UDK 669.15-194:539.377
Original scientific article/Izvirni znanstveni članek

ISSN 1580-2949
MTAEC9, 47(3)335(2013)

ENERGY- AND TIME-SAVING LOW-TEMPERATURE THERMOMECHANICAL TREATMENT OF LOW-CARBON PLAIN STEEL

PRIHRANKI ENERGIJE IN ČASA PRI NIZKOTEMPERATURNI TERMOMEHANSKI OBDELAVI MALOOGLJIČNEGA PLOŠČATEGA JEKLA

Hana Jirkova[1], Daniela Hauserova[2], Ludmila Kucerova[1], Bohuslav Masek[1]

[1]University of West Bohemia, The Research Centre of Forming Technology – FORTECH, Univerzitni 22, 306 14 Pilsen, Czech Republic
[2]COMTES FHT, a.s., Prumyslova 995, 334 41 Dobrany, Czech Republic
h.jirkova@email.cz

Prejem rokopisa – received: 2012-09-21; sprejem za objavo – accepted for publication: 2012-10-16

Reduction of energy is one way of cutting the cost of finished steel products. In this context heat treatment is a costly stage of the production. This paper presents a method of reducing soft-annealing times. The method termed as ASR (accelerated spheroidization and refinement) was employed for improving the cold formability of the ferrite-pearlite steel.
In this study, plain low-carbon RSt-32 steel was used as the experimental material. The influence of deformation below the A_{c1} temperature on grain refinement and carbide spheroidization, as well the influence of the temperature cycling around the A_{c1} temperature within the temperature intervals of various widths were explored. In addition, attention was paid to the effects of the holding time between deformation steps and to the amount of deformation heat.
The initial lamellar pearlite was converted into a recrystallized structure with fine ferrite grains of about 3 µm and fine spheroidized cementite. The final hardness was about 150 HV10. This is by about 25 % lower than the hardness of the initial ferrite-lamellar pearlite structure. Significant time and energy savings can be reached as the treatment shortens the thermomechanical exposure from several hours to several minutes.

Keywords: pearlite morphology, soft annealing, incremental deformation

Zmanjševanje porabe energije je ena od poti za zmanjšanje stroškov končnih jeklenih proizvodov. V tem kontekstu je toplotna obdelava draga faza proizvodnje. Članek predstavlja metodo za zmanjšanje časa mehkega žarjenja. Metoda, označena z ASR (pospešena sferoidizacija in zmanjšanje zrn) je bila uporabljena za izboljšanje hladne preoblikovalnosti feritno-perlitnega jekla.
Za eksperimentalni material v tej študiji je bilo uporabljeno malooglj ično jeklo RSt-32. Preiskan je bil vpliv deformacije pod temperaturo A_{c1} na zmanjšanje velikosti zrn in na sferoidizacijo karbida, kot tudi vpliv nihanja temperature okrog A_{c1} v različno širokih temperaturnih intervalih. Dodatna pozornost je bila posvečena še učinku časa zadržanja med posameznimi deformacijami in na delež deformacijske toplote. Začetni lamelarni perlit se je pretvoril v rekristalizirano strukturo z drobnimi zrni ferita, velikosti okrog 3 µm in drobno sferoidiziranim cementitom.
Končna trdota je bila okrog 150 HV10. To je okrog 25 % nižje od trdote začetne strukture s feritom in lamelarnim perlitom. Mogoče je doseči pomembne prihranke v času in energiji, saj termomehanska obdelava skrajša potreben čas od nekaj ur na nekaj minut.

Ključne besede: morfologija perlita, mehko žarjenje, prirastek deformacije

1 INTRODUCTION

Reducing soft-annealing times is one of today's efforts in cutting down the production costs of cold-formed parts. Initial microstructures of the materials suitable for cold forming have a high formability. Such microstructures can be obtained through spheroidization of the cementite shape in pearlite.

Cementite can be spheroidized using several standard heat-treatment procedures. These include the following: a) isothermal annealing at a temperature slightly below A_{c1}, b) soaking at a temperature just above A_{c1} with slow cooling in the furnace, or with a hold just below A_{c1}, c) thermal cycling in the vicinity of A_{c1} [1]. In this context, the new ASR (accelerated spheroidization and refinement) procedure is highly effective[2,3] (**Figure 1**). It is an energy-saving thermomechanical-treatment procedure based on incremental deformation.

2 EXPERIMENTAL WORK

2.1 Experimental Material

The experimental material was cold-drawn, plain, structural steel RSt37 (S232 JRC) (**Table 1**). The as-received microstructure consisted of ferrite and lamellar pearlite. The ultimate strength, yield strength, elongation and hardness of the as-received material were 516 MPa, 450 MPa, 20 % and 200 HV10, respectively. The pearlite fraction found with an image analysis was 9 %. The ferrite-grain size was approximately 30 µm. The A_{c1} temperature found by dilatometric testing was 777 °C.

2.2 ASR Trial

To obtain the resulting microstructure of a very fine ferrite with spheroidized cementite, a number of processing parameters had to be optimised: the strain magni-

Table 1: Chemical composition of the RSt37-2 (S232 JRC) steel in mass fractions (%)
Tabela 1: Kemijska sestava jekla RSt37-2 (S232 JRC) v masnih deležih (%)

C	P	S	Mn	Si	N
0.08	0.022	0.023	0.65	0.16	0.004

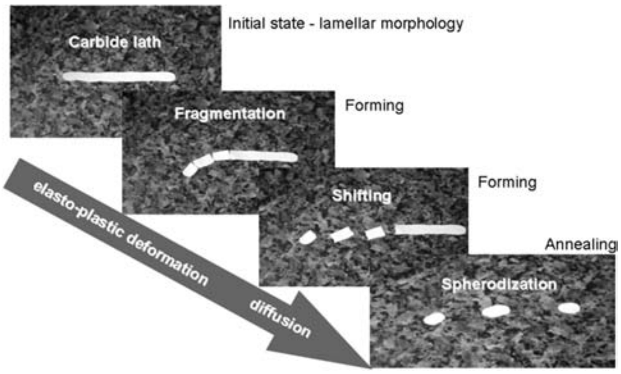

Figure 1: Scheme of the newly developed ASR process
Slika 1: Shematski prikaz novo razvitega postopka

tude, the deformation temperature and the holding time upon deformation. The effects of deformation heat and thermal cycling in the vicinity of A_{c1} were explored as well. The processing was performed in a thermomechanical simulator.[4]

With the aim to reduce spheroidization times as much as possible, pearlitic cementite lamellae must be not only fractured but also shifted further apart (**Figure 1**). This is why the schedules with two deformation steps were used for the initial experiment (**Table 2**). The first step was the tensile deformation with a strain magnitude of φ = 0.3, whereas the second step included intensive compressive deformation. The strain magnitude φ varied from 1.7 to 0.3 (**Table 2**). The effects of a 300 s hold following the deformation upon recrystallization were mapped. The soaking temperature and the time were 740 °C and 10 s, respectively. The heating rate was 30 °C/s. The schedules were followed by air cooling.

The effect of the thermal cycling between 740 °C and 780 °C, i.e., around A_{c1}, for 50 s (**Table 3**) was investigated. Two schedules were designed: one included deformation prior to the thermal cycling and the other was without deformation. An additional schedule included soaking at a reduced temperature of 700 °C and a thermal cycling within the range of 700–780 °C for 50 s.

The effect of deformation heat on the specimen temperature and carbide spheroidising was explored in the subsequent schedules (**Table 4**). At 700 °C, the tensile and compressive deformations with the magnitudes of 0.3 and 0.4 were applied with varied holding times between the deformation steps. The holding times were between 5–30 s and 5–9 deformation cycles were used. Finally, the specimens were water quenched for the mapping of the microstructure evolution.

While the initial schedules included deformation at a constant temperature, the additional schedules were used to explore the effects of the non-isothermal deformation, during which the specimen was cooled in air (**Table 5**). The increase in the specimen temperature due to deformation heat, the microstructure evolution and its morphology, the refinement and, in particular, the spheroidization processes were examined. A soaking temperature of 700 °C was used in both schedules of this stage.

Table 2: Thermomechanical-treatment parameters used for exploring the effect of magnitude of compressive strain and the impact of the hold
Tabela 2: Parametri termomehanske obdelave, ki je bila uporabljena za iskanje velikosti tlačnih napetosti in vpliv časa zadrževanja

T_A/°C	φ Tension+ compression	Hold upon def. (s)	HV10	R_m/ MPa	A_{5mm}/%
740	0.3 + 1.7	–	166	465	8
	0.3 + 1.7	300	121	421	20
	0.3 + 0.8	300	143	–	–
	0.3 + 0.3	300	141	–	–

Table 3: Effect of thermal cycling on microstructure evolution
Tabela 3: Vpliv toplotnega nihanja na razvoj mikrostrukture

T_A/°C	φ Tension + compression	Temp. range (°C)	HV10	R_m/ MPa	A_{5mm}/%
740	0.3 + 1.7	740–780	146	426	22
740	–	740–780	145	479	37
700	–	700–780	149	/	/

Table 4: Impact of deformation heat on microstructure evolution during a repeated deformation
Tabela 4: Učinek deformacijske toplote na razvoj mikrostrukture med ponavljanjem deformacij

T_A/°C	No. of def. steps	Time between def. steps (s)	HV10	R_m/ MPa	A_{5mm}/%
700	9	30	150	352	22
	9	10	155	–	–
	9	5	197	260	14
	5	30	140	–	–
	9	30 water	189	502	22

Table 5: Impact of non-isothermal deformation on microstructure evolution
Tabela 5: Vpliv neizotermne deformacije na razvoj mikrostrukture

T_A/°C	No. of cycles	Hold time between def. (s)	HV10
700	9	1	225
700	9	0	192

3 RESULTS AND DISCUSSION

3.1 Effects of Strain Magnitude and Holding Time

Using the ASR schedule with the soaking temperature of 740 °C and the tensile and compressive deformations (φ = 0.3 + 1.7), we broke up the cementite lamellae into the particles (**Figure 1**) of about 1 µm and refined the ferrite grains. The obtained microstructure showed a notable banding. The observation made with a scanning electron microscope revealed that the cementite spheroidization was extensive. The material's hardness, the ultimate strength and the A_{5mm} elongation were 166 HV10, 465 MPa and 8 %, respectively (**Table 2**). The elongation was rather low.

Then, an additional 300 s hold was incorporated, following the tensile-compressive deformation, to promote the recrystallization and to improve the carbide-spheroidising conditions. This hold caused a ferrite coarsening, a local carbide spheroidization and a more uniform distribution of carbides in the ferrite matrix (**Figure 2**). These microstructure changes were reflected in a low hardness of 121 HV10 and a low strength of 421 MPa. Recrystallization led to a higher elongation of 20 % (**Table 2**).

However, the amount of the strain used is too large for some technical applications. At the edges of the test specimen, where the nominal strain was somewhat lower, the ASR process appeared to be less intense. Based on this finding, two schedules were proposed, where the amount of strain in the second deformation step was decreased from φ = 1.7 to 0.8 and 0.3 (**Table 2**). The total strain levels in these schedules were φ = 1.1 and φ = 0.6. The reduction in the total amount of strain was reflected in the reduced hardness values of 143 and 141 HV10. The specimens treated with both schedules contained large lamellar-pearlite colonies.

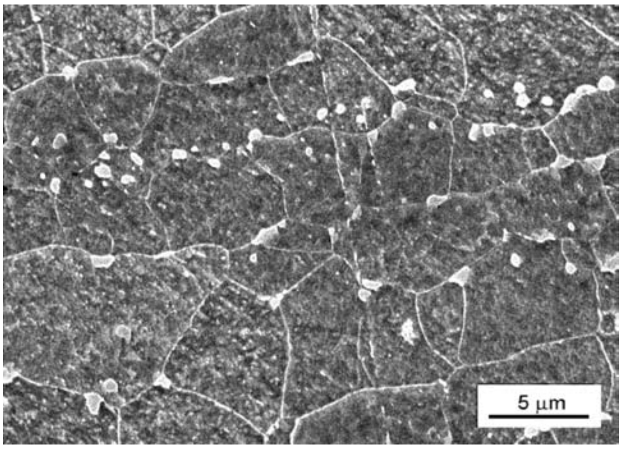

Figure 2: 740 °C/10 s – 2-times deformation step: tension + compression (φ = 2.1) with a hold of 300 s

Slika 2: 740 °C/10s – 2-krat stopnja deformacije: nateg + stiskanje (φ = 2.1) z zadrževanjem 300 s

3.2 Effects of Thermal Cycling on Microstructure Evolution

This stage of the study was aimed at verifying the theory that the thermal cycling with the upper limit above A_{c1} accelerates cementite spheroidization through a repeated dissolution of cementite and a formation of new nuclei (**Table 3**). Using the schedule with the thermal-cycling range of 740–780 °C, i.e., in the vicinity of A_{c1}, the specimen microstructure consisted of the ferrite with the grain size of above 20 µm and the pearlite colonies along the grain boundaries with the hardness of 145 HV10 (**Table 3**, **Figure 3**). When a lower heating temperature of 700 °C and a cycling within a wider temperature range were used, the resulting microstructure was coarser but showed the same hardness. The incorporation of a two-step tensile-and-compressive deformation cycle (φ = 0.3 + 1.7) at 740 °C, prior to the thermal cycling in the range of 740–80 °C led to a finer

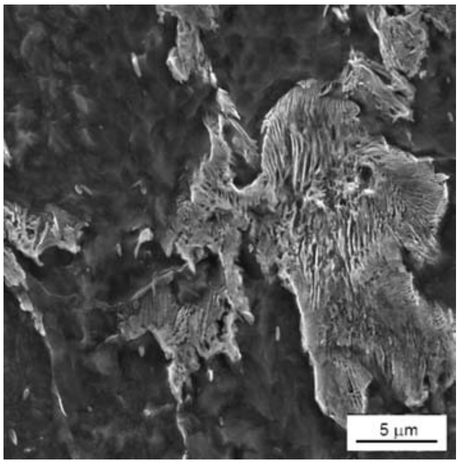

Figure 3: Effects of thermal cycling in the temperature range of 740–780 °C without deformation

Slika 3: Učinek toplotnih ciklov v temperaturnem področju 740–780 °C brez deformacije

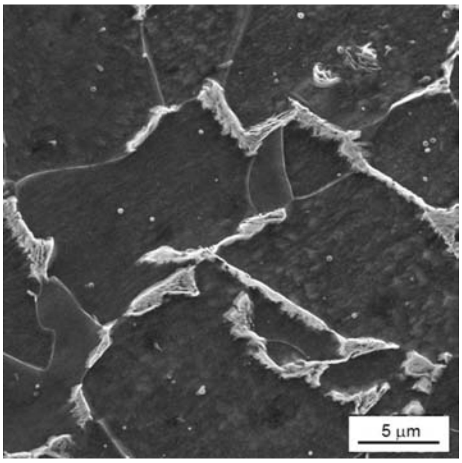

Figure 4: Effects of thermal cycling in the temperature range of 740–780 °C with deformation

Slika 4: Učinek toplotnih ciklov z deformacijo v temperaturnem področju 740–780 °C microstructure with a similar hardness value (**Table 3**, **Figure 4**). The grains were fully recrystallized and had a size of approximately 10 μm. In none of these cases the cementite precipitation within the ferrite grains occurred and the pearlite morphology was mainly lamellar.

3.3 Effects of Deformation Heat on Microstructure Evolution

At this stage of the study, the feasibility of the cementite spheroidization and microstructure refinement by applying deformation heat alone was explored. This deformation heat was to be generated by means of a two-step deformation at 700 °C, combined with the pauses of varying lengths (**Table 4**).

The schedule with 9 deformation cycles and 30 s pauses led to an increase in the specimen temperature to 720 °C over the first 5 deformation cycles. The fine, elongated ferrite microstructure with disintegrated pearlite islands and a hardness of 150 HV10 was obtained (**Figure 5**). Cementite was predominantly found along the ferrite-grain boundaries. However, there were some particles within the ferrite grains as well. The microstructure was substantially refined by the forming process. The ferrite-grain size was approximately 5 μm and most of the cementite particles were globular. The steel in this condition had a strength of 352 MPa and an elongation of 22 % (**Table 4**). Where 10 s pauses between deformation cycles were used instead of the 30 s ones, the resulting extent of recrystallization was lower. The final microstructure showed a strong banding and disintegrated, globular pearlite islands indicating the flow direction. The fact that the pauses were shorter by 20 s had no significant impact on the hardness. However, reducing the pauses further to 5 s led to a large increase in the hardness amounting to 197 HV10. The microstructure was similar to that obtained in the previous case. Where the number of deformation cycles was reduced from 9 to 5, the coarser ferrite was recrystallized (**Figure 6**). Its hardness was 140 HV10 (**Table 4**). The pearlite colonies disintegrated partially, remaining lamellar in character and situated on the ferrite-grain boundaries.

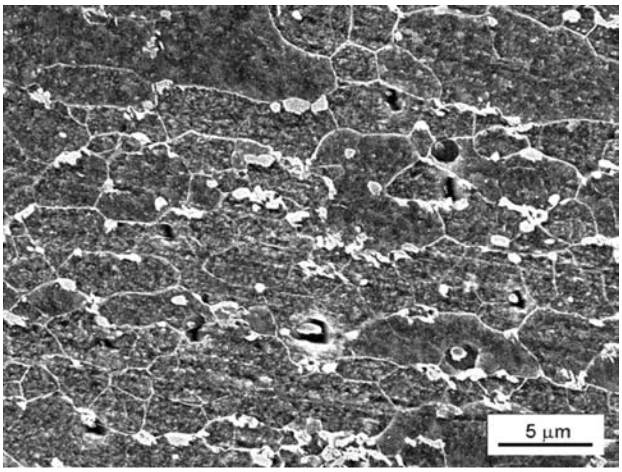

Figure 5: 700 °C/10 s – 9-times tension + compression (φ = 7.2), 30 s pause between deformation cycles
Slika 5: 700 °C/10 s – 9-krat nateg + tlak (φ = 7.2), 30 s premor med cikli deformacije

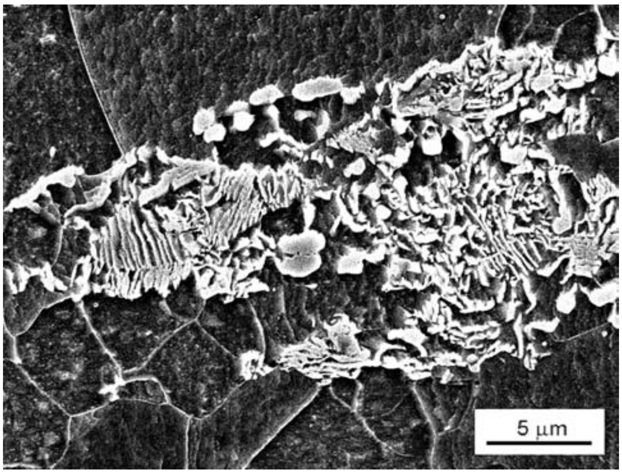

Figure 6: 700 °C/10 s – 5-times tension + compression (φ = 4), 0 s pause between deformation cycles
Slika 6: 700 °C/10s – 5-krat nateg + tlak (φ = 4), 0 s premora med cikli

3.4 Impact of Non-Isothermal Deformation on Microstructure Evolution

The last series of optimisation schedules was aimed at exploring the deformation schedules similar to the previous ones, except that the specimen was not kept at the heating temperature during either the deformations or the deformation pauses (**Table 5**). As the specimen was cooled in still air, the pause between deformation steps was either 1 s or zero.

The schedule with 1 s pauses between deformations led to a specimen failure in the 6^{th} cycle at 520 °C. The deformation heat was not sufficient to compensate for the heat losses, which is why the specimen temperature

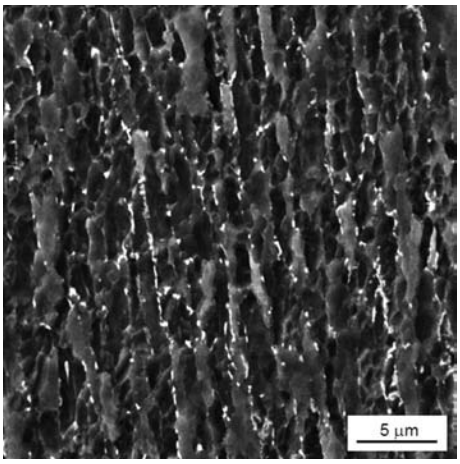

Figure 7: Effects of non-isothermal deformation without pauses
Slika 7: Učinek neizotermne deformacije brez premora

could not exceed 700 °C. The continuous deformation without pauses generated a deformation heat that increased the specimen temperature to 724 °C. The temperature decreased below 700 °C no sooner than during the 4th deformation cycle. In this case the specimen failed during the 7th cycle at 680 °C. Both schedules resulted in highly distorted microstructures with the fine, ferrite-grain and banded, elongated areas with globular cementite (**Figure 7**). Large strains led to the hardness values of 225 and 192 HV10.

4 CONCLUSION

The experimental programme consisted of a gradual optimisation of the low-temperature thermomechanical treatment of the RSt37-2 structural steel.

It was found that the processes of carbide spheroidization, grain refinement and cementite redistribution from the bands formed upon deformation are governed by the pause between deformation steps. Other important preconditions for a successful ASR process include the presence of strain components of sufficient intensity capable of breaking up and separating fragmented cementite particles through a plastic deformation. The spheroidization process can be accelerated substantially under these conditions. The optimum results of the experimental ASR process were achieved using the schedule with the soaking temperature of 740 °C and two-step tensile-compressive deformation with the following 300 s pause. This procedure led to a microstructure with fine, ferrite-grain and globular carbides. The yield strength of the resulting material was approximately 200 MPa, its ultimate strength was 421 MPa and the elongation was 20 %.

Acknowledgements

This paper presents the results achieved in the project GA CR P107/10/2272 "Accelerated Carbide Spheroidization and Grain Refinement in Steels". The project has been subsidised from specific resources of the state budget for research and development.

5 REFERENCES

[1] A. Kamyabi-Gol, M. Sheikh-Amiri, Spheroidizing Kinetics and Optimization of Heat Treatment Parameters in CK60 Steel Using Taguchi Robust Design, Journal of Iron and Steel Research International, 17 (**2010**) 4, 45–52

[2] B. Masek, H. Jirkova, L. Kucerova, Rapid Spheroidization and Grain Refinement Caused by Thermomechanical Treatment for Plain Structural Steel, Materials Science Forum, 706–709 (**2012**), 2770–2775

[3] D. Hauserova, J. Dlouhy, Z. Novy, J. Zrnik, M. Duchek, Forming of C45 Steel at Critical Temperature, Procedia Engineering, 10 (**2011**), 2955–2960

[4] B. Mašek et al., Physical modelling of microstructure development during technological processes with intensive incremental deformation, The Mechanical Behaviour of Materials X, 345–346 (**2007**), 943–946