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Effect of the forming method on part shape quality in cold roll forming high strength Ti-6Al-4V sheet

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ABSTRACT

High strength titanium alloy sheet, in particular Ti-6Al-4V, is used for structural applications; roll forming has been found to be an appropriate cold forming process for the manufacture of long components in Ti-6Al-4V. Roll forming Ti-6Al-4V at room temperature requires extensive FEA-assisted process development and optimisation to keep springback and part shape defects to a minimum. Currently the material behaviour of Ti-6Al-4V in the roll forming process is not well understood. Two major roll forming approaches, the constant bend radius and the constant arc length method, are used in roll forming but the effect of each approach on springback or final part shape in high strength sheet materials such as Ti-6Al-4V is not well documented. A fundamental understanding of this will enable rapid and reliable process design for the cold roll forming of high strength titanium alloys.

The primary aim of this study is to explore the potential use of different roll forming methods to reduce springback and part shape defects in the cold roll forming of Ti-6Al-4V sheet and to develop a deeper understanding of the material behaviour of Ti-6Al-4V in the process. For this, experimental roll forming trials and their simulation are performed and a novel constitutive material model based on the homogeneous anisotropic hardening (HAH) approach is used to represent the forming behaviour of Ti-6Al-4V under cold forming conditions. The experimental and numerical results indicate that the constant radius forming method leads to fewer shape defects in the process and reduced springback. A detailed discussion is provided explaining in part the observed trends.

1. Introduction

High strength titanium sheet such as Ti-6Al-4V offers desirable characteristics such as high specific strength and structural stiffness with excellent heat and corrosion resistance [1]. Ti-6Al-4V is increasingly used in aerospace [2], marine [3] and automotive industries [4] but given its high strength and limited formability it generally has to be formed at elevated temperature which results in high manufacturing costs [5]. Recently Badr et al. [6] experimentally showed that Ti-6Al-4V sheet could be cold roll formed; in this process, a metal strip is gradually formed into the required profile by passing it through a series of contoured rolls. The same study also revealed that roll forming Ti-6Al-4V at room temperature creates challenges in the controlling of springback and part shape defects. At present, there is only a limited understanding of the behaviour of Ti-6Al-4V in cold roll forming.

Springback in roll forming has been found to be lower compared with that in simple bending operations and this has been linked to the incremental nature of the process [7] and to the effect of redundant deformation [8]. Springback in roll forming increases with material strength [9], the ratio of the bend radius to the sheet thickness [10] and decreasing elastic modulus of the material [11]. There is also an effect of the process and tooling design and recent studies suggest that springback in roll forming decreases with the number of forming passes used [12].

In roll forming, the material fibers at the strip edges travel a longer distance than those in the web leading to longitudinal edge strain [8]. If this strain exceeds the elastic limit of the material, shape defects such as edge ripple, bow and twist result. Previous studies suggested that the likelihood of permanent longitudinal deformation in the strip edge reduces with increasing material strength; this leads to reduced forming defects in form of bow when forming higher strength steels [13,14] or high strength Ti-6Al-4V titanium compared with softer sheet metal. Additionally, longitudinal edge strain depends heavily on the component geometry and generally decreases with increasing flange length of the

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Table 1
Mechanical parameters and anisotropy coefficients of Ti-6Al-4V at room temperature [19,21].

θ°	E [GPa]	ε_0 $\left[mm/mm\right]$	$\sigma_{0.2\%}$ [MPa]	$\sigma_{U.T.S}$ [MPa]	H [MPa]	n	Uniform elongation[%]	r-value
0	104	0.0115	1018	1176	1346	0.06	9.22	2.82
45	107	0.0104	993	1055	1116	0.03	10.13	4.15
90	112	0.0107	1083	1170	1265	0.04	8.56	3.35

Table 2
Anisotropy coefficients of the non-quadratic YLD2000-2D for Ti-6Al-4V at room temperature [19,21].

YLD2000-2D	M	A_1	A_2	A_3	A_4	A_5	A_6	A_7	A_8
	12	1.106	0.907	1.110	0.944	0.944	0.991	1.070	0.909

Table 3
Constitutive hardening parameters of the HAH model for Ti-6Al-4V determined with the inverse analysis at room temperature [19].

q	k	k_1	k_2	k_3	k_4	k_5
2	30	150	95	0.25	1.0	5.0

part [15]. Process parameters have a large effect and longitudinal edge strain reduces with an increasing number of forming stations used and less forming angle formed per pass [16]. Depending on the material and the resulting forming length [17], edge strain also has been shown to decrease with increasing distance between forming stations [18].

In roll forming, two forming methods are commonly used; the “constant arc length” and the “constant bend radius method” [8]. Schematics of both roll forming methods are given in Fig. 2 below. In the first, the metal strip is deformed keeping the profile arc length of the bend constant in all stations while progressively bending to the final radius. In the second approach, in each forming station only a small length of the arc is bent to the final radius in each pass. The first method results in an overall shorter flange length during forming and a wider bending region which may improve springback and longitudinal edge strain in the process. This possibility has not been explored before and the current work will investigate the potential of reducing springback and bow in the roll forming of Ti-6Al-4V by finding an optimised forming method. To investigate this, extensive numerical and experimental analysis is performed using a newly developed HAH model in combination with the Barlat 2000 yield surface to account for kinematic hardening effects and material anisotropy.

2. Material

A Ti-6Al-4V sheet of 2.0 mm thickness and a microstructure composed of approximately 94% volume fraction of hexagonal close-packed (hcp) α phase and of 6% ± 0.6 body-centered cubic (bcc) β phase, with an average grain size of 1.3 ± 0.7 μm was selected for the current study. The material was received as mill annealed (at 820 °C) cold rolled sheet. The nominal chemical composition and detailed information with regard to the microstructure and mechanical properties at room temperature are given in [6]. The hardening characteristics of the Ti-6Al-4V in cyclic pure bending and tension- compression were analysed in a previous study and are explained in detail in [19]. The following sub-sections therefore will only summarize the main procedures used for each test.

2.1. Uniaxial tensile and anisotropic properties at room temperature

The tensile stress – strain behaviour and anisotropic coefficients (r-values) of Ti-6Al-4V were taken from previous work [6,19]. There, specimens oriented in 0°, 45° and 90° to the rolling direction (RD) were tested using a 100 kN tensile tester and tensile properties measured following the Australian Standard AS 1391–1991 [20]. The mechanical properties determined this way and fitted with the Swift power law (i.e., $\bar{\sigma} = H(\varepsilon_o + \bar{\varepsilon})^n$) are summarized in Table 1 with the strength coefficient H and the strain hardening index n. The yield stress, $\sigma_{0.2\%}$ was determined using the 0.2% offset strain method.

2.2. Constitutive material hardening behaviour for FEA

2.2.1. Review on the constitutive material model for Ti-6Al-4V

Recently, Badr et al. [21] presented a constitutive model that enables the prediction of the forming behaviour of Ti-6Al-4V in bending dominated forming processes such as roll forming at room temperature. A constitutive equation was proposed based on the experimental results obtained by Badr et al. [21] where the yielding behaviour of Ti-6Al-4V is represented by the anisotropic YLD2000-2D yield function optimized with an exponent of M = 12. This yield locus was then integrated into the homogeneous yield function based anisotropic hardening model, the so- called HAH model proposed by Barlat et al. [22], as a stable function. The evolution of the distortional hardening behaviour of Ti-6Al-4V which results from continuous loading path changes (strain path reversals) and pre-deformation is captured at the continuum level by a fluctuating function embedded in the HAH model according to Barlat et al. [22]. A detailed description of the elasto - plastic finite element formulation as well as the numerical implementation with the material user subroutine “UMAT” for the proposed Ti-6Al-4V constitutive model combined with the YLD2000-2D (M = 12) and the fluctuating function can be found in [21]. The HAH model is applied in the FEA simulation of the roll forming process of this study (Section 4) to numerically investigate the effect of the roll forming strategy (constant length of neutral line and the constant bend radius forming method) on the forming behaviour of Ti-6Al-4V at room temperature. In the next Section the identification of the constitutive material hardening parameters for the HAH model are briefly described.

2.2.2. Determination of the constitutive hardening parameters

In order to describe the quasi-static deformation behaviour of Ti-Al-4V at room temperature several sets of material coefficients are required according to [22]. The determination of those coefficients was described in detail in previous work [19] but a brief review is presented in this section. The anisotropy coefficients ($A_1 \rightarrow A_8$) that are required for the evolution of the optimized yield locus of Ti-6Al-4V were determined using the non-quadratic YLD-2000-2D (M = 12) as given in Table 2.

The material parameters required for the constitutive hardening evolution were determined along the transverse direction (90°) since this direction is of interest for the roll forming process where the major deformation mode is that of transverse bending. A Young’s modulus of 92 GPa and a Poissons’s ratio of 0.365 were used [19].The isotropic hardening behaviour was defined with the Swift equation ($\bar{\sigma} = H(\varepsilon_o + \bar{\varepsilon})^n$ and the parameters are given in Table 1. The FE- code formulation developed in [21] was integrated into Abaqus Standard using a “UMAT” subroutine. The evolutionary