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TRANSFORMATION-INDUCED PLASTICITY IN STEEL FOR HOT STAMPING

VPLIV PRETVORBE NA PLASTIČNOST JEKLA ZA VROČE ŠTANCANJE

Bohuslav Mašek[1], Ctibor Štádler[1], Hana Jirková[1], Peter Feuser[2], Mike Selig[3]

[1]Research Centre of Forming Technology – FORTECH, University of West Bohemia in Pilsen, Univerzitní 22, 306 14 Pilsen, Czech Republic
[2]Daimler AG, Bela-Barenyi-Str. 1, 71063 Sindelfingen, Germany
[3]AutoForm Development GmbH, Technoparkstrasse 1, 8005 Zürich, Switzerland
ctibor@email.cz

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The hot-stamping process for manufacturing car-body components was patented in 1977. Its main advantages include the precision of the product shape, the reduced spring-back effect and the resulting high strength of steel parts upon hardening. Boron- and manganese-alloyed steels have been specially developed for this process. The 22MnB5 grade is a typical representative of this group with its strength up to 1500 MPa.
For the desired mechanical properties to be achieved, the final microstructure should consist primarily of martensite without any substantial amounts of other phases. Further development of press hardening, therefore, requires all the phenomena associated with the phase transformations during the cooling between dies to be well mapped. Significant parameters, in this respect, include phase-transformation temperatures and the data on a number of additional phenomena, including transformation-induced plasticity. Transformation-induced plasticity is manifested when a part held between dies undergoes a phase transformation, typically, when being under stress. In the course of a lattice rearrangement, this stress causes the atoms to occupy more favourable positions in terms of energy. At the macro-level, this can be detected as a change in the dimensions, which, at the same time, significantly relieves the stress, therefore, eliminating the spring back. Despite a profound importance of this phenomenon for the press-hardening process, it has not been explored in detail up to now.
For these reasons, a 22MnB5 steel grade was employed in this project. The impacts of the tensile and compressive stresses occurring during phase transformations, upon the changes in the expansion of the sheet specimens, were explored using the schedules that simulated real-world hot-stamping and press-hardening processes.

Keywords: press hardening, hot stamping, spring-back effect, 22MnB5, transformation-induced plasticity

Postopek vročega štancanja za izdelavo komponent karoserije avtomobilov je bil patentiran leta 1977. Njegove glavne prednosti so natančnost oblike izdelka, zmanjšan vzmetni učinek in visoka trdnost jeklenih delov po toplotni obdelavi. Posebno za ta postopek so bila razvita jekla, legirana z borom in manganom. Značilen predstavnik te skupine je jeklo 22MnB5 s trdnostjo do 1500 MPa.
Za doseganje želenih mehanskih lastnosti mora biti končna mikrostruktura martenzitna, brez večjih deležev drugih faz. Nadaljnji razvoj utrjevanja pri stiskanju zahteva, da se obvladajo vsi pojavi, ki so povezani s faznimi premenami med ohlajanjem v orodju. S tega vidika so pomembni parametri, ki vključujejo temperature faznih premen in podatki o številnih drugih pojavih, vključno z vplivom fazne premene na plastičnost. Vpliv fazne premene na plastičnost se pokaže, ko se v delu med orodjema zgodi fazna premena, navadno pod tlakom. Med preureditvijo mreže napetosti povzročijo, da atomi zasedejo energijsko bolj ugodne položaje. Na makronivoju se to kaže kot sprememba dimenzij, ki istočasno zmanjšajo napetosti in odpravijo učinek vzmeti. Kljub pomembnosti ta pojav utrjevanja pri stiskanju do sedaj še ni bil podrobno raziskan.
Zato je bilo v tej raziskavi uporabljeno jeklo 22MnB5. Raziskani so bili učinki nateznih in tlačnih napetosti, ki se pojavijo med fazno premeno pri spremembi širjenja vzorcev pločevine, s simulacijo realnega vročega štancanja in procesa utrjevanja s stiskanjem.

Ključne besede: utrjevanje s stiskanjem, vroče štancanje, vzmetni učinek, 22MnB5, vpliv pretvorbe na plastičnost

1 INTRODUCTION

Transformation-induced plasticity is an all-too-often overlooked phenomenon in manufacturing today. One of the reasons for this is the fact that its impact on the outcome of the entire manufacturing process is not readily visible. Yet, there are technological problems in the industry that may be caused by transformation-induced plasticity and other issues that could be resolved by making use of the very same transformation-induced plasticity phenomenon.[1,2] An example of the important role of transformation-induced plasticity is the production of sizable forgings, namely, their heat treatment.[3] Only recently have these phenomena received more attention and the findings are reflected in FEM simulations. Their descriptions have become more detailed, having an effect on the current material models. Transformation-induced plasticity has an important role in the process of hot sheet forming with the subsequent press hardening, known as hot stamping. In the hot-stamping process, transformation-induced plasticity combined with other effects reduces the spring back. Consequently, the final pressed parts achieve greater shape precision than the high-strength deep-cold-drawn sheet products.[4] Since this phenomenon typically occurs in the production of complex-shape deep-drawn sheet products, it is difficult to assess it accurately. Without an exact description of its effect, no production-relevant and sufficiently accurate material-based model can be constructed.[5] This was the background of the present experiment.

2 EXPERIMENTAL WORK

Modified tension-test pieces with a 10 mm width, 50 mm length and a thickness of 1.5 mm were used in this study. The schedules were simulations of real-world hot-stamping and press-hardening processes. The material was a standard 22MnB5 steel grade (**Table 1**).

Table 1: Chemical composition of the 22MnB5 grade in mass fractions (*w*/%)
Tabela 1: Kemijska sestava jekla 22MnB5 v masnih deležih (*w*/%)

C	Cr	Mn	Si	B	P	S	Al
0.22	0.2	1.25	0.2	0.0029	0.025	0.015	0.006

The main objective of the research was to explore the intensity of the transformation-induced plasticity phenomenon during the cooling process. The hot-stamping process was simulated by heating the specimens to 950 °C. The specimens were kept free from the longitudinal stress during the heating. They were held at the above temperature for 3 min and then cooled down to 770 °C in 10 s. This step was a simulation of cooling the trimmed feedstock during handling. Between 770 °C and 600 °C, the stress within the specimen increased linearly from 0 to the prescribed level, representing the stress formation in a real-world process. This stress level was then maintained during the subsequent constant-rate cooling. The cooling rates were specified on the basis of the CCT diagrams constructed under the conditions identical to real-world processes. The cooling rates of 25 °C/s and 40 °C/s were selected as the characteristic values resulting in various microstructural states. The first cooling rate led to a formation of a mixed microstructure of bainite, martensite and some ferrite. The higher cooling rate led to a transformation into martensite. Consequently, the differences between the final dimensions of the final disparate microstructures could be compared.

The changes in the length of the test specimen were monitored in the course of the experiment, while the longitudinal stress in the part was controlled.

The amount of stress was defined on the basis of the measurements of the stress-strain characteristics at the constant temperature of 600 °C, carried out at the beginning of this research. It was less than one quarter of the stress that caused plastic deformation. In the subsequent tests, this amount was gradually increased to twice and three times its value. Hence, the stress was kept in the elastic region at all times to prevent any substantial contribution to the elongation of the test specimen, caused by the ordinary plastic deformation and creep during the testing. These stress levels were as follows: (31, 62 and 93) MPa. The ratio of the extension caused by the elastic deformation under the highest load to the sum of the overall contraction and the deformation due to transformation-induced plasticity was no more than a mere fraction of one percent (**Figure 1**).

3 RESULTS AND DISCUSSION

In the region of transformation, the experiment revealed a non-linear extension of the material along the applied stress direction (**Figure 1**). This is a definite evidence of the profound effects of transformation-induced plasticity. Transformation-induced plasticity takes effect at the moment of lattice reconfiguration, when the atoms take their new positions. The new positions are consistent with the transition into a lower-energy, more favourable state. This is the main cause of the permanent deformation, manifested as the non-linearity on the specimen elongation curve.

The experiment showed that the length of the test specimen decreased by about 0.5 mm upon the cooling from 600 °C to 70 °C without any longitudinal stress. This corresponds to the 0 % transformation plasticity. When the longitudinal stress of 31 MPa was applied, the contraction was approximately 0.35 mm. The contraction of the test specimen was, in this case, by 0.15 mm lower than in the previous case, due to the transformation plasticity. Once the longitudinal stress doubled, the contrac-

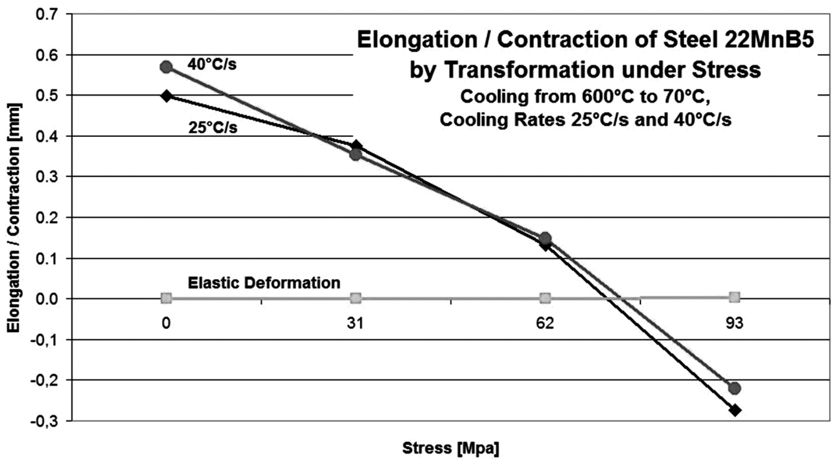

Figure 1: Effect of stress on the length of the test specimen
Slika 1: Vpliv napetosti na dolžino preizkušanca

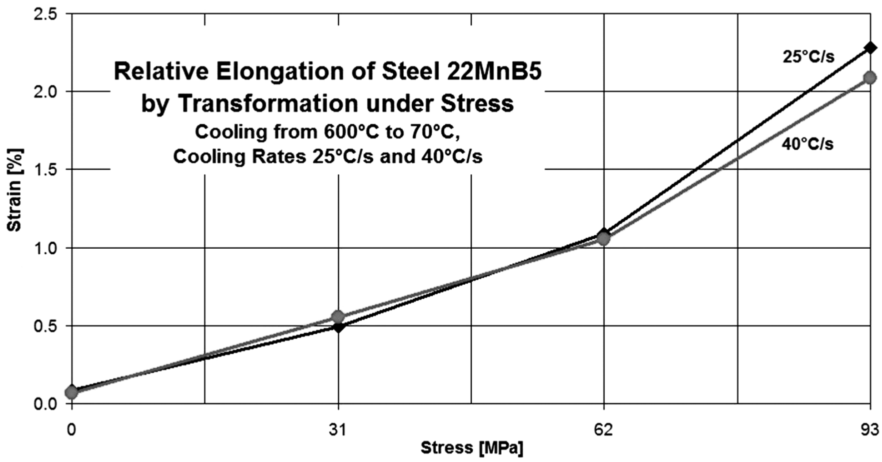

Figure 2: Relative elongation versus longitudinal stress
Slika 2: Relativni raztezek v odvisnosti od vzdolžne napetosti

tion was 0.13 mm. At the triple stress value, the contraction caused by the cooling was outweighed by the transformation-induced plasticity effect, causing the specimen to extend by an amount between 0.22 mm and 0.27 mm.

In this experiment, the effect of diffusion should be taken into account as well, as it contributes to the process even though its extent varies. However, its impact cannot be explored separately from the other effects. The experiment showed that at the lower cooling rates – when the times available for diffusion were longer – the elongation increased, though slightly. The impact of creep increases with the stress level.

At the stresses above 70 MPa, the effect of transformation-induced plasticity can compensate for the contraction, thus eliminating residual stresses (**Figure 1**).

The relative extension between 600 °C and 70 °C rose from 0 %, which was detected during the cooling without any stress applied, to approximately 0.55 % at 31 MPa. It then increased almost linearly with the increasing longitudinal stress to twice as high a value. At 62 MPa, it reached 1 % (**Figure 2**). When the stress was increased further by one third of its value, the relative extension was doubled, reaching more than 2 %.

4 CONCLUSION

The experiment conducted on the sheet specimens made from the 22MnB5 steel involving the cooling rates of 25 °C/s and 40 °C/s and various applied stress levels revealed the intensity of the transformation-induced plasticity effects during hot-stamping and press-hardening processes. At the temperatures between 600 °C and 70 °C, the test specimens contracted. The contraction was compensated for by an expansion due to the longitudinal tensile stress and transformation-induced plasticity. With the longitudinal stress increasing from 0 to 93 MPa, the relative extension of the test specimen becomes non-linear, increasing from 0 % up to 2 %. The results show that at the stresses above 70 MPa, transformation-induced plasticity and additional related phenomena can compensate for the contraction due to cooling, thus reducing the spring back.

The present experiment was not intended to exactly match the real-world contraction behaviour of the press-hardening process. Its purpose was to provide an insight into and the data on the transformation-induced plasticity under the specific cooling conditions of the hot-stamping process.

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