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NEW CONCEPT FOR MANUFACTURING CLOSED DIE FORGINGS OF HIGH STRENGTH STEELS

NOV KONCEPT IZDELAVE ODKOVKOV IZ VISOKOTRDNOSTNIH JEKEL V ZAPRTIH UTOPIH

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In the automotive industry, there is an ever growing demand for steel components with enhanced mechanical properties. Typically, this involves steels with high strength combined with adequate ductility. With improved properties, the structural components of these steels can be less bulky, requiring less material, energy and lower costs.
Processing a material to obtain high strength and high ductility at the same time used to be rather difficult. Today, it can be accomplished by incorporating retained austenite in a martensitic matrix. A new heat-treatment method for closed-die forgings, termed Q&P process (quenching and partitioning), leads to a combination of martensite and retained austenite with strengths above 2000 MPa and an elongation of 10-15 %.

Keywords: Q&P process, retained austenite, AHSS, closed-die forgings

V avtomobilski industriji narašča zahteva po komponentah iz jekla z izboljšanimi mehanskimi lastnostmi. Ta zadeva tudi jekla z visoko trdnostjo, v kombinaciji s primerno duktilnostjo. Zahvaljujoč izboljšanim lastnostim so te komponente iz jekel dimenzijsko manjše, ker je zanje potrebnega manj materiala, manj energije in tudi stroški so manjši.
Izdelava materiala, ki bi istočasno imel visoko trdnost in dobro duktilnost je težavna. Danes je to mogoče doseči in sicer z vključitvijo zaostalega avstenita v martenzitno osnovo. Nova metoda toplotne obdelave odkovkov iz utopov je Q&P postopek ali kaljenje in delitev, kar povzroči kombinacijo martenzita in zaostalega avstenita, s trdnostjo nad 2000 MPa in raztezkom 10–15 %.

Ključne besede: Q&P postopek, zaostali avstenit, AHSS, odkovki iz utopov

1 INTRODUCTION

Closed-die steel forgings produced by hot forging are made from preforms, which are converted into the desired part shape using plastic deformation in impression dies. Then, the workpiece microstructure must be altered to obtain the desired mechanical properties. A typical microstructure upon quenching consists of martensite. It exhibits high strength but very poor ductility. This causes problems in parts which may fail in service under their operating load. Hence, parts that contain martensite are normally tempered after quenching. Today, a handful of modern metallurgical procedures are available for achieving higher ductility. They include long-time low-temperature austempering, intercritical processing of TRIP steels, and the Q&P process. Long-time low-temperature austempering can produce tensile strengths of up to 1500 MPa and hardness levels of 600-670 HV10.[1] Long-time low-temperature austempering is characterised by holding times of several tens of hours at low temperatures. The resulting microstructure consists of very fine bainitic ferrite (**Figure 1**).[2] Due to the long processing times, this method has failed to find industrial use. The concept of TRIP steels relies on a mixture of bainite, ferrite and retained austenite formed by intercritical annealing and isothermal holding at the bainitic transformation temperature during a controlled cooling process[3] (**Figure 2**). The third method is the Quenching and Partitioning (Q&P) process, which allows strengths of more than 2000 MPa to be obtained, together with an elongation of about 10 %. An important factor in this process is the stabilisation of austenite in the martensitic matrix (**Figure 3**). One of the ways of obtaining a martensitic structure with the desired fraction of retained austenite is a special heat treatment procedure described

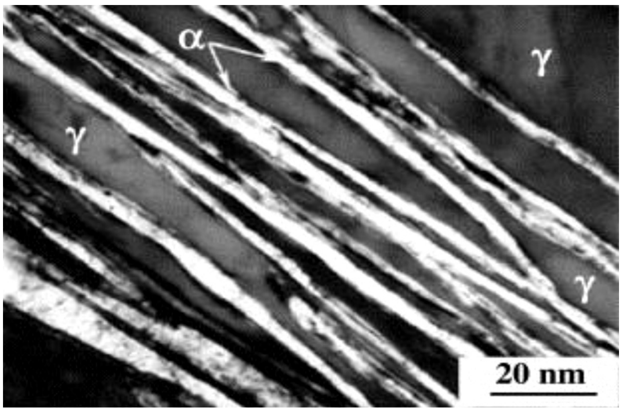

Figure 1: Microstructure produced by long-time austempering[1]
Slika 1: Mikrostruktura nastala pri dolgotrajnem austempranju[1]

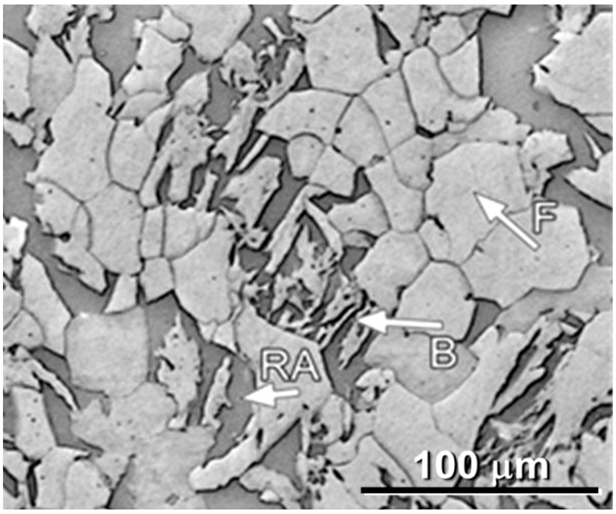

Figure 2: Typical microstructure of TRIP steel produced by intercritical annealing
Slika 2: Značilna struktura TRIP jekla po interkritičnem žarjenju

below. It is characterised by rapid cooling from the austenite region to a temperature between the M_s and M_f. During such cooling, martensite forms, whereas a portion of austenite remains untransformed. During subsequent isothermal holding, the retained austenite becomes stabilised thanks to carbon which migrates from the super-saturated martensite to austenite. According to current knowledge, this austenite exists primarily in the form of thin films between martensite laths or plates.[4–6] The present paper focuses predominantly on the Q&P process, a novel metallurgical procedure for heat treating forged parts. So far, this process has led to the best mechanical properties.

2 EXPERIMENTAL PROCEDURE

A major issue that affects the use of the Q&P process in practice is the necessity to interrupt the quenching between the M_s and M_f temperatures. With this challenge in mind, four new experimental steels have been proposed. Their particular compositions were designed to reduce the M_s and M_f temperatures (**Table 1**). In all of these experimental steels, the M_s and M_f temperatures were depressed through the addition of manganese. To increase the material's strength, silicon and chromium have been added as well. Silicon was chosen in order to prevent carbide formation and thus to provide adequate super-saturation of martensite with carbon. Molybdenum was employed to both reduce the M_s and M_f temperatures and shift the start of ferritic and pearlitic transformations towards lower cooling rates. Nickel was added in small amounts to stabilise austenite during cooling, to enhance hardenability and to provide solid solution strengthening. The carbon content was the same in all steels: between 0.42 % and 0.43 %.

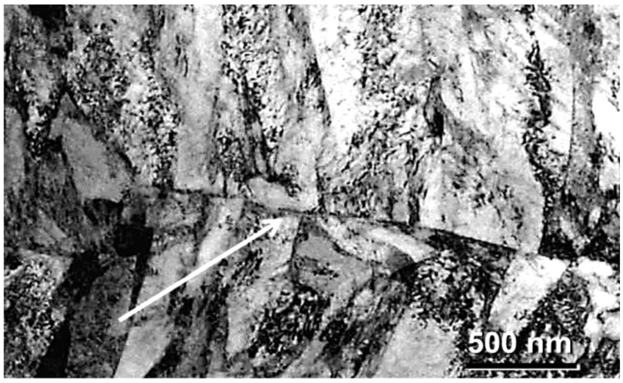

Figure 3: Prior austenite grain identified in martensitic matrix
Slika 3: Prvotna meja avstenitnih zrn, odkritih v martenzitni osnovi

In the AHSS-1 steel, the manganese level was 2.5 % and the silicon level was 2 %. The JMatPro software was used for calculating the approximate transformation temperatures. The calculated M_s and M_f temperatures in this steel were 218 °C and 88 °C, respectively. In order to map the effect of molybdenum on microstructural evolution and the shift in transformation temperatures in the AHSS-2 steel, its content was increased to 0.16 %. This increase in molybdenum content, however, has not altered the M_s and M_f temperatures in any substantial way. The M_s temperature was 214 °C and the M_f was 83 °C. In AHSS-3, the nickel level was set at 0.5 %, to achieve the desired hardenability and to depress the martensitic transformation temperatures. The M_s and M_f temperatures were 209 °C and 78 °C, respectively. In the AHSS-4 experimental steel, the molybdenum content was increased along with the nickel content. The combination of these elements led to the lowest transformation temperatures: M_s = 204 °C and M_f = 73 °C.

Table 1: Chemical compositions of experimental steels AHSS-1-4, in weight percents (*w*/%)
Tabela 1: Kemijska sestava eksperimentalnih jekel AHSS-1-4, v utežnih odstotkih (*w*/%)

	C	Mn	Si	Cr	Ni	Mo
AHSS-1	0.43	2.5	2.03	1.33	0.07	0.03
AHSS-2	0.428	2.48	2.03	1.46	0.08	0.16
AHSS-3	0.419	2.45	2.09	1.34	0.56	0.04
AHSS-4	0.426	2.46	1.99	1.33	0.56	0.15

2.1 Application of Q&P process to heat treatment of closed-die forgings

First, a heat treatment schedule for the forged parts has been developed. The development involved testing of various austenitising temperatures (T_A), two different quenching temperatures (*QT*), and various carbon partitioning temperatures (*PT*), using small specimens in a thermomechanical simulator MTS 810 (Material Test System). **Table 2** lists the parameters of the physical simulation, the resulting elongation values A_{5mm} and the fractions of retained austenite (*RA*) in the matrix.

Based on the results of this modelling, two experimental steels were chosen: AHSS-2 and AHSS-3. To verify the process, two complex-shaped closed-die forgings were made of these steels (**Figure 4**) by three forging steps. Two different bar dimensions were used for the forging process, with diameters of 45 mm, 31 mm and length of 160 mm, 180 mm. The forging was done at an automotive industry forging factory. These forgings were then heat-treated and their microstructures and mechanical properties evaluated using small flat specimens for tensile test machined from the forged parts with dimensions of 5 mm reduced section and a cross section 2 mm × 1.2 mm.

Table 2: Processing parameters of closed-die forgings in the physical simulation
Tabela 2: Parametri predelave odkovkov pri fizikalni simulaciji

T_A(°C)/ t_A (s)	Cooling rate (°C/s)	QT (°C)	PT (°C) /t_{PT} (s)	A_{5mm} (%)	RA (%)
850/300	1	150	200/600	15	18
850/100	1	150	200/600	10	10
850/100	1	100	150/900	15	14
850/100	16	125	175/600	6	9
850/100	16	150	200/600	8	11
850/100	16	100	150/600	4	8

3 RESULTS AND DISCUSSION

The best results of the physical simulation were obtained with the cooling rate of 1 °C/s. The ultimate strength was in the range of 2000–2400 MPa; the elongation was 15 % which corresponds to the higher volume fraction of retained austenite in the martensitic matrix, up to 18 % by volume.

Figure 4: Demonstration products: AHSS steels forgings heat-treated using the Q&P process
Slika 4: Demonstracijski proizvodi: odkovki iz AHSS jekla, toplotno obdelani z uporabo Q&P postopka

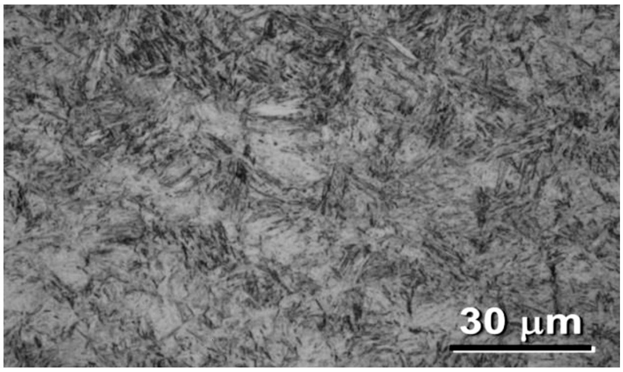

Figure 5: Light micrograph of martensitic structure with a small proportion of bainite. The processing sequence involved quenching in an oil bath at a temperature of 150 °C and austenite stabilisation in a furnace at 200 °C
Slika 5: Svetlobni posnetek martenzitne strukture z majhnim deležem bainita. Sekvenca obdelave je vključevala kaljenje v oljni kopeli pri temperaturi 150 °C in stabilizacijo avstenita v peči na 200 °C

Based on these findings, a low cooling rate has been recommended for processing the forgings. Heating to the austenite region was carried out in a furnace; the temperature was approx. 850 °C. Subsequent quenching in hot oil finished at 150 °C. Austenite was stabilised at 200 °C, thanks to the carbon which migrates from the super-saturated martensite to austenite. After the forgings heat treatment, the microstructure was examined and mechanical tests were carried out. Electron microscopy revealed the presence of a martensitic microstructure with a small amount of bainite (**Figures 5** and **6**). Quenching with hot oil led to an ultimate strength of up to 2300 MPa and an elongation of approximately 12 %. The retained austenite fraction in the martensitic matrix was 15 %.

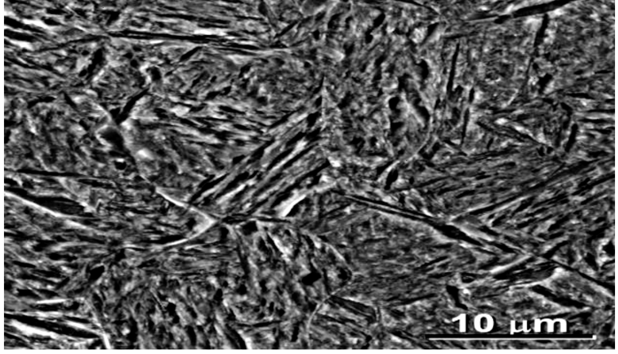

Figure 6: Scanning electron micrograph of a martensitic structure with a small proportion of bainite. The processing sequence involved quenching in an oil bath at a temperature of 150 °C and austenite stabilisation in a furnace at 200 °C.
Slika 6: SEM-posnetek martenzitne strukture z majhnim deležem bainita. Sekvenca obdelave je vključevala kaljenje v oljni kopeli pri temperaturi 150 °C in stabilizacijo avstenita v peči na 200 °C.

4 CONCLUSION

Heat treatment of forgings made of newly-developed experimental steels led to martensitic microstructures with a fraction of stabilised retained austenite. The heat-treating sequence was based on the quenching and partitioning process (Q&P).

First, physical simulation was carried out on specimens. The findings were then translated into the processing of real-life demonstration forgings. The physical simulation led to strengths of up to 2300 MPa and A_{5mm} elongation levels of approximately 12 %. As the amount, morphology and distribution of retained austenite have decisive impact on the resulting mechanical properties, an X-ray diffraction examination has been conducted. The retained austenite fraction was up to 15 %.

After the findings and parameters were translated into a real-life process, a simple heat treatment of actual forgings led to equivalent values of mechanical properties. The processing was carried out with hot quenching in oil to 150 °C and a furnace at a partitioning temperature of 200 °C.

The results of both physical simulation and real-life processing open new opportunities for closed-die forging. The key tasks for the future involve an optimisation of the cooling rate, a correct choice of cooling media and, where relevant, their unconventional application. High ultimate and fatigue strengths will permit the designs of forged parts to be altered towards thinner walls and more complex shapes. As a result, the utilization of material will improve and the weight of forgings will decrease, while the desired specifications of the product will still be met.

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