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Full Length Article

Experimental and numerical analysis of industrial warm forming of stainless steel sheet

Tomasz Trzepiecinski[a,*], Tomasz Malinowski[b], Tomasz Pieja[b]

[a] Department of Materials Forming and Processing, Rzeszow University of Technology, Al. Powst. Warszawy 8, 35-959 Rzeszów, Poland
[b] Pratt & Whitney Rzeszów S.A., ul. Hetmańska 120, 35-078 Rzeszów, Poland

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ABSTRACT

In this paper, the development of the industrial forming process of drawpieces is investigated experimentally and numerically. The drawing process presented in this work was achieved with a form of 17-4PH stainless steel sheet with a sheet thickness of 1 mm. Due to the high ratio of yield stress to ultimate tensile strength and large amount of springback of the formed material, to ensure that the shape and dimensions of drawpiece are suitably accurate, the forming process is divided into two stages: forming of the drawpiece using a rubber punch and calibration of the drawpiece at elevated temperature. A 3D finite element (FE) coupled thermo-mechanical model was built using the commercial FE-package eta/DynaForm 5.9.3. This package allows physical models of real processes to be analysed, placing special emphasis on nonlinear material behaviour, large deformations, and complex friction phenomena. The distribution of the drawpiece shape error obtained by the GOM ATOS system and thickening measurements confirmed that the developed methodology is suitable for industrial manufacture of bearing housings for aircraft fan engines.

1. Introduction

The sheet metal forming is a process in which the sheet metal blank is plastically deformed into a 3D shape by the application of forces without much change in sheet thickness. The forming forces cause stresses in the sheet blank, influencing the thickness of the drawn part, which varies in different parts of the drawpiece. The main sheet metal forming processes are deep drawing, bending, and flanging. Sheet forming processes are widely used to manufacture geometrically complex parts in many industries such as the automotive, chemical, nuclear, aircraft, and machine building industries [1,2].

Stainless steels are iron-based alloys that contain a minimum of approximately 11% chromium (Cr); this content is important as it is needed to create a passivating layer of chromium-rich oxide to prevent rusting on the surface [3]. Stainless steels are classified into four families. Three of these are based on their crystallographic structures, namely austenitic, duplex (ferritic-austenitic), and martensitic. The fourth group is based on the type of heat treatment used in the manufacturing process and is called precipitation-hardenable (PH). Precipitation hardening is defined as hardening caused by the precipitation of a constituent from a supersaturated solid solution [3]. These materials are essentially nonmagnetic in the annealed condition and can be hardened only by cold working. The non-magnetic properties combined with exceptionally high toughness at all temperatures make these steels an excellent choice for aircraft applications [4].

Stainless steel alloys have low proportionality limits and extended strain-hardening capability [5]. The forming temperature is one of the basic parameters in materials-processing technologies. Forming of materials at room temperature ($T < 0.35\,T_m$, where T_m represents the metal melting temperature) takes advantage of strain hardening to increase the strength of the material under the penalty of higher forming forces, while hot forming ($T > 0.55\,T_m$) lowers the yield stress and allows simultaneous recrystallization, which controls the grain size refinement [6]. To avoid high temperatures and forces, warm forming ($0.35\,T_m < T < 0.55\,T_m$) is used, which makes it possible to increase the material formability without recrystallization. Enhancement of formability allows a higher maximum possible deformation to be reached in a single step, and hence parts of larger depth or complex geometry can be formed [1]. This reduces the number of production steps and increases productivity, and in many cases it is necessary in order to obtain parts with the desired geometry. A suitable choice of forming temperature and its stabilization in a possible limited range determines the quality of the formed elements. Despite an intensive increase of the

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* Corresponding author.
E-mail addresses: tomtrz@prz.edu.pl, tomasztrz@wp.pl (T. Trzepiecinski).

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use of warm forming methods in many areas of industry, there is still a need for research on determining the appropriate treatment temperature and its effect on the mechanical properties and formability of the material. With regard to sheet metal forming processes realized under warm conditions, the investigations are focused on identifying the forming limit diagrams [1,7], mechanical properties, and forming parameters of many kinds of alloys (i.e., [1,8,9]). The forming limit curve has been commonly used to evaluate the formability of sheet metals and to diagnose production problems in the sheet metal forming of stainless steel [10].

In sheet metal forming industries, the prediction of springback is one of the most important technical issues. Springback is the main source of both dimensional and shaped inaccuracy of drawpieces [11,12]. The change in the shape of formed elements is a result of relaxation of internal stresses after unloading [13]. The effect of the temperature on the springback of a stainless steel sheet under warm forming conditions has been studied by Stachowicz et al. [6]. Investigations conducted by Carden et al. [14] have demonstrated the effect of friction on the value of the springback of sheet metal. In the last few decades, springback has been successfully predicted by using numerical modelling [15,16]. Lee et al. [17] presented the importance of modelling the Bauschinger effect in springback prediction through comparisons of simulations and experiments on several sheet stamping problems. Yoshida and Uemori [18] also concluded that since bending and subsequent springback comprise a process of typical forward/reverse elastic-plastic deformation, for accurate simulation of springback, it is necessary to take into account the Baushinger effect and to select the appropriate material model. The effect of normal anisotropy on the springback value is analysed by Verma and Haldar [15]. Finite element (FE) analysis has shown that springback is lowest for an anisotropic material.

An accurate description of the stress–strain behaviour and anisotropic properties of stainless steel is essential for accurate numerical simulation of the forming process. Plastic anisotropy is the result of the distortion of the yield surface shape due to the material's microstructural state and can be classified into two types: *normal* and *planar anisotropy*. In normal anisotropy, the properties differ in the thickness direction; in planar anisotropy, however, they vary with the orientation of the plane of the sheet [19]. The stainless steel material is characterized by a nonlinear stress–strain curve that differs from that typically exhibited by hot-finished carbon steel but shows similarities with other construction materials such as cold-worked steel and aluminium [20]. The most widely used material models for the description of stainless steel behaviour are based on the general expression originally proposed by Ramberg and Osgood [21] and modified by Hill [22].

The behaviour and formability of stainless steel sheet during warm forming have been the subject of a number of investigations. The formability of austenitic and ferritic stainless steels at a warm forming temperature has been studied by Bong et al. [23]. Takuda et al. [24] performed warm cup drawing experiments on an austenitic stainless steel and examined the distribution of martensite content in the specimens after the tests. Stachowicz et al. [6] studied the effect of the forming temperature on the mechanical properties of an AMS5604 stainless steel. Iguchi and Ujiro [25] investigated the effect of the temperature gradient on the stretch-formability of ferritic stainless steel in stamping.

The frictional behaviour in warm sheet forming depends on several parameters such as the contact pressure, sliding velocity, tools, and sheet surface roughness as well as the lubricant conditions. When two smooth metal surfaces are brought into contact, asperities, or high points, and not the nominal areas are in contact. Under static loading, deformation of the asperities occurs until the real contact area increases to support the load [26]. One of the major problems in forming of stainless steel sheet is galling of tools due to lubricant film breakdown, leading to scoring and bad surface quality [27]. The galling mechanism affects the value of frictional resistances and surface quality of the final product. Galling initiation in lubricated sheet metal forming processes can be avoided by the application of smooth tool surfaces with enhanced thermal conductivity and lubricants which form boundary layers with a high critical temperature [28]. A high surface finish of the forming tool, that is, Ra < 100 nm or better, is a prerequisite for avoiding or decreasing the risk of galling [29]. Additionally, a significant decrease of friction has been found by Borsetto et al. [30] when using carbon as a solid state lubricant.

Table 1
Chemical composition of 17-4PH stainless steel sheet (wt.%).

Element	C	Cr	Ni	Mn	Si	Mo	Nb
Content	0.07	16.5	4.0	1.00	1.00	0.5	0.30

Fig. 1. The fan engine bearing housing.

In this paper, the development of the industrial forming process of the drawpiece is investigated experimentally and numerically. The formed element is made of stainless steel 17-4PH. Taking into account the low formability of this material at ambient temperature and high springback, a two-stage forming process is developed. Firstly, the blank is formed at ambient temperature using a rubber punch. Finally, the drawpiece is calibrated at elevated temperature.

2. Experimental

2.1. Material

The fan engine bearing housing is made of martensitic precipitation-hardening 17-4PH stainless steel sheet with a nominal thickness of 1.00 mm. The chemical composition of the tested sheet is presented in Table 1. A tensile test according to EN ISO 6892-1:2009 [31] was carried out on a universal testing machine to determine the mechanical properties of the sheet. The properties determined in this test are the yield stress σ_y, ultimate tensile strength σ_u, elongation A_r, and anisotropy coefficient r. The strength coefficient K and strain hardening exponent n are determined based on the approximation of true stress. Those −strain relation using the Hollomon function, $\sigma_y = K\varphi^n$, where φ is the true strain. Dog-bone samples were cut from the annealed sheets at 0°, 45°, and 90° with respect to the rolling direction. Five samples were tested at each temperature and the average values of basic mechanical parameters were determined.

2.2. Drawn element

The aim of the investigations was to develop the technology for manufacture of a fan engine bearing housing (Fig. 1) that will