Finite Elements in Analysis and Design 81 (2014) 69–81

Contents lists available at ScienceDirect

Finite Elements in Analysis and Design

journal homepage: www.elsevier.com/locate/finel

Numerical modelling of the tailored tempering process applied to 22MnB5 sheets

B.T. Tang [a,b], S. Bruschi [b,*], A. Ghiotti [b], P.F. Bariani [b]

[a] School of Materials Science and Engineering, Shandong Jianzhu University, Fengming Road, 250101 Jinan, China
[b] DII University of Padova, Via Venezia 1, 35131 Padova, Italy

ARTICLE INFO

Article history:
Received 17 June 2013
Received in revised form
6 November 2013
Accepted 22 November 2013
Available online 28 December 2013

Key words:
Tailored tempering
Boron steel
Phase transformation kinetics

ABSTRACT

In order to enhance the crash characteristics and geometrical accuracy, components hot formed in a fully martensitic state have gained in the last few years more and more importance. However, the very high strength exhibited by these components makes subsequent operations such as cutting difficult due to the high process forces and associated high wear of the cutting tools. Moreover, for some applications, such as B-pillars and other automotive components that may undergo impact loading, it may be desirable to create regions of the part with softer and more ductile microstructures. The novel process called the tailored tempering process allows doing this by suppressing the martensitic transformation in those zones of the sheet located under heated parts of the tools.

In the paper, a numerical model of the tailored tempering process was developed, accurately calibrated and validated through a laboratory-scale hot forming process. Using the commercial FE code Forge™ a fully coupled thermo-mechanical-metallurgical model of the process was set up. The influence of the phase transformation kinetics was taken into account by implementing in the model phase transformation data, namely the shift of the TTT curves due to the applied stress and the transformation plasticity coefficients, gained from an extensive dilatometric experimental campaign and analysis. A laboratory-scale hot-formed U-channel was produced using segmented tools with heated and cooled zones so that the cooling rate of the blank can be locally controlled during the hot forming process. The part Vickers hardness distribution and microstructural evolution predicted by FORGE™ were then compared with the experimental results, proving the validation of the numerical model by taking into account the influence of the transformation plasticity and deformation history on the phase transformation kinetics.

1. Introduction

Sheet metal working operations at elevated temperatures have gained in the last few years more and more importance, due to the possibility of producing components characterized by a high strength to mass ratio, with, at the same time, a significant increase of their mechanical properties thanks to the microstructure obtainable at the end of the process. Besides the warm forming of light and ultra-light alloys, whose main objective is to increase the material formability limits, the hot stamping of high strength steel is nowadays quite widely utilized in the automotive industry to produce components such as bumpers and pillars with enhanced crash characteristics and geometrical accuracy due to reduced springback. In the hot stamping process, the blank is heated up above the austenitization temperature, transferred to the press, and simultaneously formed and quenched between cooled dies; the component then presents a fully martensitic microstructure at room temperature. Geiger et al. [1] carried out basic research concerning the material properties of the hot stamping steel 22MnB5. Mori and Okuda [2] showed that heating the sheets reduces the forming load, prevents springback, and greatly improves formability. Karbasian and Tekkaya [3] reviewed the hot stamping process in detail and demonstrated that the use of the hot stamping process of boron steels has steadily increased in recent years and has been widely accepted by the automotive industry.

However, because of the high strength exhibited by the hot stamped components, So et al. [4] mentioned that subsequent operations such as cutting are difficult due to the high process forces and associated high wear of the cutting tools and, therefore, cost intensive methods such as laser cutting are necessary. Moreover, hot stamped components exhibit a low ductility, which is crucial regarding the crash-performance in security relevant

* Corresponding author. Tel.: +39 049 8276822; fax: +39 049 8276816.
E-mail addresses: tbtsh@hotmail.com (B.T. Tang), stefania.bruschi@unipd.it (S. Bruschi), andrea.ghiotti@unipd.it (A. Ghiotti), paolo.bariani@unipd.it (P.F. Bariani).

0168-874X/$ - see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.finel.2013.11.009

parts such as the B-pillars. Nowadays, more and more researchers are focussing on the modification of the hot stamping process to manufacture components with functionally optimized mechanical properties leading to a better crash-performance as well as lower cutting forces and wear of the tools. Kolleck et al. [5] presented different approaches to reach local different strength distributions in hot stamped components. Maikranz-Valentin et al. [6] proposed a new type of thermo-mechanical tailored processing based on the application of differential heating and cooling strategies. Bardelcik et al. [7] examined the strength and strain-rate sensitivity of Usibor® 1500P subjected to various cooling rates ranging from 14 K/s to 50 K/s, which result in as-quenched microstructures ranging from bainite to martensite respectively. This hot stamping process is called the tailored tempering process, and allows the suppression of the martensitic transformation in those zones of the sheet located under heated parts of the tools. The tailored tempering process provides then the possibility of adjusting blank regions with very high strength and regions with enhanced ductility in the same part, with a gradual transition of the properties. The locally differentiated heat field within a tool system can also be achieved by using tool materials characterized by varied thermal conductivity as proposed by Casas et al. [8], structured tool surface by Mori and Okuda [2], integrated partial contact gaps by George et al. [9], and differentiated temperature distribution in the blank by Mori et al. [10]. No matter which methods are used, the adjustment of the local mechanical properties is fulfilled by varying the sheet cooling rate: high cooling rates will induce a fully martensitic phase transformation, whereas low cooling rates will result in the development of different microstructures such as bainite, ferrite, and pearlite that exhibit lower strength but higher ductility. However, the minimum value of the cooling rate assuring a fully martensitic transformation depends on the applied stress and strain levels, and therefore it is mandatory to know the influence of the latter parameters on the sheet steel phase transformation kinetics.

Several literature papers witness the importance of the effect of stress or strain on the material transformation kinetics. Barcellona and Palmeri [11] showed that the deformation during quenching of boron steels causes the CCT diagram to shift left or towards lower quenching times, which can lead to the formation of ferrite. Merklein and Svec [12] showed that the CCT diagram shifts towards the left as the material is deformed. Riera et al. [13] emphasized that the deformation modifies the phase transformations of the austenite during continuous cooling. As the level of deformation increases, the austenite becomes more unstable and the hardenability of the material diminishes: the critical cooling rate for the complete martensitic transformation can shift from 27 to 60 °C/s with a pre-strain equal to 0.28. The time needed to start the transformation of austenite into ferrite decreases, the bainitic transformation is favoured, and the martensite start temperature is lowered. Turetta et al. [14] evaluated the actual phase transformation kinetics for the material under deformation conditions.

The scientific literature reports several studies about the tailored tempering process, but most of them are devoted to experimental studies, and very few propose a numerical model of the process. Svec and Merklein et al. [15] used various die materials with different thermal conductivities to experimentally study the influence of new steel grades for the tools on the heat transfer between the sheet and the tool. Banik et al. [16] produced a B-pillar made of material MBW1500+AS and tested the micro-hardness distribution to show the validity of the required property distribution by the tailored tempering process. Behrens [17] and Feuser [18] have developed an advanced material model including phase transformation and implemented in the commercial FE-Code LS-DYNA™, but their numerical model cannot reflect the effect of stress on the movement of TTT curves. George et al. [9] developed a numerical model of the tailored tempering process using LS-DYNA™ to predict the part Vickers hardness; the model is able to capture the hardness trend with respect to the heated die temperature; however, the predicted Vickers hardness of the soft region is over-predicted by approximately 28% in comparison to the experimental measurements. This result can be ascribed to the used material model by Åkerström that does not account for the deformation effect on the microstructure prediction. Hippchen [19] has modified the material model *MAT_244 proposed by Åkerström in order to model the kinetics of phase transformation with more accuracy for an indirect hot stamping process. It shows that it is possible to model the incubation time and the rate of decomposition close to the measured decomposition of austenite. Ertürk et al. [20] developed a coupled thermo-mechanical-metallurgical model using the FE code AutoForm-ThermoSolver$^{plus™}$ accounting for the formation of martensite and bainite and generation of latent heat. The numerically predicted mechanical properties of a B-pillar were compared with the ones obtained from samples cut from a hot-formed B-pillar, showing a satisfactory agreement. However, the measurements were carried out on part locations positions where either no (flat blank) or very little (top of B-pillar) plastic strain raised during the process. Thus, the numerical model proposed by Ertürk et al. [20] does not show a complete ability in taking into account the effect of the deformation history on the phase transformation kinetics.

In this paper, a fully coupled thermo-mechanical-metallurgical numerical model of the tailored tempering process was developed using the commercial FE code FORGE™. The model was calibrated by implementing accurate material data, with particular regard to phase transformation kinetics as a function of the applied stress. The material data were obtained through an extensive experimental campaign conducted at the Metal Forming labs of DII-Univ. of Padova. The numerical model was then validated thanks to a laboratory-scale tailored tempering process conducted at Shandong Jianzhu University to produce a U-channel part, using segmented tools with heated and cooled zones allowing the local control of the blank cooling rate during the hot forming process. The part Vickers hardness distribution and microstructural evolution predicted by FORGE™ were compared with the experimental results, proving the validation of the numerical model by taking into account the influence of the applied stress on the phase transformation kinetics.

2. Application case

A novel experimental apparatus for sheet metal forming testing at elevated temperature was developed at the Shandong Jianzhu University enabling the conduction of physical simulation experiments of the tailored tempering process applied to a U-channel part. The experimental apparatus comprises an external furnace, where the steel blanks are heated above the austenitization temperature, a 500 kN hydraulic forming press with a maximum punch velocity of 40 mm/s, segmented forming tools with local heating and cooling zones, and a temperature acquisition system, including a heat controller, a temperature acquisition device, and thermocouples to measure both the blank and the lower die thermal field (Fig. 1 on the left). The blank material is the 22MnB5 boron steel, provided in 1.6 mm thick sheets. Since the blanks were not coated, a nitrogen atmosphere was supplied during heating to prevent excessive oxidation. The metal blanks were austenitized at 950 °C in the furnace for 3 min, and then transferred to the press in less than 5 s, where they were deformed by moving the punch at 40 mm/s (formed parts in Fig. 1 on the right). Afterwards, the deformed blanks were kept between the dies for further 10 s to allow complete quenching.