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Rapid communication

A novel approach to control the properties of austenitic stainless steels in incremental forming

T. Katajarinne, S. Louhenkilpi, S. Kivivuori

Department of Materials Science, School of Chemical Technology, Aalto University, PO Box 16200, FI-00076 TKK, Finland

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ABSTRACT

This rapid communication presents a novel approach for controlling the material property evolution for austenitic stainless steels during incremental sheet forming (ISF), offering a route to affect the strength and ductility of the parts produced. The method relies on the modelling and control of the formation of strain induced martensite.

1. Introduction

Incremental sheet forming (ISF) is an agile method for small batch and rapid prototype production. The process relies on a small tool following a layer-by-layer forming path on the surface of a rigidly clamped sheet. Deformation is highly local as it is concentrated at any moment to the area of the tool/sheet contact along the forming path. Draw-in is absent and all of the strain is determined by the tool path and the tool/sheet contact, as the amount of inflicted strain is directly linked to the forming angle. The process is highly digitalised as the part design, generation of forming trajectories and the forming control itself are all numerically controlled by CAD/CAM. The process requires only simple or, optimally, no dies. This enables a swift and effortless change of forming geometries, with a more in depth description of the process and its limitations found in the Ref. [1].

The occurrence of strain induced phase transformation during the forming of austenitic stainless steels is well known. However, only very few papers about the phenomenon for ISF exist [2,3]. The transformation is related to the instability of the austenitic (γ) phase near ambient temperatures. The volume of transformation is regarded as depending on the composition, stacking fault energy, amount and rate of deformation, as well as temperature. There are two kinds of martensite that form: ε and α'; of the two phases, α' is structured as BCC and has a more significant contribution to the mechanical properties [4,5]. The formation of martensite can be divided into stages of nucleation and growth, with micro-shear band intersections within the grains as the most preferred sites for nucleation [6]. The formation has been shown to follow a sigmoid Johnson–Avrami–Mehl type of behaviour, where the degree of plastic deformation defines the transformed amount [7].

$$X = 1 - e^{a\varepsilon^b} \tag{1}$$

where X is the transformed fraction (0–1) of martensite, ε the amount of strain, and a and b are material parameters. For a predefined geometry and material, only the deformation rate and temperature can be affected. Additionally, the strain rate has been proposed to affect the process through adiabatic heating [8]. This would translate to an ability to control the transformation through temperature control. The agile setup of the incremental forming process readily allows for such control, provided a control algorithm is available.

2. Materials and experiments

Four different austenitic stainless steels were used in the present study, an EN 1.4404 (AISI 316L) grade, an EN 1.4318 (301LN) grade and two EN 1.4301 (304) grades. The materials vary in their compositions and, thus, their tendency for phase transformation. Table 1 lists the compositions and the M_{d30}-temperatures as given by the supplier. The reader is referred to a previous article for further details [2].

E-mail address: Tuomas.Katajarinne@aalto.fi (T. Katajarinne).

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Table 1
Compositions (wt%) and M_{d30}-temperatures (°C) of the steels.

	C	N	Cr	Ni	Mn	Si	Cu	Mo	Co	M_{d30}
316L	0.025	0.039	16.6	10.19	1.26	0.40	0.40	2.07	0.09	−67.4
304_1	0.047	0.042	18.1	8.14	1.70	0.55	0.37	0.34	0.13	−12.5
304_2	0.033	0.024	18.3	8.29	1.52	0.38	0.20	0.10	0.10	9
301LN	0.026	0.014	17.5	6.47	1.11	0.41	0.26	0.14	0.08	22

The forming angle in incremental forming correlates directly to the amount of strain inflicted. To achieve different levels of strain, a cone shaped forming geometry (diameter 180 mm) with the wall angle alternating from steep to shallow (60°→45°→30°) was used. Five different forming speeds (10, 20, 40, 80, 100 mm/s) were utilised to achieve different forming temperatures. A higher forming speed translated to higher temperatures as there was less time for the adiabatic heat to level off. As the forming proceeded, the diameter continuously diminished and the deformation concentrated to a smaller area. This locally reduced the available time for cooling, compensating for the lesser adiabatic heating, as the forming shifted towards more shallow angles. The temperatures for each individual speed condition remained within 2–3 °C throughout the forming.

Additionally, a second set of tests were performed with either external heating or cooling present to determine the effect of adiabatic heating. A fluid-containing vessel acting as a support tool was utilised for the temperature control. During the forming, the test piece pushed into the container, displacing the fluid, thus ensuring contact between the sheet and fluid. A standard radiator fluid cooled to −18 °C was used to cool and hot water heated to 70 °C for heating. After forming, the martensite fractions for different temperatures and strains were determined using ferritescope measurements [9]. The ferritescope relies on measuring the magnetic permeability of the BCC structure and thus only α' is considered in the present work. The process temperatures were measured using a laser pyrometer (Raytek RAYMX4PD). Additionally, an extensive set of tensile tests were applied to clarify the effects of deformation and martensite on strength and ductility.

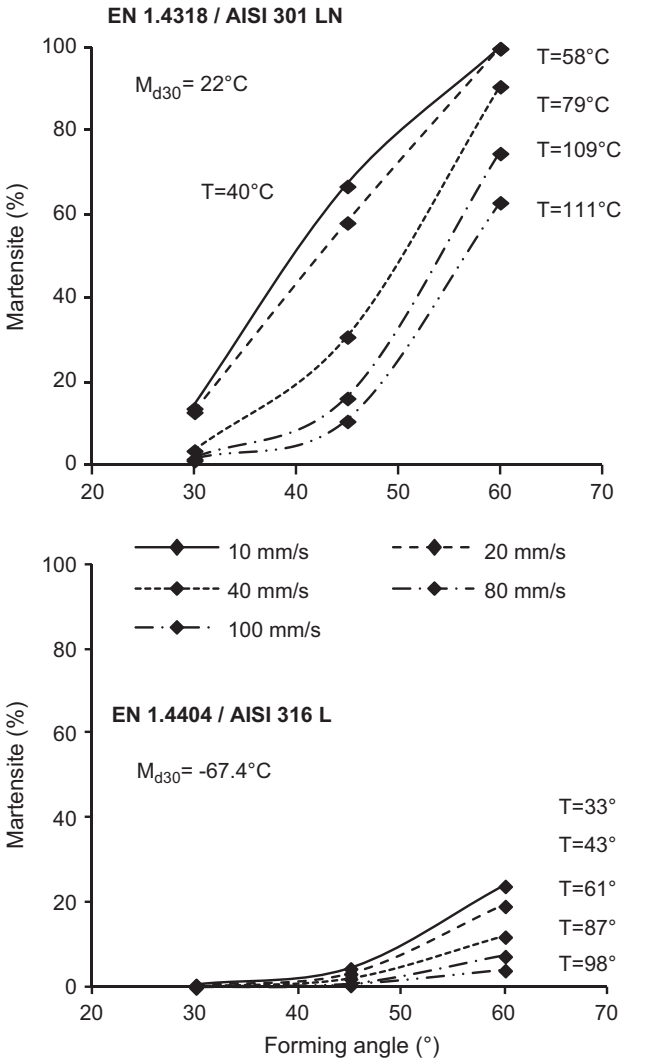

Fig. 1. The measured fractions of martensite for AISI 301LN and AISI 316L, as functions of temperature and forming angle.

3. Results and discussion

M_{d30} temperature is defined as the temperature at which 50% martensite is transformed at a true strain of 0.3. For the materials, the martensite transformation tendency is enhanced below the M_{d30}-temperature. The higher the M_{d30}-temperature, the higher is the instability of the austenite structure. Fig. 1 shows the martensite formation for the two grades exhibiting the extremes in transformation tendency. The 301LN grade shows 100% transformation for the two lower temperatures at the highest 60° forming angle. For the 316L grade, only about a 20% transformation is reached at the corresponding conditions. It is evident that the increase in temperature suppresses the transformed fraction. Congruent behaviour was found for the two AISI 304 grades, with the transformed fractions falling between these two extremes.

Adiabatic heating rather than the strain rate has been proposed as the contributing factor to the retardation of strain induced martensite formation. By applying an external temperature source, the transformation tendency can be strongly affected as seen in Fig. 2. For the AISI 316L grade, cooling increases the transformation from an average of 15% at room temperature to an average of 30%. Heating suppresses the transformation almost completely, resulting in an average of only 3% martensite. For AISI 304_1, the same behavioural tendency is observed. Cooling increases transformation from an average of 40% martensite to an average of 90%. Similarly, heating suppresses the congruent fraction averages from 40% to 13%. A small difference remains in the transformed fractions between the two forming speeds presented in Fig. 2. An area of slightly higher temperatures was observed trailing the forming tool, this is a result of the strong adiabatic heating and poor heat conductivity of the austenitic stainless steels. The present setup with heat control liquid on the opposite side of the sheet is unable to fully suppress this behaviour.

Temperature clearly has the most pronounced effect on martensite transformation. Thus, temperature is a suitable control parameter for the process. Above in Fig. 1, forming speed was utilised to produce different process temperatures. However, the speed combinations apply only to the present deformation conditions. To increase applicability, the measured data was fitted utilising Eq. (1) in two stages. First, for each material, the five different temperatures and corresponding fractions were fitted to obtain each individual value for parameters a and b. In the second stage, the five obtained parameter pairs for each material were fitted to find the temperature dependence. A good linear dependence was found for all four materials, the two extremes are shown in Fig. 3. Table 2 lists the results and correlation for all four materials. The relation of strain (ε) and forming angle (α) in the present case is given as

$$\varepsilon = \ln(1/\cos\ \alpha) \quad (2)$$