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ACCELERATED CARBIDE SPHEROIDISATION AND REFINEMENT (ASR) OF THE C45 STEEL DURING INDUCTION HEATING

POSPEŠENA SFEROIDIZACIJA IN UDROBNENJE KARBIDOV (ASR) MED INDUKCIJSKIM SEGREVANJEM JEKLA C45

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The present research focused on improving the mechanical properties of the C45 structural carbon steel. The microstructure of this material can be transformed, with the accelerated carbide spheroidisation and refinement (ASR) process, to increase the proof stress and ultimate tensile strength, as well as plasticity and toughness. In this study, the heat-treatment cycle was carried out using induction heating, which offers high heating rates. The process consists of rapid heating of the feedstock to the austenitizing temperature, a short hold, cooling down and rapid cycling at around the transformation temperature A_{c1}. Within a short interval of time, of the order of no more than a few minutes, this cycle produces a microstructure of fine ferrite grains with globular carbides. The present paper describes the impact of ASR process parameters on the mechanical properties and microstructure of the C45 steel.

Keywords: induction heating, grain refinement, carbide spheroidisation

Ta raziskava je bila usmerjena v izboljšanje mehanskih lastnosti konstrukcijskega ogljičnega jekla C45. Mikrostruktura tega materiala se lahko spremeni s postopkom pospešene sferoidizacije in udrobnenja karbidov (ASR), kar poviša mejo plastičnosti, natezno trdnost, kot tudi plastičnost in žilavost. V tej študiji je bil izveden cikel toplotne obdelave z indukcijskim segrevanjem, ki omogoča velike hitrosti segrevanja. Postopek sestavlja hitro segrevanje ogrevanca na temperaturo avstenitizacije, kratko zadržanje, ohlajanje in hitro cikliranje okrog temperature transformacije A_{c1}. V časovnem intervalu – ne več kot nekaj minut – to cikliranje povzroči nastanek mikrostrukture iz drobnih feritnih zrn z globularnimi karbidi. Članek opisuje vpliv procesnih parametrov ASR na mehanske lastnosti in mikrostrukturo jekla C45.

Ključne besede: indukcijsko segrevanje, udrobnenje zrn, sferoidizacija karbida

1 INTRODUCTION

Grain refinement in steels is a traditional process for enhancing their strength. It is often used in plain carbon steels where the appropriate treatment increases the yield strength and ultimate strength without additional alloying or hardening, thus saving costs.[1] In addition to the grain size, carbide morphology is important with regard to toughness. Where high toughness is required, globular carbides are the right choice, whereas lamellar pearlite is not a suitable type of microstructure. When obtaining the optimum combination of strength and toughness, the ideal microstructure consists of fine ferrite grains and globular carbides.

ASR (Accelerated Spheroidisation and Refinement) is a process producing fine grains and globular carbides throughout the workpiece in a very short time: of the order of no more than a few minutes.[2] This paper describes the results of an optimization of the ASR process using induction heating. This heating method allows the workpiece temperature to be changed very rapidly in contrast with conventional annealing in a furnace.[3]

2 EXPERIMENTAL WORK

The experimental material was hot rolled and normalized C45 structural steel. The chemical composition of the steel is listed in **Table 1**. The initial microstructure consisted of pearlite and ferrite with areas of lamellar pearlite (**Figures 1a** and **b**). The ferrite grain size was about 20 µm.

Heat treatment was carried out using a medium-frequency converter. The number of coils of the inductor was selected in such a way as to provide as homogeneous an electromagnetic field as possible in the coil centre, leading to a uniform temperature field. The heating was controlled by a PLC unit and the temperature was measured by means of a pyrometer and thermocouples (**Figure 2**). The heat-treated specimens were 15-mm-diameter bars with a length of 400 mm.

Table 1: Chemical composition of the C45 steel in mass fractions (*w*/%)
Tabela 1: Kemijska sestava jekla C45 v masnih deležih (*w*/%)

C	Mn	Si	P	S	Cr	Ni	Mo
0.47	0.70	0.23	0.026	0.017	0.07	0.02	0.007

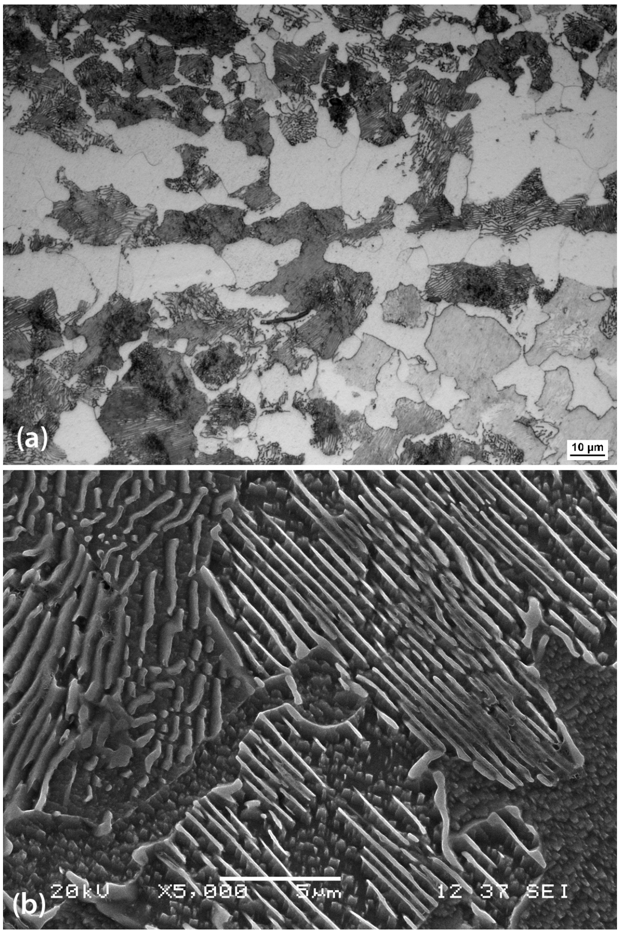

Figure 1: a) Optical micrograph of the initial microstructure, b) scanning electron micrograph of the initial microstructure
Slika 1: a) Svetlobni posnetek začetne mikrostrukture, b) SEM-posnetek začetne mikrostrukture

For the purpose of converting lamellar carbides to a globular morphology, schedules were designed with the temperature cycling at around or slightly above A_{c1} (see **Table 2**). The A_{c1} temperatures for both heating rates were determined from the temperature-time records of induction heating. A_{c1} for the heating rate of 80 °C/s was 762 °C and for 20 °C/s it was 747 °C. All the schedules comprised rapid induction heating, subsequent rapid temperature cycling and air cooling. Each of schedules 1, 2 and 3 had four temperature cycles. The maximum and minimum cycle temperatures varied. The difference between the maximum and minimum cycle temperatures was 60 °C. In schedule 1, the maximum cycle temperature was 740 °C; in schedule 2, it was 760 °C and in schedule 3, it was 780 °C. These schedules took 200 s, starting with heating and ending with cooling the specimen to 550 °C.

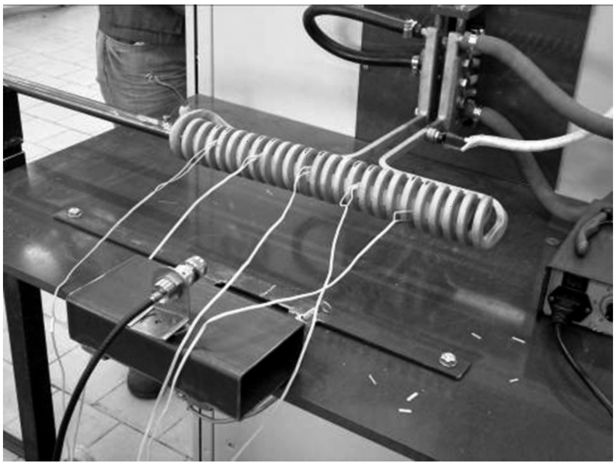

Figure 2: Induction heating of a sample
Slika 2: Indukcijsko segrevanje vzorca

Table 2: List of schedules
Tabela 2: Seznam zaporedja ukrepov

Schedule	Heating rate (°C/s)	Austenitizing (°C)	T_h/°C	T_l/°C	Number of cycles
1	80	–	740	680	4
2	80	–	760	700	4
3	80	–	780	720	4
4	80	840/25 s	–	–	–
5	80	840/25 s	740	670	4
6	80	840/25 s	780	720	4
7	20	–	760	700	4
8	20	–	780	720	4
9	20	840/25 s	780	720	4

Schedule 4 was designed for a microstructure refinement. It comprised austenitizing and the subsequent air cooling, i.e., essentially, a normalizing process. The combined normalizing and carbide spheroidising were intended to create fine ferrite grains with globular carbides (schedules 5 and 6). The austenitizing temperature was 840 °C. Schedule 5 included austenitizing at 840 °C, cooling in air to 600 °C, heating to 740 °C and additional three cycles at around this temperature. Schedule 6 was only different in the cycling temperature that was 780 °C. An overview of the schedules is given in **Table 1**. Schedule 4 took 250 s, while schedules 5 and 6 took about 300 s between the start of heating and cooling to the temperature of 550 °C.

Schedules 7, 8 and 9 were proposed with the aim of finding the influence of the heating rate on the material properties and microstructure. The heating rate was reduced from 80 °C/s to 20 °C/s. Apart from the heating rates, the pairs of schedules 7 and 2, schedules 8 and 3, and schedules 9 and 6 were identical.

3 RESULTS AND DISCUSSION

3.1 Metallography

The temperatures achieved with schedules 1 and 2 were not sufficient for an extensive austenitization of the microstructure. When compared with the initial microstructure, the grain size remained almost unchanged; part of the cementite lamellae in pearlite transformed to rod-like particles.

The temperature record for schedule 3 showed a temperature hold during cooling, indicating a pearlitic transformation. Temperature cycling, therefore, led to a partial austenitization accompanied by cementite dissolution. Cementite lamellae underwent a partial fragmentation (**Figures 3a** and **b**). The micrographs on these figures show a partial spheroidisation of cementite lamellae and a certain expansion of cementite into the ferritic regions.

Schedule 4 led to an almost complete microstructure austenitization. The resulting microstructure consists of ferrite and pearlite. Part of the pearlitic cementite is lamellar and part is spheroidised. Lamellar cementite was probably newly formed. Globular cementite appears to be the original spheroidised cementite that did not dissolve during the schedule. Cooling in air resulted in a rapid eutectoid transformation and the undissolved cementite lamellae acted as a nucleation agent.[4] It was mainly this schedule that produced considerably refined ferrite grains: from 20 μm to less than 10 μm.

Schedules 5 and 6 were designed as a combination of normalisation and the temperature cycling at around critical temperature A_{c1}. The initial stage of the sche-

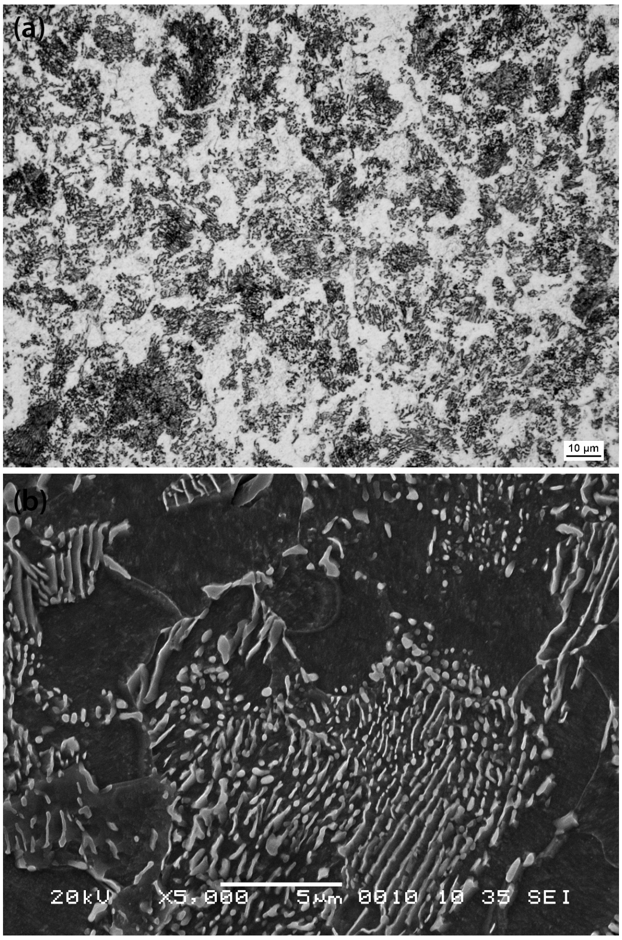

Figure 3: a) Optical micrograph after schedule 3, b) scanning electron micrograph after schedule 3

Slika 3: a) Svetlobni posnetek mikrostrukture po ukrepu 3, b) SEM-posnetek mikrostrukture po ukrepu 3

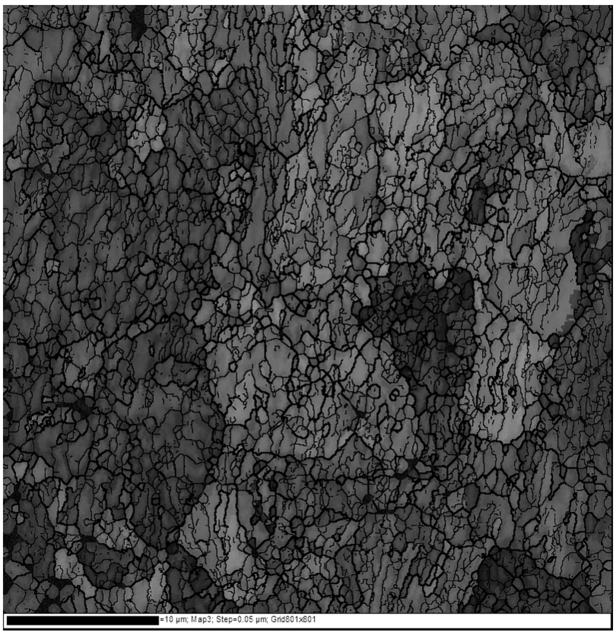

Figure 4: EBSD map with grain boundaries after schedule 5

Slika 4: EBSD-posnetek zrn z mejami zrn po ukrepu 5

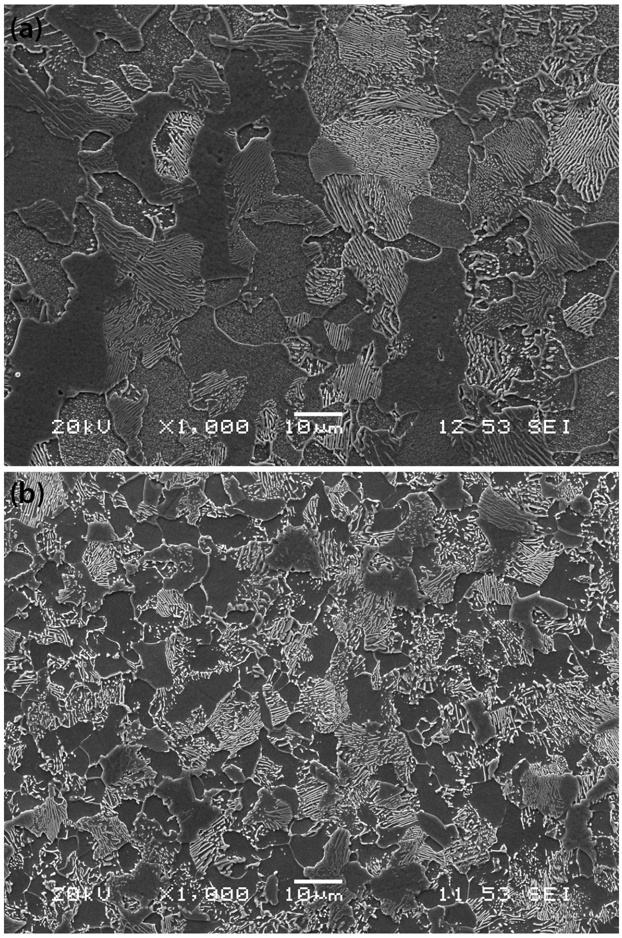

Figure 5: a) Scanning electron micrograph of the initial state, b) scanning electron micrograph after schedule 9

Slika 5: a) SEM-posnetek začetne mikrostrukture, b) SEM-posnetek mikrostrukture po ukrepu 9 dules was intended to refine the grains, whereas the cycles at a lower temperature were to spheroidize the carbides. The microstructures after schedules 5 and 6 were very similar. These schedules led to a grain refinement in the steel producing new carbide regions between the new finer grains, as did schedule 4. The cycling at around A_{c1} fragmented and partially spheroidised the cementite lamellae. The EBSD map (**Figure 4**) shows a substructure of the ferrite grains both in pearlite and ferrite regions. The thick lines represent high-angle boundaries (>15°) and the thin lines represent low-angle boundaries (from 2° to 15°).

In the schedules with lower heating rates, the temperature of 760 °C (schedule 7) was sufficient for a partial austenitization and a certain expansion of the cementite into ferritic regions to take place. It was due to the fact that, at lower heating rates, transformation start temperatures become lower. A partial austenitization at 760 °C is evidenced by the temperature record as well. The temperature records for all the schedules with lower heating rates (schedules 7, 8 and 9) showed a temperature plateau on the cooling curve, indicating a pearlitic transformation. Temperature cycling, thus, leads to a partial austenitization accompanied by cementite dissolution. The cementite lamellae underwent a partial fragmentation and the structure underwent a grain refinement. **Figures 5a** and **b** illustrate a comparison between the scanning electron micrographs of the initial state and the heat-treated sample 9. The heat-treated specimen underwent a grain refinement and a partial carbide spheroidisation (ASR).

3.2 Mechanical Properties

Tension tests were performed on the specimens with the diameter of 8 mm and length of 50 mm. The specimens used for impact testing were of the miniature Charpy type, with the size of 3 mm × 4 mm × 27 mm and a 1 mm deep V-notch. Hardness values were measured on the Vickers HV30 scale.

In **Table 3** you can see the results of proof stress (*PS*), ultimate tensile strength (*UTS*), elongation (A_5), area reduction (*RA*), impact toughness (*KCV*) and Vickers hardness (HV). The results for the initial state were: *PS* = 309 MPa, *UTS* = 642 MPa, elongation A_5 = 27 %, *RA* = 47 %, impact toughness *KCV* = 37 J/cm^2 and hardness reached 179 HV.

For schedules 1, 2 and 3, the proof stress increased with the growing temperature of the cycles. Schedules 1 and 2 led to a significant increase in the toughness that could have been caused by a recovery of ferrite grains. Schedule 3 did not cause a significant increase in the notch toughness, probably due to a formation of new fine lamellar pearlite.

The specimens treated according to schedule 4 showed a higher proof stress, a slightly higher ultimate strength and a higher toughness. This was due to the grain refinement. Schedule 5 led to a similar enhancement of the mechanical properties as schedule 4 but resulting in the highest proof stress and in a higher toughness. The specimens of schedule 6 did not have a higher toughness than the initial material. This might be attributed to the formation of a large amount of new lamellar pearlite during the final cycling at around 780 °C and 720 °C.

Table 3: Mechanical properties
Tabela 3: Mehanske lastnosti

Schedule	*PS*/ MPa	*UTS*/ MPa	A_5/%	*RA*/%	*KCV*/ (J cm^{-2})	HV
OS	309	642	27	47	37	179
1	381	645	29	48	99	165
2	387	645	30	49	93	167
3	390	633	32	57	41	169
4	417	653	30	56	52	174
5	431	660	29	55	58	178
6	426	643	32	61	38	174
7	356	613	32	60	61	169
8	403	635	31	58	58	178
9	423	638	32	60	62	180

A trend in the proof-stress values was apparent in the specimens treated with the schedules involving the heating rate of 20 °C/s or higher heating rates. The proof stress rose upon cycling at around a higher temperature, i.e., 780 °C. The specimens that were austenitized and subjected to cycling at around 780 °C exhibited an even higher proof stress: 423 MPa. Their ultimate strength was slightly lower or equal to that of the initial material. However, elongation as well as impact toughness increased for all three specimens. The highest impact-toughness and hardness values were found in the specimens for schedule 9. In this case, the impact toughness is higher than that of the specimen treated with the schedule with the highest heating rate. This might be attributed to the lower amount of new cementite lamellae. Despite that the difference in the mechanical properties of the specimens heated at higher and lower rates was not substantial. Hence, no significant impact of the heating rate on the mechanical properties of the material was found.

4 CONCLUSION

Grain refinement and partial carbide spheroidisation were achieved in the AISI C45 steel using induction heating. The temperature cycling at around the A_{c1} temperature was responsible for the change in the cementite morphology. Ferritic grain size was reduced by the austenitization and the following cooling in air. These changes in the microstructure were reflected in an increase in the proof stress, ultimate tensile strength and impact toughness, whereas the elongation value remained unchanged. The proof stress was increased by 120 MPa, the ultimate tensile strength by 20 MPa and the impact toughness by 20 J/cm^2 in comparison with the initial state. The schedule that led to this improvement in the mechanical properties took about 300 s and consisted of the normalizing and subsequent cycling at around the A_{c1} transformation temperature.

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