Materials and Design 66 (2015) 618–626

Contents lists available at ScienceDirect

Materials and Design

journal homepage: www.elsevier.com/locate/matdes

Forming of high strength titanium sheet at room temperature

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ARTICLE INFO

Article history:
Available online 12 March 2014

Keywords:
Cold formability
Ti–6Al–4V
Forming limit diagram
V-bending
Roll forming
Springback

ABSTRACT

The forming behaviour of high strength Ti–6Al–4V alloy was studied at room temperature. Tensile tests and swing folding trials were performed to determine the mechanical properties and the minimum bending radius of the material. The forming limit diagram (FLD) was established and the springback behaviour of the Ti–6Al–4V analysed via V-die bending tests. The results show that the material has limited formability combined with very low material hardening and a high tendency to springback. This suggests that the stamping or deep drawing of Ti–6Al–4V at room temperature is not possible. Roll forming trials were performed and those show that the Ti–6Al–4V can be roll formed to simple longitudinal sections at room temperature. Improved formability was observed and the tendency to springback in roll forming was significantly lower compared to that determined in V-die bending. Additionally to that the Ti–6Al–4V showed a low tendency for shape defects commonly observed in roll forming due to its high material strength. This suggests that roll forming maybe a potential solution for the room temperature forming of high strength Titanium sheet to structural sections for the aerospace or automotive industry.

1. Introduction

The advantages of Titanium sheet such as its high specific strength, lightweight and high structural stiffness are becoming more recognised. High strength titanium alloys such as Ti–6Al–4V are therefore no longer only used in aerospace, but also have become a potential candidate for structural components in other industries including automotive [1] marine and the chemical industry [2]. Ti–6Al–4V sheet exhibits limited formability and high springback at room temperature and this causes significant issues with conventional forming methods such as stamping and press forming [3]. Although the forming limits can be improved and springback reduced by forming at elevated temperatures, manufacturing at room temperature is preferred to save on costs [4]. Roll forming allows the forming of structural components from materials that show high strength combined with limited formability and is increasingly used in the automotive industry for the forming of Advanced High Strength Steels (AHSS) and Ultra High Strength Steels (UHSS) [5,6]. In this process a metal strip is gradually formed via bending into the desired profile in successive roll stands [7]. Roll forming allows the forming of tighter radii [5] and leads to lower springback [8] compared to conventional bending; in addition springback compensation can be achieved with simple and flexible methods [9]. The process therefore represents a promising technology for the manufacture of structural parts from Ti–6Al–4V at room temperature. Previous research has mainly focused on the forming of Ti–6Al–4V at elevated temperatures [10,11] for conventional cold forming processes such as stamping [12] and tube bending [13]. Currently there is only a limited understanding of the forming behaviour and formability of Ti–6Al–4V at room temperature [3]. In the present work the material properties and forming limits of Ti–6Al–4V were investigated experimentally at room temperature via tensile and hemispherical stretch forming tests. Additionally to that roll forming and V-die bending trials were performed to analyse the material limits and springback behaviour of Ti–6Al–4V. The results of this study suggest that roll forming may be a potential forming technology for the production of low cost Titanium sections at room temperature.

2. Experimental work

2.1. Material

The Ti–6Al–4V investigated in this study is mill annealed (at 820 °C) cold rolled sheet stock with a thickness of 2.0 mm and the nominal chemical composition given in Table 1.

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http://dx.doi.org/10.1016/j.matdes.2014.03.008
0261-3069/

Table 1
Chemical composition of the Ti–6Al–4V determined by Optical Emission Spectrometry (OES).

Element	C	Si	Mn	Fe	Mo	Cr	Ni	Zr	Cu
%	0.037	0.015	0.0021	0.0341	0.0041	0.0032	<0.001	0.0017	<0.002
Element	Nb	Al	V	O	N	H		Ti	
%	0.035	6.01	4.15	0.02	0.02	0.002		Rest	

2.2. Microstructure analysis

The microstructure of the as- received Ti–6Al–4V sheet was investigated by scanning electron microscopy (SEM).The specimens were sectioned at angles 0° and 90° to the rolling direction. After this the grinding process was performed using 240, 600, 1200 and 4000 grit SiC papers. The specimens were then polished according to ASM standard procedure [14]. A SEM based angular selective backscattered (SEM-AsB) imaging technique was employed for the microstructure characterization using a field emission scanning microscope (FE-SEM; Zeiss – SUPPRA 55-VP). The average grain size was measured using a linear intercept method and the volume fraction of the constituent phases was determined.

2.3. Uniaxial tensile test

A 100 KN Instron was applied to perform the tensile test at room temperature according to Australian Standard AS 1391-1991 [15]. Specimens oriented 0°, 45° and 90° to the rolling direction were cut. The sample gauge length was 50 mm and a non–contact extensometer was used to measure the engineering strain. A cross–head speed of 2 mm/min was used and at least three tests performed for each specimen orientation. To describe the tensile behaviour, the Hook's law (Eq. (1)) and the Swift (Eq. (2)) hardening equation were fitted to the true stress–strain (σ–ε) data for each sample direction tested [16].

$$\sigma_e = E\varepsilon_e \tag{1}$$

$$\sigma_y = K(\varepsilon_0 + \varepsilon_p)^n \tag{2}$$

In above equations E is the Young's modulus, K the linear hardening parameter, n the hardening coefficient, ε_0 the strain offset constant, ε_e the equivalent elastic strain and ε_p the equivalent plastic strain.

2.4. Forming limit diagram

Stretch forming tests with a hemispherical punch were carried out on an Erichsen testing machine at room temperature to determine the Forming Limit Diagram (FLD); the test set up is shown in Fig. 1.

Due to the limited amount of material available a punch diameter of 60 mm was used; this is lower than recommended in the ISO standard [17]. An optical strain measurement system

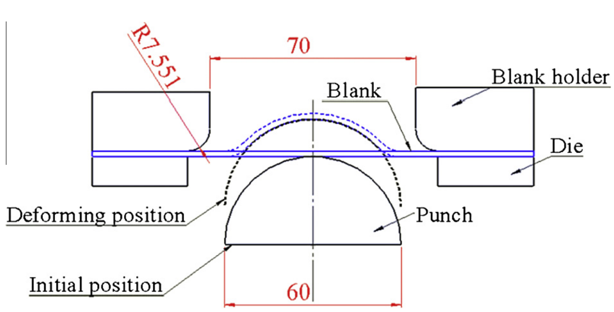

Fig. 1. Schematic diagram of the tool setup used in the stretch forming test.

"Autogrid Vario" [18] equipped with four progressive scanning CCD cameras was employed to record the complete deformation history of each specimen. The material was screen printed with a square grid of 2 mm and specimens of various shapes (Fig. 2) were formed to test a range of different strain paths.

To reduce the friction at the interface between the specimen and the punch, a sandwich construction of mineral lubricant together with two polypropylene (PP) films was used, similar to that used by Weiss et al. [19]. During the tests the specimens were placed on the bottom die, aligned accordingly, and then clamped on their edges with a blank holder force of 225 KN. The specimens were formed with a constant punch speed of 0.1 mm/s until cracking occurred. Three replicates were performed for each set-up. The deformation of the square grids during testing was evaluated using the Autogrid Vario optical strain measurement system at a frame frequency of 3–5 pictures per second. The major and minor forming strains were determined for each frame over a section cut that was oriented perpendicular to the direction of the crack (Fig. 3a and b).

The forming limit strains are defined as the forming strains at the onset of necking indicated by an increase in strain gradient $F(x)$ calculated using:

$$F(x) = \frac{f(x+h) - f(x)}{h} \tag{3}$$

where h represents the interval distance between two major strain points on the graph $f(x)$ (Fig. 4a). To determine the onset of necking the true major strain $f(x)$ and the gradient of true major strain $F(x)$ were plotted as a function of the cross section length x for different test time delays Δt before fracture (Fig. 4a and b).

A slight increase in strain and strain gradient can be observed at "Δt = 33 sec" and at a cross sectional length of "x = 30 mm" and this indicates the onset of necking. The FLD was obtained by constructing a line connecting the major and minor strain values determined for all samples at the onset of necking. Previous studies have shown that stretch forming tests over hemispherical punch can lead to errors in FLD analysis due to the effect of the punch curvature. Charpentier showed experimentally that the forming limit strains increase with increasing punch curvature [20]. Shi and his co-worker found that the forming limit strains determined by stretching over a punch are generally higher compared to those analysed via in plane stretching and related this to strain gradients that result from the bending of the flat blank into a curved blank when formed over the punch surface [21,22]. The effect of punch curvature can be corrected for by subtracting the amount of strain that is due to bending from the measured true strains at the convex side of the specimen [23]. If a sheet is bent from flat to a particular curvature of radius R its convex surface undergoes a combined loading of stretching and bending; the measured true strains (major and minor), ε_m at any point on the curved surface can be written as:

$$\varepsilon_m = \varepsilon_{streching} + \varepsilon_{bending} \tag{4}$$

The true bending strain at a point on the convex surface distanced $y = t/2$ from the middle surface of radius R_n can be expressed as follows [16]:

$$\varepsilon_{bending} = ln\left(1 + \frac{t_f}{2R_n}\right) \tag{5}$$