CIRP Annals - Manufacturing Technology 57 (2008) 265–268

Contents lists available at ScienceDirect

CIRP Annals - Manufacturing Technology

journal homepage: http://ees.elsevier.com/cirp/default.asp

Testing formability in the hot stamping of HSS

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ARTICLE INFO

Keywords:
Sheet metal
Formability
Hot deformation
Phase transformation

ABSTRACT

This paper presents an innovative experimental procedure, based on Nakazima test, for evaluating the formability limits in the hot stamping of high strength steel (HSS) which is capable of generating formability data suitable for an FE modelling of the process. The approach is based on two complementary tests which are aimed at evaluating the actual phase transformation kinetics for the material under deformation conditions and the combinations of microstructure, temperature and straining path that lead to localized necking or fracture.

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1. Introduction

The hot stamping of high strength steels (HSSs) is a non-isothermal sheet metal forming process where the blank is formed in a single step that combines forming in hot and warming conditions with press hardening between cooled dies [1,2]. The typical temperature vs. time diagram of a hot stamping cycle is illustrated in Fig. 1. The blank, which has a ferritic–pearlitic microstructure and low mechanical properties at room temperature, is heated in a furnace above the austenitization temperature and maintained long enough to lead to the formation of a homogenous austenitic microstructure. The blank is then transferred to the press where it is simultaneously formed and quenched at a controlled cooling rate between continuously cooled dies. At the end of the cycle, the part has a fully martensitic microstructure, with strength levels above 1500 MPa [3].

Hot stamping is a relatively new process that is becoming increasingly popular, especially in the manufacturing of light-weight steel car body parts. Thanks to the final martensitic microstructure, the reduced springback and the adequate formability that HSS exhibits at elevated temperatures, thinner and more complex sheet metal parts can be produced with a high or very high strength-to-mass ratio and high geometrical accuracy as well [4–7].

Despite its advantages, hot stamping is a complex manufacturing process where the properties and quality of the final part are strongly affected by the material and the numerous parameters in the thermo-mechanical cycle, such as strain- and strain rate-paths, temperature and microstructure evolution that mutually interact during the forming and the cooling stages. Due to this complexity, fully coupled thermo-mechanical-metallurgical FE-based models of the whole cycle are an indispensable tool in designing the hot stamping process [8,9]. Thus, the generation of data to calibrate these models is the main focus of the scientific research on the topic. Most investigations are aimed at modelling the rheological behaviour of steels (in terms of flow stress and plastic anisotropy [3,10,11]) and the phase transformation (in terms of CCT and TTT diagrams [3] and transformation plasticity for each phase [12]). Other recent contributions from the scientific literature deal with the evaluation of heat transfer at the interface between sheet metal and dies [13] and the FE modelling of the thermal cycles into the dies for optimal design of hot stamping tools with integrated cooling system [7].

At the time of this writing, no investigation has been published on the testing and evaluation of friction at interfaces and formability limits at the forming temperatures, which together with rheology, phase transformation and heat transfer would complete the data system for the FE modelling of hot stamping.

This paper presents an innovative experimental procedure, based on Nakazima test for evaluating the formability limits in the hot stamping of HSS which is capable of generating formability data suitable for an FE modelling of the process. The approach is based on two complementary tests which are aimed at evaluating the actual phase transformation kinetics for the material under deformation conditions and the combinations of microstructure, temperature and straining path that lead to localized necking and fracture.

2. The approach

Several tests are commonly used to determine the formability of sheet metal at room temperature, such as the uniaxial tension test, the cupping tests, the bulge test and the tests to determine the limiting dome height (LDH) and the forming limit diagrams (FLDs) [14].

At room temperature, the two factors that have the greatest influence on formability are the properties of the sheet metal and the straining path. When a steel sheet metal undergoes plastic deformation at the elevated temperatures that are typical of hot

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0007-8506/$ – see front matter © 2008 CIRP.
doi:10.1016/j.cirp.2008.03.049

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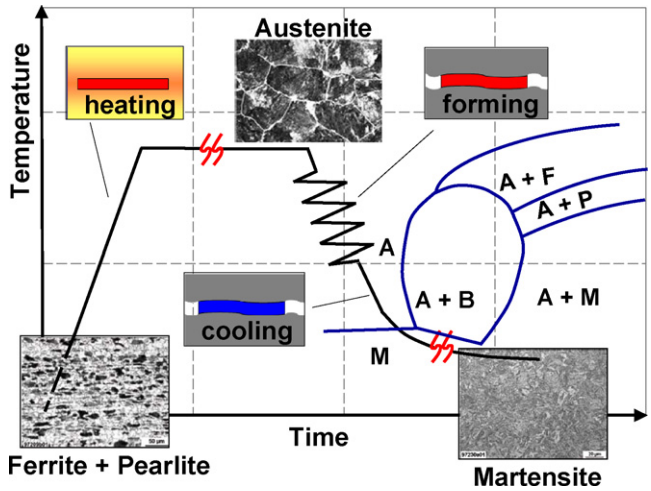

Fig. 1. Temperature vs. time diagram of the hot stamping process.

stamping, additional factors affecting formability must be taken into account in designing the test. These include: the temperature, the straining-rate and the microstructure evolution. These three factors mutually interact: (i) the higher the temperature, the higher the sensitivity of the flow stress to the strain-rate and the capability of the sheet metal to undergo large deformations and (ii) the stresses that accompany straining affect the kinetics of phase transformation causing significant changes in the times required for austenite to begin its transformation.

Therefore, an approach for testing the formability of steel sheet metals at elevated temperatures has to meet two major requirements:

- to evaluate the kinetics of phase transformation under deformation conditions, and
- to determine the combinations of microstructure, temperature, strain- and strain rate-paths that cause necking and fracture to occur.

In accordance with these requirements, two complementary tests were developed:

- a "*phase transformation test*". Designed to evaluate the kinetics of phase transformation under deformation conditions: this test provides the time that metastable austenite requires at any temperature and at different stress levels for its transformation to begin, and
- an "*elevated-temperature formability test*". In this test, the sheet metal undergoes – in the metastable austenitic phase – thermo-mechanical treatments that are carried out at different temperatures and following different paths of the strain and strain rate until the onset of necking and fracture occurs. The time available for the thermo-mechanical treatment is provided by the "phase transformation test". The scheme and procedure of the "elevated-temperature formability test" are those of the Nakajima test. For this reason, hereafter the test is named "Nakajima test at elevated temperatures". With this test, the formability limits of a steel sheet metal are provided for the metastable austenitic phase in the form of the combinations of strains that cause the onset of necking and fracture for given temperatures and average strain rates.

The thermo-mechanical cycles of the two tests together with their apparatuses and procedures are described in Section 3. Results provided by the tests and formability limits are presented in Section 4 for the 1.5 mm thick sheet metal made of steel 22MnB5 (commercially known as USIBOR 1500P), coated with an aluminium–silicon layer to avoid oxidation.

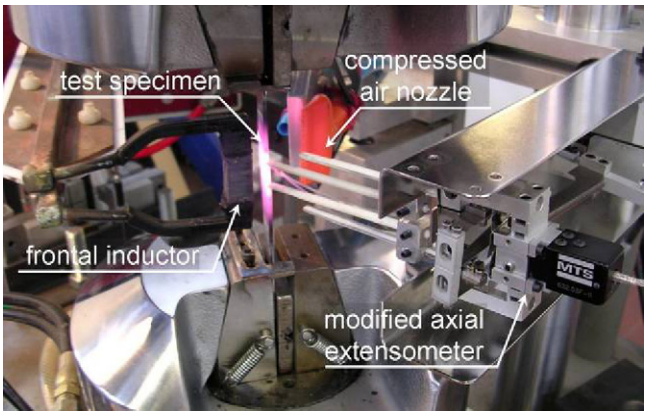

Fig. 2. Experimental apparatus for phase transformation tests.

3. Testing

3.1. Phase transformation tests

Through these tests the kinetics of phase transformation is evaluated under deformation conditions. In these tests, uniaxial tensile test samples are rapidly quenched from austenitization temperature to the testing temperature where they are loaded at a constant tensile stress until metastable austenite begins its transformation. These tests provide the time available in the "Nakajima test at elevated temperature" for the thermo-mechanical treatment to occur in the metastable austenite phase.

The tests are carried out on a 50 kN MTS™ hydraulic testing machine. Heating and temperature maintenance during the loading stage are performed by a frontal inductor connected to a 30 kW inductive heating system where the specimen temperature is controlled through a K-type thermocouple spot-welded onto the middle of the specimen surface. Very fast cooling rates are assured by the use of jets of compressed air through a set of nozzles. Beginning of austenite transformation is detected by an air-cooled MTS 632.53 high temperature axial extensometer which was adapted to work as a dilatometer (Fig. 2).

Table 1 shows the plan of the "phase transformation tests" carried out to determine the shifting of the TTT diagram for the steel 22MnB5 which is caused by the applied load. A cooling rate of approximately 100 °C/s was utilised in the quenching stage of all the experiments.

3.2. Nakajima tests at elevated temperature

Since in industrial practice high strength steels are hot stamped in fully austenitic phase, these tests are designed to give the formability limits in the metastable austenitic phase and the formability data are provided in the form of combinations of strains which cause the onset of necking and fracture for given temperatures and average strain rates. The test scheme and procedure are those of the Nakajima test according to ISO 12004 [15] with adaptations made due to the elevated temperature. Variations of the strain path and the average strain rate are obtained by preparing the specimens with different widths (from a 200 mm × 200 mm square to a 200 mmm × 20 mm rectangle) and by varying the punch speed, respectively. All the tests are run with a 0.1 mm thick graphite foil as lubricant between the sheet metal specimen and the punch. The Nakajima tests are carried out on a 1000 kN INSTRON™ hydraulic press (Fig. 3a) with a controlled ram speed in the range between 0.60 mm/s and 45 mm/s.

Table 1
Experimental plan for phase transformation tests

T [°C]	700	600	500
σ [MPa]	28–56–84	28–56–84–112	28–56–84–140

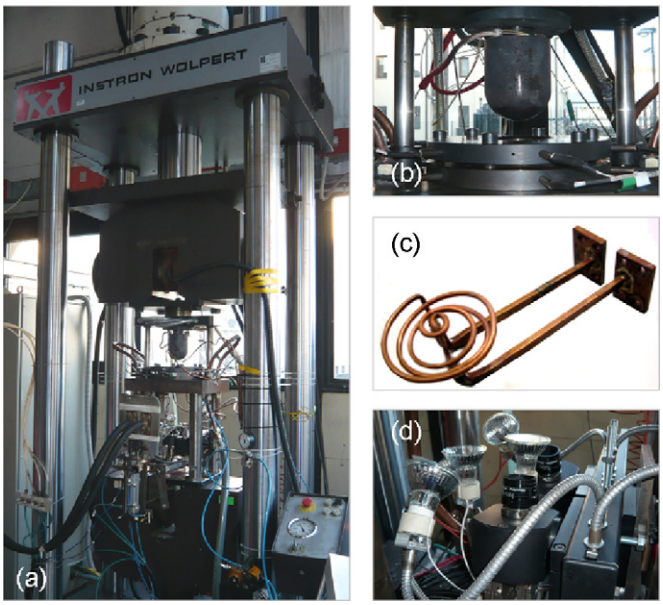

Fig. 3. Experimental apparatus for Nakajima tests at elevated temperature: (a) hydraulic press, (b) heated punch, (c) induction head and (d) lighting system.

The sheet metal blanks are heated to the austenitization temperature and then rapidly cooled to the testing temperature and deformed at that temperature until failure, while remaining all the time in the metastable austenitic phase. With a ram speed of 10 mm/s (which corresponds, in the necking zone, to an average strain rate of 1.0 s^{-1} along the whole deformation stroke), the deformation stage until fracture takes less than 2.5 s, which permits the tests to be performed on a blank in the fully austenite phase, when combined to a cooling rate of 100 °C/s.

Both the hemispherical punch (100 mm diameter) (Fig. 3b) and the blank holder are equipped with cartridge heaters to keep the temperature of the sheet metal blank during the experiment constant. The specimens are heated to the austenitization temperature by using an induction heating head whose shape and size are designed to guarantee precise control of the heating rate as well as of temperature constancy during deformation until failure [16] (Fig. 3c). The inductor head is precisely positioned and rapidly removed (less then 200 ms) by an automatic arm. The temperature of the sheet metal blank is continuously monitored through both an infrared thermo-camera and three K-type thermocouples spot-welded onto the sheet metal surface which is deformed by the punch. During the test, the maximum difference among the temperatures at the three thermocouples is kept under 30 °C.

During the test, the strains on the dome surface are continuously monitored by the Aramis™ system by using a special control of the lighting system (Fig. 3d), which compensates for the variation of the emissivity of the sheet metal with temperature and a pattern printed on the sheet metal surface capable to resist temperatures up to 900 °C. Details on the experimental apparatus, the control of the heating system and its calibration and the strain monitoring system are in [16].

4. Results

4.1. Phase transformation kinetics

Fig. 4 shows the evolution of axial strain for the steel 22MnB5 measured by the extensometer at a constant temperature of 700 °C for different levels of the applied stress. The time the curve starts to increase indicates the beginning of the transformation (from austenite to ferrite at 700 °C). As the level of applied stress increases, the time the metastable austenite needs to transform decreases. Similar results were found for testing temperatures of 500 °C and 600 °C where austenite transforms to bainite. Table 2 summarises the results in terms of shift of the phase transformation onset for three testing temperatures and four levels of the applied stress.

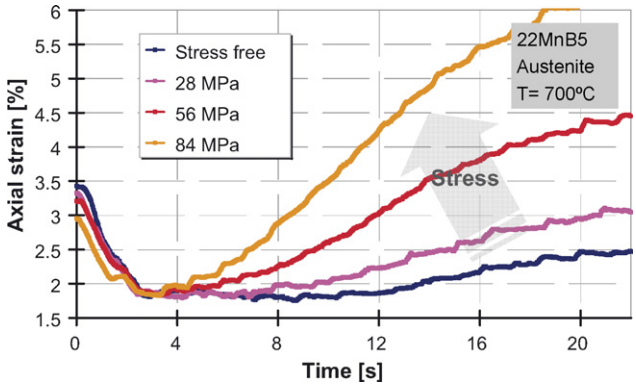

Fig. 4. Axial strain measured by the extensometer at T = 700 °C for different levels of the applied stress.

Table 2
Shift of the transformation onset as function of applied stress

T = 500 °C				
σ [MPa]	28	56	112	140
Shift [s]	1.9	2.3	4.8	6.8
T = 600 °C				
σ [MPa]	28	56	84	112
Shift [s]	0.2	2.5	3.2	3.9
T = 700 °C				
σ [MPa]	28	56	84	–
Shift [s]	4.3	8	8.2	–

It is worth remarking that the time shift of austenite transformation, which is evaluated through these tests, can be referred to TTT diagrams only. In fact, if the stress is applied during cooling (and not at a constant temperature) no shift in the transformation onset is observed.

4.2. Formability limits

The formability limits of sheet metal in hot stamping conditions are provided by the Nakajima test at elevated temperature in the form of combinations of strains that cause the onset of necking and fracture for given temperatures and average strain rates. Fig. 5 shows the major and the minor strains monitored and calculated by the Aramis™ system during a test run at 600 °C on a square (200 mm × 200 mm) sheet metal specimen of 22MnB5. The punch speed was v = 10 mm/s and a 0.10 mm thick graphite foil was used as lubricant at the interface between specimen and punch. The peak of the major strain corresponds to the large post-necking deformation and is due to the high sensitivity to the strain rate that the material exhibits at elevated temperature.

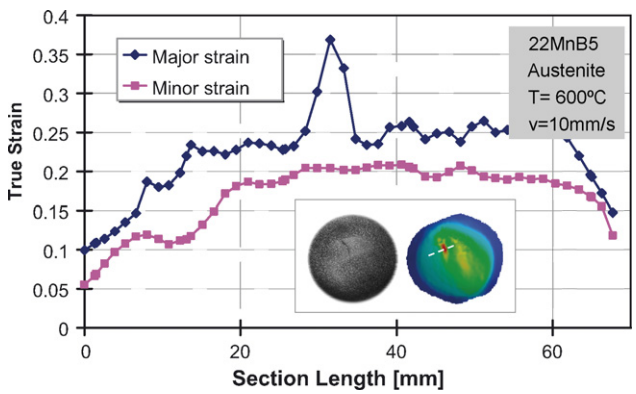

Fig. 5. Major and minor true strains across the failure zone.

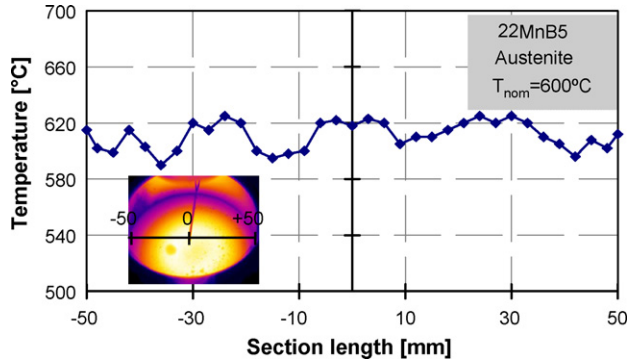

Fig. 6. Temperature distribution monitored during the test along a meridian of the dome.

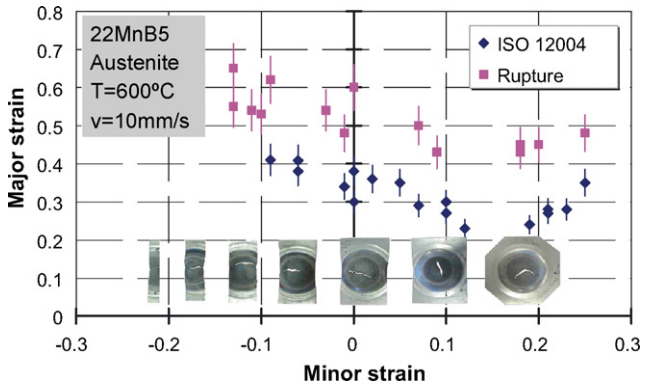

Fig. 7. Forming limit diagram at 600 °C in metastable austenite condition.

Fig. 6 shows the temperature profile along a meridian of the dome acquired by the thermo-camera during the deformation stage. Testing conditions were the same as Fig. 5.

For the same steel 22MnB5, Fig. 7 describes in the form of FLD the formability limits that were obtained at 600 °C and with an average strain rate of 1.0 s^{-1} (constant punch speed of 10 mm/s) by varying the strain path from equal biaxial stretching to uniaxial stretching. The blue dots represent the FLD according to ISO, while the red dots are calculated at failure. If the two diagrams are compared, it is evident that the increase in the formability at elevated temperature becomes significant particularly in the post-necking deformation phase.

5. Conclusions

An approach to test formability in the hot stamping of HSS was developed. Main features of the approach are that:

(i) the conditions governing the deformation of steels at elevated temperature and the onset of formability limits in the hot stamping process are accurately reproduced in the proposed laboratory tests;
(ii) the thermal, mechanical and micro-structural parameters determining the onset of localized necking and fracture can be individually controlled during the tests;
(iii) the kinetics of transformation of metastable austenite under deformation conditions is evaluated in terms of shifting of TTT diagrams;
(iv) the formability data are provided in the form of combinations of strains that cause the onset of necking and fracture for given temperatures and average strain rates in the metastable austenitic phase; and
(v) the formability data as provided by the tests are easy to implement in the database of an FE model of the process.

Thanks to the above features, the proposed approach seems to be particularly suitable for investigation and for formulation of fracture criteria for elevated temperature deformation of steel sheet metals that would represent an alternative and more effective way to define formability limits.

Acknowledgments

The research work which this paper is based on is part of the research project PRIN "S.M.A.R.T." financed by the Italian Ministry of University and Research. The authors would like to acknowledge Mr. D. Pellegrini for his contribution in carrying out part of the experiments.

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