



On the role of the residual stress state in product manufacturing



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ARTICLE INFO

Article history:

Received 26 March 2016

Received in revised form 21 May 2016

Accepted 23 May 2016

Available online 24 May 2016

Keywords:

Residual stress

Stress relaxation

Creep

Shape change

Metal forming

AISI 420

ABSTRACT

This paper concentrates on the effect of the residual stress state during product manufacturing of AISI 420 steel on the final shape of the product. The work includes Finite Element (FE) calculations of the distribution of the residual stresses after metal forming and a heat treatment. The evolution of the residual stress state is predicted employing a creep model which was calibrated through creep experiments ranging between 500 and 700 °C. The creep model is implemented in the FE software together with material specific parameters to simulate a thermal treatment of the product including residual stresses. The complete simulation is validated by a comparison of the predicted shape change with the actual cold-formed and hardened product. An important message of this paper is that, in contrast to what is commonly believed, residual stresses play a crucial role during creep and that a shape change may occur at lower temperatures, i.e. not at higher temperatures and in fact below the transformation temperature in this AISI 420 steel. This surprising conclusion is essential for keeping the shape change during product manufacturing minimal.

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1. Introduction

Modern consumer products need high precision metallic parts so as to meet the quality demands of costumers. However, the manufacturing process of high precision components suffers from a large number of complexities, i.e. the components typically have demanding geometric specifications in three dimensions and other critical-to-quality requirements, such as hardness, surface roughness and density [1–3]. Commonly used consecutive processing steps include metal forming so as to achieve the desired shape and followed by a heat treatment to obtain the required mechanical strength. In general the heat treatment makes the shape of the product less accurate. In this contribution we concentrate on the influence of the residual stress state on the shape change during hardening of a cold formed product. It is emphasized that this paper does not have the intention to measure the precise quantity of residual stresses but rather to demonstrate its influence on the combination of product and shape change.

It should be realized that in practice the complete product manufacturing consists of shaping operations (i.e. forming), heat treatments, finishing operations and assembly. When martensitic chromium steel is used as a base material, the most critical step lies in the middle of the production chain, i.e. the hardening of the steel. Here, residual stresses introduced by forming may cause plastic deformation during

hardening. However, the material is commonly known to produce little shape change during the hardening because in most applications the material is already made stress-free prior to a heat treatment. Obviously, fewer finishing processes are needed when after the hardening the product is already more accurate in shape. A reduction of the finishing processes increases the production efficiency and therefore lowers the fabrication costs. As a consequence there is a strong need to simulate the shape of the components through the various processing steps so that the consequence of any modification of the production process can be predicted in advance. Also novel products can be tested thereby decreasing the design-to-product time.

For the aforementioned hardening, a thermic driven process which should not be confused with work hardening, the typical austenitization temperature for martensitic stainless steel ranges between 925 and 1065 °C for 30 to 90 min [4]. After forming by cold work, which could include stretching and bending, the material has a high residual stress state [5]. In general we may say that there are three mechanisms responsible for the relaxation of residual stresses [6]: (i) At lower temperatures creep mechanisms (diffusional and dislocation creep affected by grain size) allow areas of tensile and compressive stresses to contract or expand; (ii) At high temperatures the yield strength decreases, promoting strain relieve through dislocation glide and dislocation creep mechanisms; and finally (iii) precipitation and ageing effects may lead to volumetric changes that can also relax the residual stress state. We should emphasize that in many circumstances it is a combination of processes and various relaxation mechanisms which may operate at the same time. When diffusional creep (Nabarro–Herring, Coble) occurs

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at low temperature it is still active at high temperature where dislocation creep and dislocation glide maybe become operational depending on the stress state, i.e. the ratio between then effective stress state and the temperature dependent shear modulus.

Several authors have investigated various aspects of the heating cycle: i.e. calculation of internal stresses during martensite forming [7], FE modeling of residual stress [8,9] and stress relaxation [10] during quenching; high temperature deformation [11] and the evolution of distortions during quenching [12]. Surm et al. [13] noticed the importance of the residual stress state during heating, attributing stress relieve to plastic deformation due to the decrease of the yield strength at high temperatures. Relaxation of residual stresses with a creep model has been shown in [14,15], however no predictions for shape change have been done and that is the novel contribution in this paper.

In general, shape change of steel during a hardening treatment is attributed to the transformation induced stress or thermal stress [7,16,17]. But, little attention is paid to the role of residual stresses in the shape change at the lower temperatures of the heating cycle. In this paper we will in particular focus on the contribution of the low temperatures heating region to the overall shape change during hardening and the role of residual stresses.

In this paper a novel approach will be proposed to predict and validate the shape change during a hardening treatment of a metal formed product in 3-Dimensions. The overall idea is that forming of a metallic product induces inhomogeneous strains resulting in residual stresses. The latter are calculated by using the commercial Finite Element (FE) software package 'Marc'. The residual stress distribution is obtained by making a comparison between the simulated work hardening with the hardness profile of the product.

Key in the simulation of the heat treatment step is the assumption that the residual stresses leads to creep and that the creep strains may predominate the shape change of the product. A creep model is calibrated in single creep experiments to predict creep strains below the austenitization temperature, and implemented in the FE calculations. The accuracy of the model is evaluated by making a comparison with the shape of a product in reality.

2. Experimental procedure

The material under investigation is a cold rolled steel strip of martensitic stainless steel of class AISI 420 with chemical composition as listed in Table 1. The product is fabricated using cold forming by deep drawing. Its shape is characterized by measuring the flatness of the bottom of the cup. This bottom flatness is determined along the circular track indicated in Fig. 1. The height profile of small domains (in the z-direction) on this track was measured with confocal microscopy, completed with a fit through the average of many neighboring domains. The shape change in the product during heating is monitored by measuring the bottom flatness before and after the hardening. (See Table 2.)

The FE calculations of the forming assume planar anisotropy (Hill 1948 [18]) and a dislocation work-hardening description (see [19]). Due to the anisotropy in the material the residual stress state will also become inhomogeneous.

The calculation for the shape change during heating includes: elasticity, thermal expansion, plasticity, and creep. The assumption here is that the various shape changes can be added linearly to the total strain, with the same global stress acting on the various individual elements. Consequently, the underlying constitutive equations for a specific mechanism can be determined individually. Hence the combined total

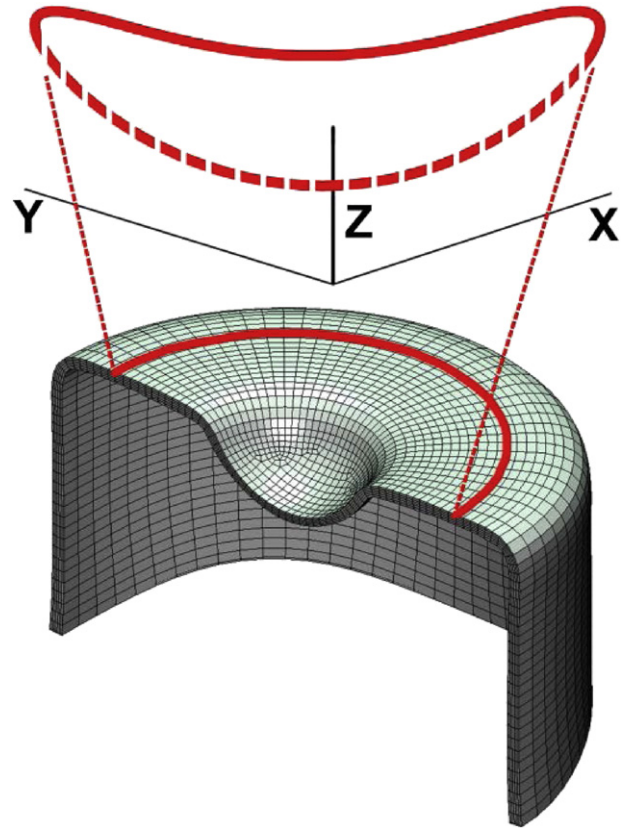


Fig. 1. Cross section of a deep drawn cup with a radius (red line) on the bottom where the z-values are measured. Top: 3D line indicating the shape change in the z-direction.

strain rate equation is written as the sum of elastic strain rate, thermal strain rate, plastic strain rate and creep strain rate:

$$\dot{\epsilon}_{tot} = \dot{\epsilon}_{elastic} + \dot{\epsilon}_{thermal} + \dot{\epsilon}_{plastic} + \dot{\epsilon}_{creep} \quad (1)$$

and all contributions to the total strain are found by integration of the various strain rate contributions over time in the subsequent order, i.e. first elastic plastic behavior followed by thermal strain, plastic strain and finally the creep strain. The description of the constitutive equations can be found in [20]. For the FE simulation of the deep-drawing (at room temperature), Eq. (1) reduces to: $\dot{\epsilon}_{tot} = \dot{\epsilon}_{elastic} + \dot{\epsilon}_{plastic}$. This initial residual stress state is further evaluated during the heating stage. The creep rate relation used in this work is only depending on temperature and stress, and can be calculated separately. By evaluating the decrease of the residual stress state due to creep strain, it can be observed that the residual stresses stay below the yield point during the heating stage. Therefore the contribution of the plastic strain is not taken into account in this trajectory.

Since creep forms an important phenomenon in our work a brief summary of the equation used in the following is given here. Strain

Table 1
Chemical composition of AISI 420 class of martensitic stainless steel (wt.%) [38].

C	Cr	Si	Mn	P	S	Fe
Min. 0.15	12–14	1	1	0.04	0.030	Bal.

Table 2
Experimentally obtained values for the functional set of variables n , Q_c and A of the creep model (see Eq. (2)) in the temperature range 500–700 °C.

	500 °C	600 °C	700 °C	500–600 °C	600–700 °C
n	2.1	5.4	5.3	$-23 + 0.033 * T(K)$	$-6.6 - 0.001 * T(K)$
Q_c				57 kJ/mol	141 kJ/mol
A				$-123 + 0.16 * T(K)$	$-12 + 0.008 * T(K)$

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