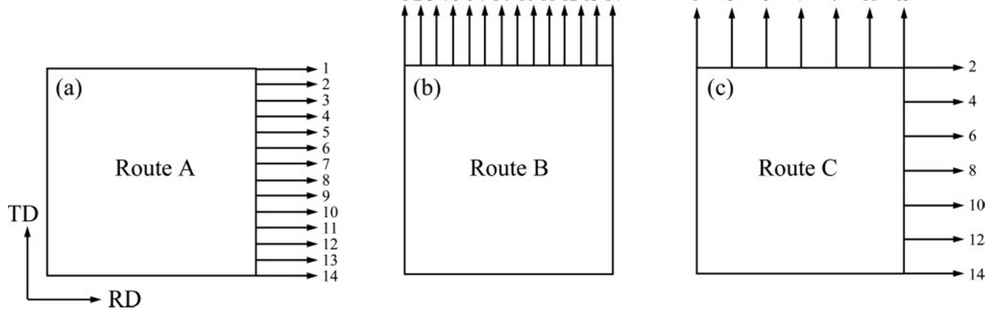

Fig. 1 Schematic diagram of three rolling routes: (a) Route A; (b) Route B; (c) Route C