7th International DAAAM Baltic Conference
"INDUSTRIAL ENGINEERING"
22-24 April 2010, Tallinn, Estonia

UNCONVENTIONAL THERMOMECHANICAL TREATMENT OF ADVANCED HIGH STRENGTH LOW-ALLOYED STEEL

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¶ **Abstract:** *Modern advanced high strength steels processed using unconventional heat or thermomechanical treatments can attain substantially better properties when compared to conventional treatments. This paper presents new possibilities of thermomechanical treatment for 42SiCr steel. Very high strength can be reached using conventional treatments, but elongation drops down to lower values. The aim of this experiment was to design and test an unconventional thermomechanical treatment procedure in order to reach a yield strength of up to 2000 MPa with elongation over 10%. For this purpose, the Q-P process (Quenching - Partitioning) was modified and optimized in several steps. The stability of retained austenite was determined by means of neutron diffraction under cold deformation. The influence of the technological process parameters on structure development was documented via metallography and the resulting mechanical properties were measured by means of tensile test.*
Key words: unconventional thermomechanical treatment, Q-P process, low-alloyed steel, neutron diffraction

1. INTRODUCTION

One of the goals when developing new kinds of steels is their economical efficiency, whereas the properties of such steels are mostly achieved not by adding high amounts of alloying elements, but using special procedures of heat treatment or thermomechanical treatment. Three new processing strategies have been developed in recent years: the TRIP-effect, long-time low-temperature annealing and the quenching and partitioning (Q-P) process. The first two methods employ the combination of bainitic ferrite and retained austenite to obtain good mechanical properties. Carbide precipitation is suppressed and carbon is used for the chemical stabilization of retained austenite during this treatment. In the case of the third treatment, the Q-P process, martensitic structure is achieved in place of bainitic ferrite. This structure enables higher strength values than in the two previous cases.

The properties of the resulting structures are influenced not only by the fraction of individual phases, but especially by their morphology and distribution. While designing new procedures it is necessary to optimize individual processing parameters, in particular the austenitization temperature, cooling rate, and both the temperature and time period of the isothermal holding time for retained austenite stabilization. When using thermomechanical treatment other parameters accrue, such as the deformation rate and its temperature interval.

The optimization of the whole technological process on real technology is generally highly time consuming and expensive due to the number of experiments which need to be carried out using the trial & error method. To considerably increase the efficiency and acceleration of the optimization process, physical, material-technological modelling can be used. This method, which has been used for the research mentioned

below, enables the optimization of relevant parameters of the real process on small amounts of material.

2. Q-P PROCESS

The Q-P process represents a new type of heat treatment for low-alloy steels. The treatment is composed of quick quenching to a temperature between M_s and M_f, low-temperature tempering and cooling to room temperature. Unlike quenching and tempering, there is no transformation of supersaturated tetragonal martensite to cubic martensite with simultaneous formation of ferrous carbides during the low-temperature tempering. Carbon diffusing from the supersaturated martensite stabilizes the non-transformed austenite which remains stable even when cooled down to ambient temperature. In this case, the creation of carbides is suppressed by choosing a suitable alloying strategy and heat treatment conditions. [1, 2] The resulting structure is composed of martensite and stabilized foil retained austenite (Fig. 1). The amount of retained austenite depends on several parameters. It is the question of the lowest supercooling temperature during quenching, low-temperature tempering temperature, holding time at this temperature and chemical composition of the material.

3. THERMOMECHANICAL TREATMENT

When optimizing the Q-P process it is necessary to determine the influence of individual parameters to obtain a sufficient quantity of retained austenite, thus ensuring excellent mechanical properties. A deformation within the cooling phase is performed in order to refine the structure. Finding a suitable temperature interval for the deformation represents another optimization parameter.

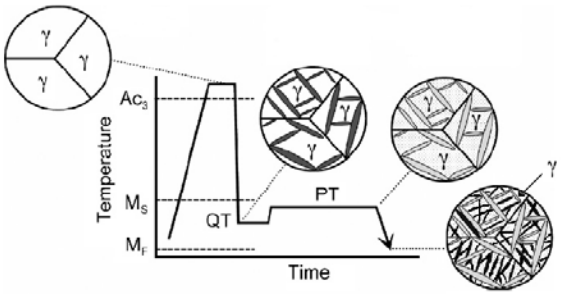

Fig. 1. Diagram of Q-P process showing microstructures [1]

3.1 Thermomechanical simulator

The material-technological modelling utilizing a thermomechanical simulator is used for the optimization process [3].
A thermomechanical simulator enabling precise operating of the temperature and deformation course mode has been developed at the Research Centre of Forming Technology FORTECH (Fig. 2). A unique control system enables

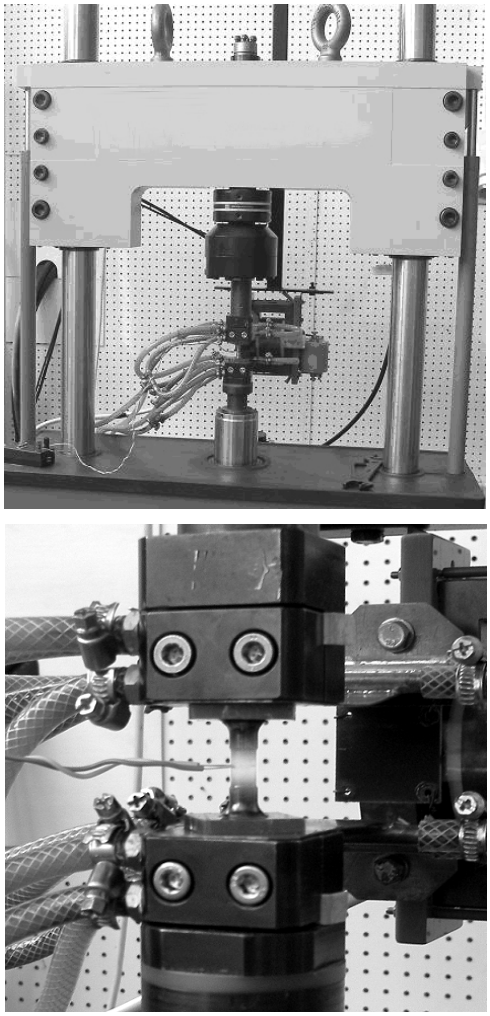

Fig. 2. Thermomechanical simulator at the Research Centre of Forming Technology FORTECH in Pilsen

rapid changes to temperature and deformation parameters, thus very accurately simulating real process conditions. For steels, temperature gradients of over 100 °C/s during the heating process and 250 °C/s during cooling can be achieved. A speed of 3 m/s can be reached by the deformation component. Apart from the in-built sensor array of the simulator, there are other external monitoring devices available which can be connected to the control and monitoring system of the simulator.

3.2 Model treatment

The model procedure of the Q-P process is used on experimental low-alloy steel designated 42SiCr. Silicon is one of the main alloying elements of this steel. It suppresses carbide formation throughout the martensite transformation. Another component is manganese, which stabilizes the austenite and reduces pearlite transformation [4]. Another alloying element is chromium which serves as a solid solution hardener.

The proposed model treatment entailed heating to 900 °C with a holding time of 100 s followed by a twenty step anisothermal deformation within a temperature interval from 900 to 820 °C. After deformation, several cooling strategies were carried out to determine their influence on the structure development, especially on the stabilization of retained austenite (RA). The RA fraction was determined using X-ray diffraction analysis, while neutron diffraction analysis was used to compare the results. The latter method enabled the deformation stability of RA to be determined in-situ.

In the experiment, the influence of the supercooling temperature between M_s and M_f and of the temperature of the holding time when carbon is isothermally redistributed was found.

In the first case the sample was cooled to 250 °C. It was held for 600 s at this holding time (Tab. 1). This temperature lies 40 °C below M_s. The resulting material

Mode	RA fraction [%]	HV 10 [-]	R_m [MPa]	A_{5mm} [%]
900°C/100s - 250°C/600s	-	604	-	-
900°C/100s - 300°C/600s	10	602	1342	4
900°C/100s - 200°C - 250°C/600s	15	546	2073	10
900°C/100s - 200°C/10s - 250°C/600s	16.5	546	2087	12
900°C/100s -water cooling to ambient temperature - 250°C/600s	4.5	558	1397	2

Table 1. Table of proposed thermo-mechanical treatment with Q-P process

structure was martensitic with hardness 604 HV10 (Fig. 3).

To determine the influence of the isothermal holding time the temperature was increased to 300 °C in the next strategy (Tab. 1). The experiment resulted in martensitic structure with visible RA areas with hardness 602 HV10 (Fig. 4). X-ray diffraction analysis determined the RA fraction to be 10%.

The influence of overcooling near the M_f temperature was examined in the next step to further support the stabilization of RA during cooling.

After multiple deformations in the temperature range 900-820 °C the sample was cooled to 200°C, which is just 20 °C

Fig. 3. Isothermal holding time 250°C/600 s

Fig. 4. Isothermal holding time 300 °C/600 s

over the M_f temperature. After cooling, the sample was heated immediately up to 250 °C, and held for 600 s (Tab. 1). Small ferritic grains were detected in the incurred martensitic structure (Fig. 5). X-ray diffraction analysis found that the retained austenite fraction significantly increased to 15%. Carbon diffusion from supersaturated martensite to austenite during the isothermal holding time probably caused reduction of hardness, as the measured hardness yielded just 546 HV10, which is 50HV less than in the case without overcooling at the same isothermal holding time. After this treatment, mechanical properties were examined by tensile testing. The tensile strength reached 2073 MPa with elongation A_{5mm} = 9.6%. In the next step it was necessary to determine if the holding time at the overcooling temperature before isothermal holding causes another increase in the RA fraction

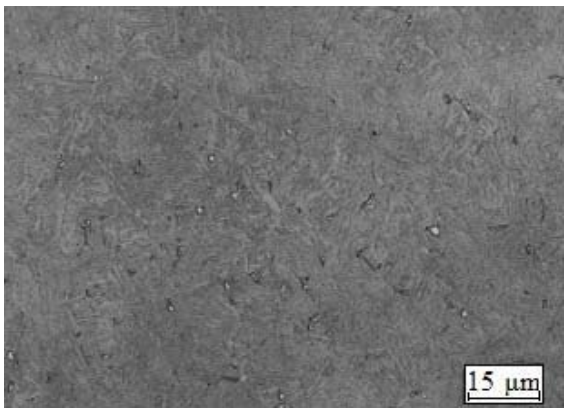

Fig. 5. Overcooling to 200 °C, isothermal holding time at 250 °C/600 s

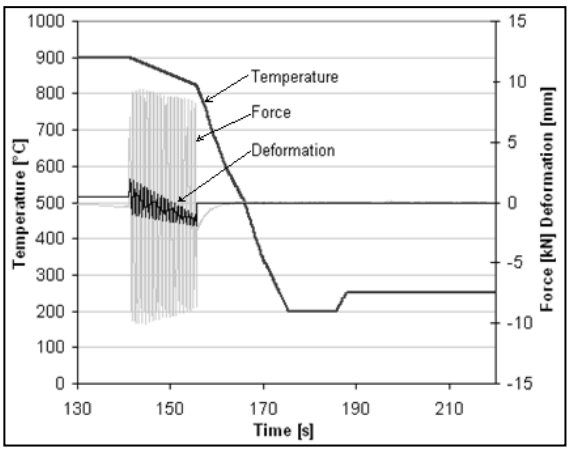

Fig. 6: TMT with twenty step incremental deformation

(Tab. 1, Fig. 6, Fig. 7). Therefore the sample was held for 10 s after overcooling at 200 °C. After this holding time, the sample was heated to 250 °C. A 600 s isothermal holding time at this temperature followed. In comparison with the previous mode without the 200 °C delay, another slight increase in the RA fraction to 16.5% occurred. The hardness of the structure remained unchanged. No significant changes to the mechanical properties were observed. Tensile strength yielded 2087 MPa and elongation A_{5mm} = 11.9%.

To compare, another structure development and RA fraction were experimentally verified on a sample rapidly cooled in water to ambient temperature with subsequent tempering at 250 °C (Tab. 1). Mainly martensitic structure with hardness 558 HV10 was observed on a confocal

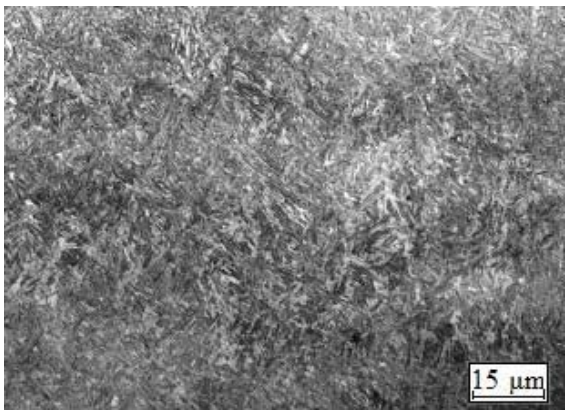

Fig. 7. Overcooling to 200 °C, delay 10 s, isothermal holding time 250 °C/600 s

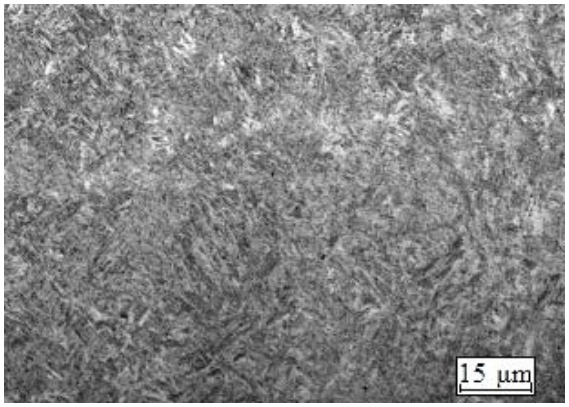

Fig. 8. Water cooling to ambient temperature with subsequent annealing at 250 °C/600 s

scanning laser microscope (Fig. 8). X-ray diffraction analysis revealed that ca. 4.5% RA was stabilized within the structure.

To compare, another structure development and RA fraction were experimentally verified on a sample rapidly cooled in water to ambient temperature with subsequent tempering at 250 °C (Tab. 1). Mainly martensitic structure with hardness 558 HV10 was observed on a confocal scanning laser microscope (Fig. 8). X-ray diffraction analysis revealed that ca. 4.5% RA was stabilized within the structure.

3.3 Neutron diffraction with tension load

To study the stability and the proportion of residual austenite during cold deformation, which have a large influence on the mechanical properties of obtained structures was used the *in-situ* neutron diffraction analysis with tensile load.

For this experiment were prepared samples with thermal scheme in which were achieved the best mechanical properties and the highest portion of retained austenite. It was the regime of 10 s holding time supercooling to 200 °C and subsequence heating to 250 °C with delay of 600 s.

The diffraction patterns were collected on the neutron powder diffractometer MEREDIT, which was equipped for this purpose with deformation rig. Course of the tensile load was controlled in the elastic region of deformation by the force applied to the sample. In the plastic deformation region it was the strain control regime with the help of the extensometer with the base of 3 mm. Neutron diffraction patterns of the deformation zone of the sample 4 x 6 mm^2 were collected in the range 10-110° 2θ with the step of 0.1° and delay of 200 sec in each step. The mosaic copper crystal monochromator was used to select the neutron beam of wavelength 1.46Å. Quantity of the retained austenite in the sample was obtained by Rietveld analysis of the collected patterns by the program FullProf [3]. Example of the measured and calculated diffraction pattern is shown in the Fig. 9. Amount of the retained austenite in the virgin sample obtained from the neutron and X-ray diffraction are in the good agreement. Evolution of the retained austenite content as a function of the total deformation is shown in the Fig. 10. In the elastic region there was a small decrease of RA content which continues also at the beginning of the plastic region of the deformation up to 0.75% of total sample deformation. Then followed by sharp decrease of RA content from 13.5% to 9%. With further deformation the RA content dwindled to around 6%. The rupture of the sample carried out with total deformation of 8%.

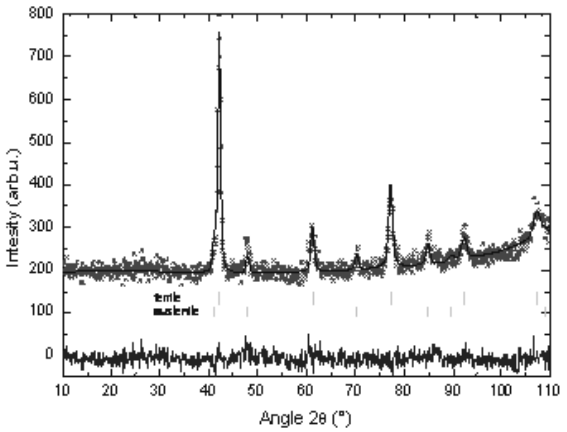

Fig. 9: Measured (stars) and calculated (line) neutron diffraction patter of the virgin state sample. Small vertical line represents the Bragg positions for two main phases as indicated.

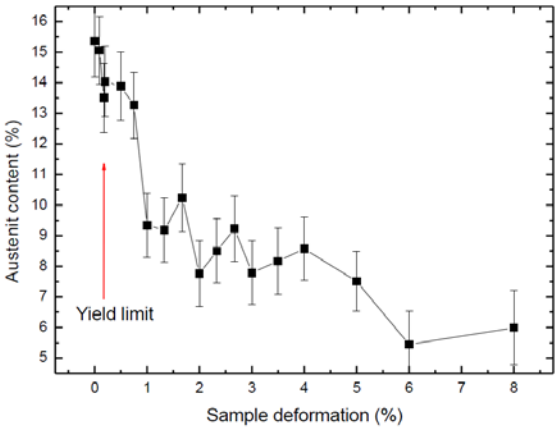

Fig.10. Evolution of the residual austenite content as a function of the total deformation.

4. CONCLUSION

In the course of the experimental programme three different cooling strategies were examined for the Q-P process. All three strategies resulted in martensitic structure with various RA fractions from 4.5 to 16.5%. It was found that the overcooling temperature between M_s and M_f temperatures plays a significant role on the stabilization of RA in the structure, and that a further increase in RA can be achieved by using suitably chosen parameters for the overcooling before heating to the temperature of the holding time, where carbon is being isothermally redistributed.

Structures with the highest RA fraction reached a tensile strength over 2000 MPa with a elongation A_{5mm} of 10%.

Neutron diffraction in-situ method during the tensile test showed that there was just a slight decrease in the RA fraction at the beginning. In the deformation range from 0.75 to 1% an intensive decrease from about 13% to 9% was observed. Further deformation caused only a slight decrease in the RA content. Even at 8% deformation, 6% of stable RA still remained in the structure.

5. ACKNOWLEDGEMENTS

This paper includes results created within the project 1M06032 Research Centre of Forming Technology and within the project 106/09/1968 Development of New Grades of High-Strength Low-Alloyed Steels with Improved Elongation Values. The projects are subsidised from specific resources of the state budget for research and development.

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