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Constitutive behaviour under hot stamping conditions

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ABSTRACT

The modelling of the hardening behaviour at high temperatures and a range of strain rates is extensively discussed. The hardening behaviour is characterized using tensile tests done in a Gleeble testing machine. The specimen is heated by an electric current, soaked to get fully austenized, cooled down to its desired testing temperature and then drawn to fracture with a given strain rate without a further drop of the temperature. One of the major challenges of this test is to achieve a uniform temperature distribution over the sample, to ensure homogeneous austenization. A dedicated tensile sample geometry enables a much more uniform temperature distribution than a regular sample geometry. Yielding and hardening behaviour have been characterized with a Kocks–Mecking plot. These characterizations have been used to fit parameters for a physically based hardening model that is applicable in a wide range of strain rates and temperatures. The predicted strains in FEM simulations that use these hardening curves match well with thickness measurements on hot stamped parts.

1. Introduction

Nowadays direct hot stamping is common practice in automotive manufacturing to produce parts with complex shapes and high strength. The hot stamping process starts with a heating step to austenize the blanks in a furnace, typically at 900 °C. When the blank is released from the furnace, it is quickly transferred to a press. During this transport the blank remains in the austenitic phase by virtue of its slow transformation kinetics. In a quick press stroke, the product gets its final shape, and is quenched to a hardening structure. The final in-press transformation ensures that no residual stresses are present in the product, and springback is minimized. For FE analysis of the hot stamping process, an accurate description of the material model is essential. Therefore, the hardening behaviour as a function of temperature and strain rate must be described for the austenitic phase. Åkerström (2004) developed a method to determine the mechanical response (flow stress) for the austenite, based on multiple overlapping continuous cooling and compression tests in combination with inverse modelling. Hein (2005) described a global approach for FE analysis of hot stamping where all parameters needed for a good simulation are described. Flow curves for the austenitic state between 650 and 900 °C for different strain rates are recommended. It is also stated that at temperatures lower than 600 °C, problems can occur due to phase transformations. Merklein et al. (2006) described the effect of strain rate on 22MnB5 tensile tests. Turetta (2008) showed hot tensile tests on standard tensile specimens according to ISO 10130. Hardening curves for different temperatures and strain rates were measured. Lechler et al. (2008) used a phenomenological model for the generation of hardening curves as a function of strain rate and temperature. This model is a multiplicative model: it assumes that the work hardening rate of the flow stress is a product of the strain rate dependency and the temperature sensitivity.

An improved sample geometry and test set-up for use in a Gleeble tensile testing machine is given to avoid the inhomogeneous heating as is observed in the standard sample. Also a physical modelling approach for the dependence from strain rate and temperature is proposed since a correct description of strain-rate/temperature sensitivity is crucial for predicting strain non-uniformities. The model recognizes two distinct strain-rate/temperature effects on the flow stress, the first being due to dislocation glide resistance which pertains to dislocation propagation, the second due to dynamic recovery and which pertains to dislocation multiplication (work hardening). They can be separated experimentally by first validating the dislocation glide resistance at the yield point, where work hardening is absent, followed by a fit of the work hardening function to the post-yield part of the hardening curve. The model is based on dislocation theory by the principle of additive contributions of yield stress, glide resistance and work hardening to the flow stress, described e.g. by Klepaczko and Chiem (1986), who discuss the fundamentals of how to construct constitutive relations on the basis that the total flow stress is

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the sum of the effective stress (or glide resistance due to surmounting local obstacles by dislocations) and the internal stress (which pertains to dislocation multiplication). They show the validity of this concept from rate jump experiments, and recognize that these contributions cause, respectively an instantaneous and a strain dependent strain rate sensitivity. van Liempt et al. (2002) published a flow stress model based on this principle of additive flow stress contributions. Also Sarkar and Militzer (2009) propose a similar approach of flow stress modelling at elevated temperatures. The individual flow stress contributions are described in several papers. Bailey and Hirsch (1960) experimentally validated the correlation between dislocation density and flow stress that was first proposed by Taylor (1934). Krabiell and Dahl (1981) described a function for the dislocation glide resistance which is the stress to move mobile dislocations at the required velocity at a specific temperature.

The work hardening theory used is based on theories using dislocation density and dynamic recovery and annihilation or alternatively remobilization of dislocations. Kocks (1976) characterized recovery as dislocations getting “annihilated or becomes ineffective in some other way at each potential recovery site”, where Bergström (1969–1970), interpreted it as remobilization of stored dislocations. The Bergström model was later developed further by Vetter and van den Beukel (1977) by incorporating the effect of dislocation density in the storage term, yielding the Bergström model mathematically identical to the Kocks–Mecking theory. Kocks and Mecking (2003) later revisited Kocks’ model, discussing further implications of the theory.

With the parameters found for the equations, a strain rate and temperature dependent hardening description can be made. The parameters were derived from a limited dataset within the hot stamping regime. To verify the accuracy of the predicted curves, they were compared with the measurements and simulations with these curves were compared with thickness measurements on a hot formed part.

2. Experimental

2.1. Basic principle

The goal for this testing programme is to have accurate measurements, which requires tensile tests with a homogeneous temperature along the deformation area of the sample, including the shoulders, for which special sample shape and set-up have been designed. Another goal is to cover a wide range of temperatures and strain rates with a limited amount of tests. Therefore the tests are parameterized with a model based on physical parameters. The use of a physical model increases the understanding of the test itself and relations between parameters are investigated and can be combined to a predictive model.

2.2. Tensile test equipment and test set up

For the tensile tests a Gleeble testing machine at Delft University of Technology is used. The Gleeble system was chosen for its excellent temperature control. According to the DSI datasheet Gleeble 3800, the Gleeble is able to create heat rates up to 10.000 °C/s (for welding simulations, depending on sample size), achieve steady state equilibrium temperatures within ±1 °C and cooling rates: up to 250 °C/s (depending on material and sample size, quench media). The tested material is a regular 22MnB5 with a thickness of 1.5 mm. The zinc coating was removed to avoid zinc deposition in the Gleeble. The sample is heated by electrical current and is subjected to a programmed cycle consisting of 60 s of heating to 900 °C, followed by an industrial soaking time for 240 s, quenching to the desired temperature, and tensile testing. An example of the cooling-testing

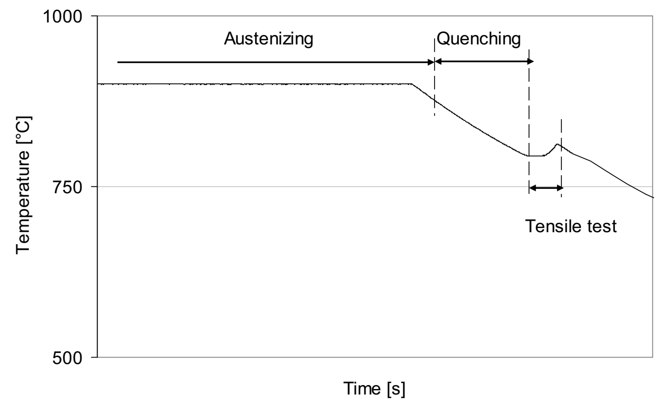

Fig. 1. Temperature cycle.

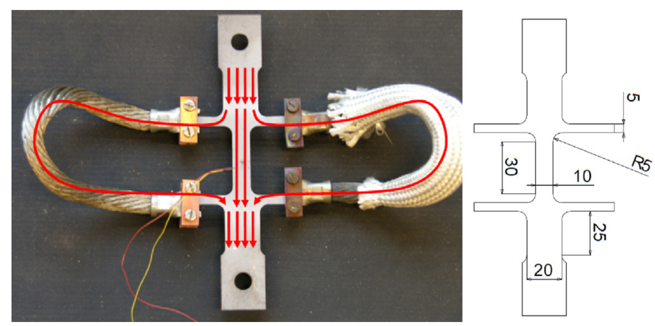

Fig. 2. Tensile sample with equal current density.

cycle is shown in Fig. 1. During tensile testing, the temperature is measured and controlled. Generally a slight heat increase is seen due to the deformation of the sample. The test is performed in vacuum to avoid decarburisation of the steel.

The temperature is measured with a thermocouple welded in the centre of the top surface of the sample. The thermocouple is also an input for the temperature control loop. The strain is measured with either a retractable strain gauge or by the crosshead displacement corrected for machine stiffness. An online strain measurement with Aramis is also possible but not used in this case.

2.3. Tensile sample shape

Since the tensile sample is heated internally and the grips are at room temperature, undesirable temperature gradients develop along the gauge section. A special sample shape was designed to ensure a homogeneous temperature distribution. The temperature homogeneity of this sample is ±10 °C over the gauge length and a large part of the shoulders. The sample shape and its dimensions is shown in Fig. 2. The sample has a gauge length of 30 mm × 10 mm which is the minimum allowable for a uniaxial tensile condition.

The four “legs” are connected with thick wires to create a shunt for the current as shown in Fig. 2. This ensures equal current density and consequently heating rate in the gauge and shoulder, so that the temperature gradient in the latter is minimized. Nevertheless there will be a local maximum in the current density when the tensile sample is necking. This will locally increase the temperature just before fracture. Since this happens after incipient necking this is not important for the further evaluation of the measured stress strain curve. Only the stresses and strains before diffuse necking are considered. In the centre of the sample a thermocouple is attached on the surface with a spot weld to measure the temperature. The temperature distribution can be analyzed with standard video camera, because the light intensity correlates well