ABSTRACT
New methods of heat and thermo-mechanical treatment have been recently developed as a result of an increasing demand for materials with advanced properties. Better mechanical properties of semi-products enables weight reduction of products, decreasing of production costs and also energy savings during production process. Therefore unconventional strategies of heat and thermo-mechanical treatment have been developed particularly for high strength steels, resulting in significant improvement of mechanical properties in comparison with conventionally treated steels. Experiments were carried out to test several strategies of thermomechanical treatment of a newly designed low-alloyed high-strength steel 42SiCr. The aim of the experiments was to achieve high strength whilst maintaining relatively high ductility. To this end, thermomechanical processing was combined with special heat treatment Q&P (Quenching and Partitioning) process. By modelling the treatment on the thermomechanical simulator, a microstructure was obtained formed of a martensite matrix and finely diffused retained austenite between martensitic laths. After thermomechanical treatment, the microstructure of the steel was analysed using light and confocal microscopy.

KEYWORDS
Unconventional thermomechanical treatment, Q-P process, low-alloyed steel, thermomechanical simulator,

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. Carvide 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 stronger 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 iso-thermal holding time for retained austenite stabilization. When using thermo-mechanical treatment other parameters accrue, such as the deformation rate and its temperature interval.

The optimization of the whole techno-logical 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.

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 $M_f$ and $M_s$ 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 carbidites 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 carbidites 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]

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 rapid changes to temperature and de-formation 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.

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

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 structure was martensitic with hardness 604 HV10 (Fig. 3). To determine the influence of the iso-thermal 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 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%.

<table>
<thead>
<tr>
<th>Mode</th>
<th>RA fraction [%]</th>
<th>HV 10 [MPa]</th>
<th>Rm [MPa]</th>
<th>A_5mm [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>900°C/100s -250°C/600s</td>
<td>-</td>
<td>604</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>900°C/100s -300°C/600s</td>
<td>10</td>
<td>602</td>
<td>1342</td>
<td>4</td>
</tr>
<tr>
<td>900°C/100s -200°C -250°C/600s</td>
<td>15</td>
<td>546</td>
<td>2073</td>
<td>10</td>
</tr>
<tr>
<td>900°C/100s -200°C/10s -250°C/600s</td>
<td>16.5</td>
<td>546</td>
<td>2087</td>
<td>12</td>
</tr>
<tr>
<td>900°C/100s -water cooling to ambient temperature - 250°C/600s</td>
<td>4.5</td>
<td>558</td>
<td>1397</td>
<td>2</td>
</tr>
</tbody>
</table>

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

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

Fig. 4. Isothermal holding time 300°C/600 s
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 (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 scanning laser microscope (Fig. 8). X-ray diffraction analysis revealed that ca. 4.5% RA was stabilized within the structure.

---

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

**Fig. 6:** TMT with twenty step incremental deformation

**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
CONCLUSION
The results proved the wide-ranging possibilities for influencing the development of structures by varying the cooling strategies and parameters of the Q-P process. 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 $\Delta_{5\text{mm}}$ of 10\%. Further optimizing steps will lead to describing further influences of Q-P process on the development of structures.

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.

REFERENCES

