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Product shape change by internal stresses

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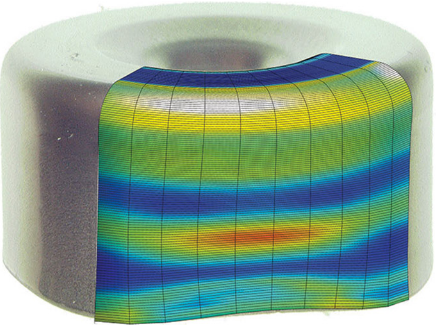
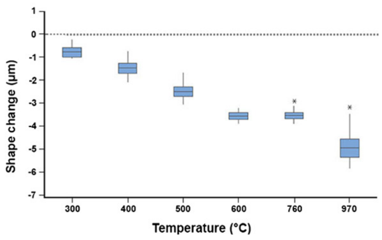
HIGHLIGHTS

- The predictability and accuracy of the shape changes in the product design
- Coupling between forming and thermal treatment
- Processing steps of forming and thermal treatment are successfully implemented in the Finite Element computer code.

GRAPHICAL ABSTRACT





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ABSTRACT

The design of a product component may require complex processing steps such as metal forming followed by a thermal treatment. The thermal treatment may improve the functional performance of the material itself, but may result in rather unwanted changes in the shape of the product. Here it is shown that Finite Element modeling of the various processes can assist in the design of a robust and accurate production process. The modeling approach presented allows a coupling between various complex material models, in such a way that full cold forming and thermal treatment processes are calculated. This coupling of material models is key for the design and concerns the novelty of the proposed approach. Cold forming by deep drawing is calculated whereby planar anisotropy is implemented. The thermal hardening treatment consists of three contributions: creep, thermal expansion and phase transformation. All models are based on experimental data, acquired from tensile and dilatometer tests, and are implemented into the material model either directly or by a simple fit. It is shown that the effects of a complete forming and heat treatment of a cup could be successfully calculated. The predicted cup shape change was compared to experiments, and shows excellent agreement.

1. Introduction

Miniaturization and net shaping are the trends in manufacturing of consumer products, electronics and automotive, resulting in narrower tolerances for smaller products and more stringent requirements. As a result, the manufacturing process of high precision components suffers from an ever increasing number of complexities, i.e. the components become geometrically more demanding by specifications in three dimensions. Other critical quality requirements such as hardness, surface roughness and density [1–3] have to be produced within narrower specification limits. To keep up with this trend, the development cost of new products as well as the development time of new products have to be reduced. This can be achieved by increasing the predictability

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of production processes by Finite Element (FE) analysis. The advantage of this numerical analysis is the ability to model complex forming processes. In contrast, the downside of FE analysis is the complexity in preparing input data from experimental results and selection of meaningful output variables.

For the fabrication of high precision metallic parts martensitic high chromium steels are often used. This class of stainless steel is soft in the as-received ferritic phase and therefore a preferred material for complex forming operations. The required hardness is achieved by a thermal hardening treatment, which should not be confused with work hardening. The thermal hardening treatment includes heating up to a temperature of 925 to 1065 °C to transform the ferritic phase into austenite [4], followed by quenching (air cooling is sufficient for this material) to room temperature, to promote the formation of the much harder martensite phase. Although this hardening heat treatment is used to improve the mechanical properties of the cold-formed ferritic product, it comes often at the expense of the shape. If the shape can be maintained and controlled during forming and hardening, the sequential finishing and assembly steps can be a less costly as well as a more energetically efficient process.

Product forming operations as deep drawing, which include stretching and bending, introduce a high residual stress state [5]. Residual stresses arise from the natural shape between different regions, parts or phases [6,7]. These stresses can be measured by destructive techniques such as sectioning, contour, hole-drilling, ring-core and deep-hole [8] through the release of residual stresses upon removal of material from the specimen [9], either on a macroscopic scale or at a local scale [10,11]. Non-destructive methods as X-ray or neutron diffraction [6,12–14], ultrasonic methods and magnetic methods, usually measure a microstructure stress-related parameter [6,9]. The effect of residual stresses on shape changes has been investigated with FE, but focused on individual process steps: during cold forming by finite element modeling [15,16], phase transformation [17] and quenching [18,19].

However, as the individual processes are studied in depth, there is a gap for coupling the dedicated individual models. The aim of this study is to calculate and predict the shape change based on interaction between phenomena rather than presenting a detailed constitutive modeling of the individual material phenomena. The shape change during the thermal treatment calculated with the FEM approach is compared with measurements of the geometry of the real product.

2. Experimental and modeling procedure

The material used in this investigation is a cold rolled strip of the martensitic stainless steel of class AISI 420 with the chemical composition as shown in Table 1.

The studied cup shaped products were fabricated using cold forming, following the design rules and procedures described in [21]. A disk of metal (the blank) is placed in a die with a hole in the middle. The hole is about half the diameter of the disc. The blank is pushed through the hole in the die with a cylindrical punch, causing the sides of the blank to bend over. This bending has to be carefully designed as the material has to be compressed. In this case a tractrix shape (hyperbolic radius) was used for the bending to avoid that the blank has to be pressed flat with a blank holder, and so damaging the ears. The blank is 0.35 mm thick and has a diameter of 32 mm. The resulting cup after this deep drawing has a diameter of 20 mm and a height of about 10 mm. Typically the forming process is followed by a thermal hardening treatment reaching a temperature between 925 and 1065 °C for 30 to 90 min to obtain the desired hardness and strength [4]. The treatment in this work consists of heating with a ramp of 4 °C/s to a temperature of 970 °C. After a dwell time of 900 s, the cups are cooled down to room temperature using a cooling rate 6 °C/s. As it will be described with more details in the following section, the temperature evolution of the yield stress of this material during heating and cooling was experimentally determined using compression (carried out in a plastodilatometer) and tensile tests. The temperature evolution of the relative change in length and the volume fractions of austenite (during heating) and martensite (during cooling) were also obtained using high resolution dilatometry experiments.

Table 1
Chemical composition of AISI 420 class of martensitic stainless steel (wt%) [20].

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

The shape of the cup was recorded at different stages in the process: after forming, during stress relaxation, during annealing and after thermal hardening. The critical geometric parameter for the shape change is the bottom flatness and defined as indicated in Fig. 1. The bottom flatness is defined as the angle between the side of the cup and the top, and measured by scanning the top with a Nanofocus µscan confocal microscope [22]. A radial measurement has been performed at points $r =$ 9 mm (y_1) and $r =$ 7 mm (y_2). The absolute difference between y_1 and y_2 then quantifies the bottom flatness of the cup. To point out the effect of the thermal cycle on the shape change, the flatness after forming was taken as a reference. The shape change Δ is therefore expressed as $\Delta = (y_1 - y_2)_{\text{forming}} - (y_1 - y_2)_{\text{hardening}}$. The measured values of y show angular variations caused by the anisotropy in the material. The final value of y is the average over the circumference. To be able to make a statistical comparison and distinguish between reproducible shape defects and distortions, the experiment was repeated for a set of 50 specimens.

Calculation of the cup shape change during forming and the subsequent heat treatment was done using Finite Element Method (FEM). The shape change (or total strain) can be expressed mathematically as the sum of material phenomena; the elastic strain ($\varepsilon_{elastic}$), plastic strain ($\varepsilon_{plastic}$), creep strain (ε_{creep}), thermal strain ($\varepsilon_{thermal}$) and transformation strain ($\varepsilon_{transformation}$):

$$\varepsilon_{tot} = \varepsilon_{elastic} + \varepsilon_{plastic} + \varepsilon_{creep} + \varepsilon_{thermal} + \varepsilon_{transfomation}. \tag{1}$$

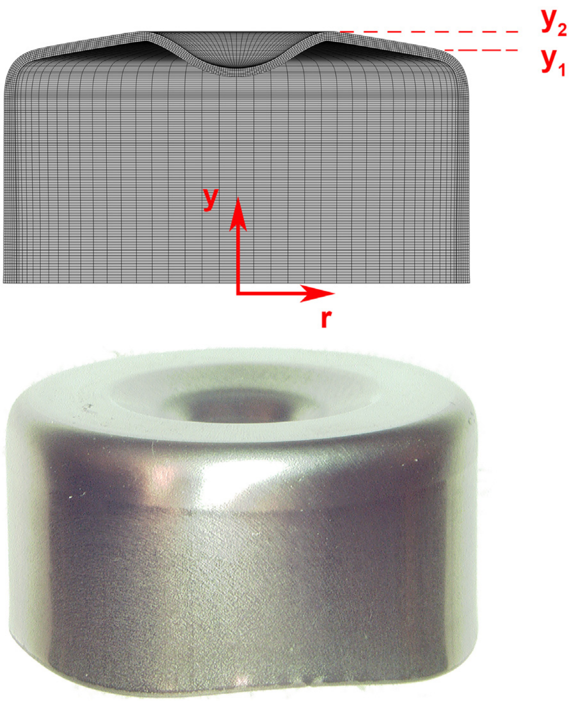

Fig. 1. Real fabricated cup (bottom) and its cross section with points y_1 and y_2. The absolute difference between y_1 and y_2 defines the bottom flatness of the cup.