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Various Approaches to Accelerated Carbide Spheroidization of 54SiCr Steel

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Abstract. Changing the lamellar morphology of pearlite to a globular morphology significantly enhances the formability of pearlite-ferrite steels. This change is conventionally achieved by soft annealing. Annealed structures possess low yield strength and excellent ductility and this ensures their good cold formability. The problems of these technologies lie not only in long processing times, but also in high energy consumption which makes the final product quite expensive. The time necessary for cementite spheroidization can be shortened by unconventional heat treatment around A_{c1} temperature combined with deformation applied at various processing stages. Several processing methods were utilized for spring steel 54SiCr with ferrite-pearlite original microstructure and lamellar pearlite morphology. The hardness of this structure reached 290 HV10. Three main strategies were tested in this work, using either tensile and compression deformation with following hold applied at heating temperature, temperature cycling around A_{C1} temperature, or deformation cycles applied at heating temperature. First of all, various heating temperatures in the region of 680-740°C were tested to determine the most suitable heating temperature for this steel. Subsequently, the influence of the character and intensity of applied deformations on cementite spheroidization and ferrite grain refinement were investigated. Carbide morphology and distribution were determined by the means of light and scanning electron microscopy and mechanical properties were determined by hardness measurement. Spheroidized carbides evenly distributed in fine ferrite matrix were obtained after the optimization of processing parameters.

Introduction

Cold formed parts find applications in many branches of the industry. Steels with lamellar pearlite have low deformability in comparison to microstructures with globular carbides. Time consuming soft annealing at a temperature just below or around A_{C1} is therefore conventionally used to ensure carbide spheroidization [1]. Soft annealed microstructures possess good formability due to their low yield point and high ductility. Their properties are influenced also by carbide size and distribution. Globular carbides provide a much lower number of defect initiation sides than lamellar carbides. Shortening of the spheroidization process will significantly decrease energy consumption and therefore also processing costs.

This work describes new concepts of thermo-mechanical processing resulting in a more efficient spheroidization process. Thermo mechanical processing can also refine the ferrite matrix at the same time. The main aim of the experimental work was to design new cost-saving methods of low-temperature thermo-mechanical processing of low carbon steel 54SiCr with implemented incremental deformation. The processing strategies used in this work combine different heating temperatures and deformation schedules, which influence carbide morphology, size, distribution and the overall texture of the material.

Experimental program

Spring steel 54 SiCr with higher silicon content was used for this experimental work (Tab. 1). The original microstructure was ferritic-pearlitic with lamellar morphology of pearlite. Transformation temperatures of this steel, according to material sheets, are as follows: A_{C1} = 765°C, A_{C3} = 815°C, M_s = 310°C. The tests carried out on the simulator however suggested that for the processing parameters used in this work, particularly for a high heating rate of 30°C/s, the A_{C1} temperature of this steel is around 720°C. The samples were processed on a thermo-mechanical simulator which allows the exact control and monitoring of deformation and temperature parameters of the process, which might include rapid incremental deformations. Due to these abilities, precise temperature and deformation parameters can be set up, similar to the real processes of technology or material development. This equipment also enables rapid changes in process parameters. Particularly for steels, temperature gradients of over 250°C per second for heating and cooling can be achieved and a speed of 3 m/s can be reached by the deformation component.

Tab. 1. Chemical composition of 54SiCr steel in weight % (ČSN 41 4260)

C	Mn	Si	Cr	Ni	Cu	P	S
0,5–0,6	0,5–0,8	1,3–1,6	0,5–0,7	max 0,5	max 0,3	max 0,035	max 0,03

Thermo-mechanical processing. To obtain a new processing strategy which would guarantee good formability of processed material and at the same time keep the processing efficient, several processing parameters have to be optimized (Tab.2).

Different processing strategies were therefore designed and carried out to obtain a microstructure with a fine dispersion of globular cementite in a matrix of fine-grained ferrite. Based on the results obtained previously at RSt37-2 steel [3], three main strategies were tested. The first one consisted of one tensile and one compression deformation and subsequent hold of 100s applied at soaking temperature. It was already observed that the hold in this case supports the diffusion process in cementite and has a positive effect on the final microstructure [4,5]. First of all, to maintain the low energy consumption of the process, it is necessary to keep a soaking temperature at the lowest possible value. The first experiments were therefore dedicated to the choice of the most suitable soaking temperature. Four temperatures, 740, 720, 700 and 680°C were tested; the hold at the temperature was always 10s and subsequent deformation steps consisted in all three cases of tensile and compression with logarithmic deformation 0.3 and 0.544, respectively. The hold at heating temperature after deformations was 100s. It is further assumed that the size of deformation might influence the size and distribution of the carbides. The best results were obtained after soaking at 700°C and this temperature was therefore used for all following experiments. The processing with a heating temperature of 700°C was therefore repeated with compression deformation increased to φ=1.7. The hold at 700°C was at the same time prolonged from 100s to 300s to support diffusion, recrystallization and cementite spheroidization. For the processing with heating at 680°C followed by tensile and compression with logarithmic deformation 0.3 and 0.544, respectively, even longer hold of 1000s was necessary to obtain globular carbides with regular distribution (Tab. 2).

The second processing strategy was based on heating below AC1 and temperature cycling around AC1 temperature. The temperature was varied between 700 and 740°C ten times. In one case, tensile and compression deformations at 700°C preceded the temperature cycling and in the second case were applied only temperature cycles without any deformation were applied (Tab.2).

The third processing strategy used deformation cycling at 700°C, which generated enough deformation heat to increase the temperature of the sample above AC1 temperature. The strategy consisted of five deformation cycles applied at the soaking temperature of 700°, either with or without 5s holds between individual deformation cycles. Each cycle consisted of tensile and compression with logarithmic deformation 0.3 and 0.544.

Tab. 2. Parameters of thermo-mechanical treatment and hardness HV 10

<table>
<tr><td>Heating
[°C] / [s]</td><td>Logarithmic deformation
tensile +compression</td><td colspan="2">Hold after deformations
[°C] / [s]</td><td>HV 10</td></tr>
<tr><td>740 /10</td><td rowspan="5">0.3 + 0.544</td><td colspan="2">740 /100</td><td>286</td></tr>
<tr><td>720 /10</td><td colspan="2">720 /100</td><td>262</td></tr>
<tr><td>700 / 10</td><td colspan="2">700 / 100</td><td>262</td></tr>
<tr><td rowspan="2">680 / 10</td><td colspan="2">680 / 100</td><td>293</td></tr>
<tr><td colspan="2">680 / 1000</td><td>273</td></tr>
<tr><td rowspan="2">700 /10</td><td rowspan="2">0.3 + 1.7</td><td colspan="2">700 /100</td><td>302</td></tr>
<tr><td colspan="2">700 /300</td><td>273</td></tr>
<tr><td></td><td></td><td colspan="2"></td><td></td></tr>
<tr><td>Heating
[°C] / [s]</td><td>Logarithmic deformation
tensile +compression</td><td colspan="2">Temperature cycles of heating and cooling</td><td>HV 10</td></tr>
<tr><td rowspan="2">700/10</td><td>0.3 + 0.544</td><td colspan="2" rowspan="2">10 cycles from 700 to 740°C</td><td>261</td></tr>
<tr><td>-</td><td>266</td></tr>
<tr><td></td><td></td><td colspan="2"></td><td></td></tr>
<tr><td>Heating
[°C] / [s]</td><td>Logarithmic deformation
tensile +compression</td><td>Number of deformation cycles</td><td>Hold between deformations [s]</td><td>HV 10</td></tr>
<tr><td rowspan="2">700/10</td><td rowspan="2">0.3 + 0.4</td><td rowspan="2">5</td><td>5s</td><td>271</td></tr>
<tr><td>-</td><td>277</td></tr>
</table>

Results

Microstructure. Four different heating temperatures 680, 700, 720 and 740°C were tested with two deformation steps and 100s hold at heating temperature (Fig. 1- Fig. 3). Deformation heat generated by applied deformation consisting of tensile and compressive step (φ=0.3+0.544) caused, at all investigated temperatures, an increase of the temperature of the material to 736, 757, 745 and 767°C respectively. This means that even though heating temperature was below A_{C1}, the temperature during the processing increased above A_{C1}. The microstructures were ferritic-pearlitic with very different carbide morphology. The heating temperature of 700°C was found out to be the most convenient one, as the final microstructure possessed relatively fine globular cementite. The size and distribution of carbides is not completely heterogeneous, there are several areas where carbides were predominantly found at grain boundaries (Fig. 3). However, most of the carbides are distributed evenly within the ferrite grains. Higher heating temperatures resulted in coarsening of cementite and formation of lamellar pearlite (Fig. 2) and purely lamellar pearlite was obtained at the highest heating temperature (Fig. 1). The lowest heating temperature of 680°C was also sufficient to obtain globular carbides, however their distribution was very uneven and they formed visible bands in the final microstructure (Fig. 4). Ten times longer hold at 680°C (1000s) was necessary to ensure more regular distribution of carbides (Fig. 5).

Higher compressive deformation with φ=1.7 applied at 700°C was able to achieve dispersion of finer carbides (Fig. 6), however the carbides formed more pronounced bands in the final microstructure in comparison with the same processing with lower compressive deformation with φ=0.544 (Fig. 3). Prolongation of the hold from 100 to 300s did not caused any significant changes in the final microstructure. The bands of spheroidized cementite were found in the ferrite matrix.
Processing strategies based on temperature cycling offered very distinguished different results depending on the application of deformations during the cycling. Pure heat treatment without deformation did not succeeded in changing the original lamellar morphology of cementite. Very coarse lamellar pearlite dominated the final microstructure (Fig. 7). Addition of tensile and compressive deformations to temperature cycling however refined and spheroidized the cementite.

Globular cementite of various sizes was formed in bands and its distribution was not homogeneous (Fig. 8).

The third processing strategy used deformation cycling at 700°C with or without 5s hold between deformation cycles. Deformation heat of each deformation cycle influenced the temperature of the sample. For the processing with 5s hold between the cycles the sample temperature was increased to 740°C during the first deformation cycle and only to 724°C during the second cycle. The rest of the deformations already did not increase the temperature above 720°C, which is the value of A_{C1} determined for this material heated at 30°C/s. In the case of the processing without the hold the temperature of the sample increased to 745°C during the first deformation and it remained at this level till the third deformation cycle. The processing with 5s holds obtained globular carbides with more homogeneous distribution, however even in this case the carbides slightly follow deformation texture of the material (Fig. 9). The texture is more apparent after the processing without the holds between deformations. Very fine areas of a mixture of pearlite and globular carbides form bands in the ferrite matrix (Fig. 10).

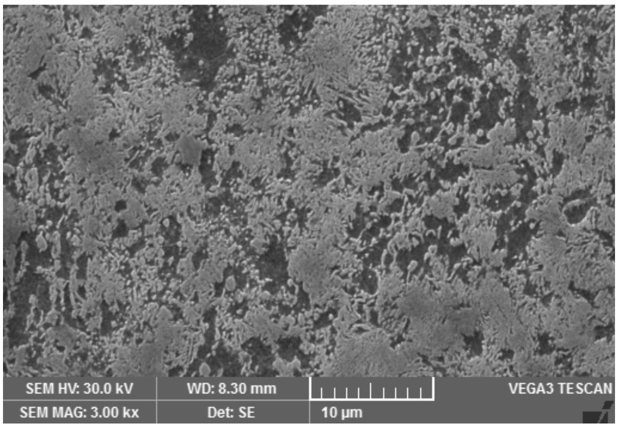

Fig. 1. 740°C-(0.3+0.544)-100s, lamellar pearlite

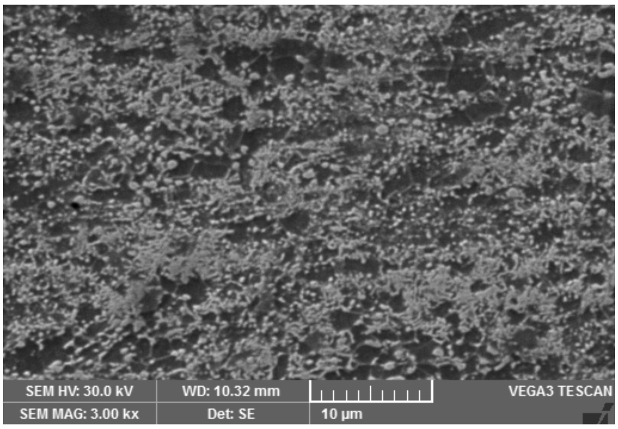

Fig. 2. 720°C-(0.3+0.544)-100s finer areas of lamellar pearlite

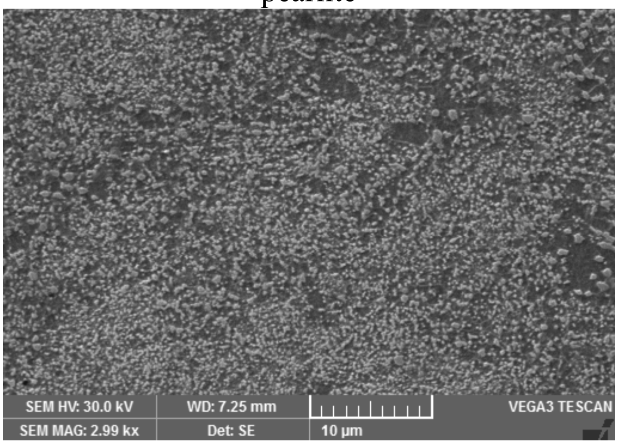

Fig. 3. 700°C-(0.3+0.544)-100s, globular cementite with area of uneven size and distribution of particles

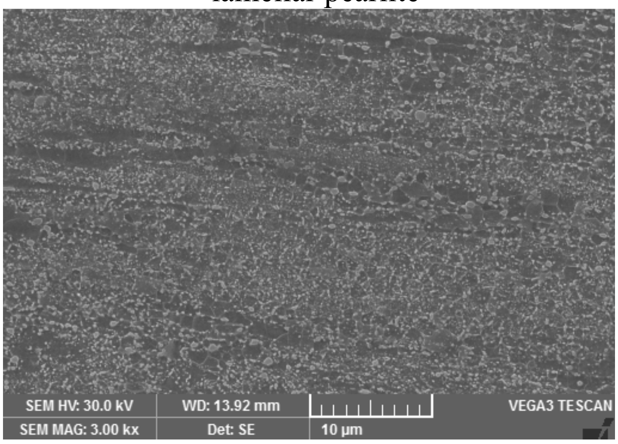

Fig. 4. 680 °C (0.3+0.54) -100s, fine distribution of globular carbides of various sizes, bands of ferrite grains without carbides

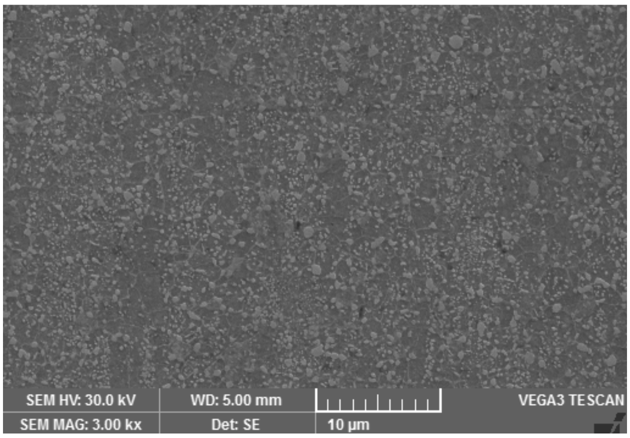

Fig. 5. 680°C – (0.3+0.54) -1000s, globular cementite, uneven size and realtively regular distribution of particles

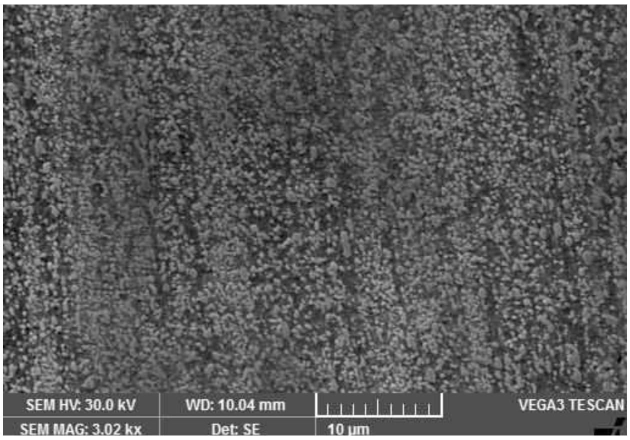

Fig. 6. 700°C-(0.3+1.7)-100s, particles of globular cementite form bands

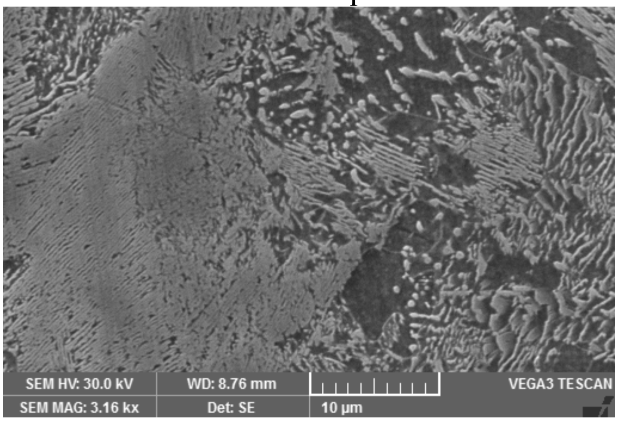

Fig. 7. 700°C-temperature cycles without deformation, coarse pearlite

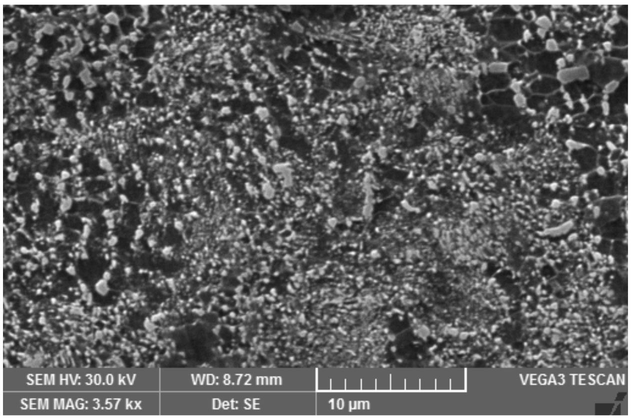

Fig. 8. 700°C-(0.3+0.544)-temperature cycles, globular cementite with uneven size and distribution

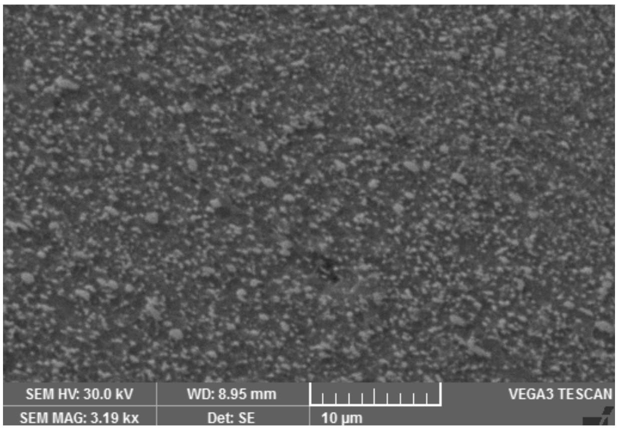

Fig. 9. 700°C- 5 deformation cycles-5s, globular cementite with uneven size and relatively regular distribution of particles

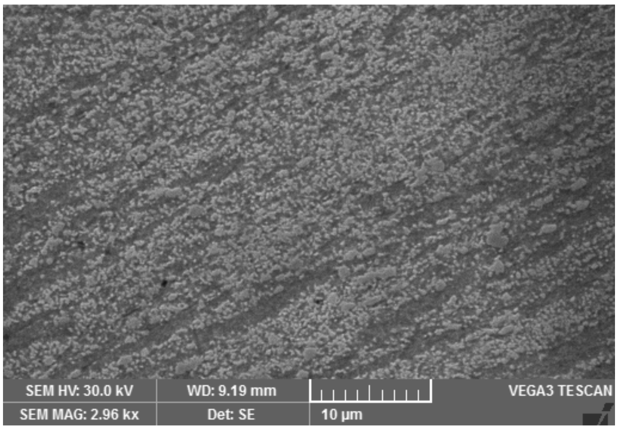

Fig. 10. 700°C- 5 deformation cycles-without hold, bands of globular cementite and very fine pearlite

Hardness Final hardness is an important parameter of soft annealed steels and therefore hardness HV10 was evaluated for all processing strategies used in this work (Tab. 2). HV 10 reached different values from 261 to 302. The hardness of initial state with lamellar pearlite morphology was 290 HV10. Higher amount of applied deformation and higher heating temperature generally increased the hardness of the final microstructure. The highest hardness 302 HV10 was measured in the microstructures processed by higher compressive deformation and shorter hold at the heating temperature 700°C.

Conclusions

Three main strategies of thermo-mechanical processing were designed and tested with the aim of obtaining a microstructure with spheroidized carbides evenly distributed in a ferrite matrix. The strategies used either tensile and compression deformation with following hold applied at heating temperature, temperature cycling around A_{C1} temperature, or deformation cycles applied at heating temperature. Spheroidization of carbides was achieved for each strategy by optimization of processing parameters. The carbides were formed not only at grain boundaries, but also inside of ferrite grains. The typical ferrite grain size was in the range of micrometers. However, the distribution of globular carbides has remained an issue, as carbide formation tended to follow deformation texture of the matrix.

The results suggested that the energy of the applied deformation is important for segmentation of cementite lamellas while holds of suitable length at deformation temperatures are necessary to support carbon diffusion. Very important for the final carbide morphology turned out to be the combination of heating temperature and the amount of deformation applied at this temperature. Decrease of the heating temperature from 740 to 700 °C had a positive effect on microstructure refinement and spheroidization of cementite. Increase of compressive component of deformation from $\varphi= 0.5$ to 1.7 did slightly refine carbide size but it brought further heterogeneity into carbide distribution. Carbide particles formed more pronounced bands as the result of severe plastic deformation of the whole material.

The most suitable microstructures with globular carbides and little texture resulted from the processing with heating temperature of 700°C, tensile and compressive deformation utilized at this temperature and subsequent 100s hold or from heating at 680°C followed by the same deformations as in the previous case and subsequent hold of 1000s. This result is very promising for possible practical application in the future, as it is in keeping with the general trend of thermo-mechanical treatment aimed at enhancement of cost and energy efficiency.

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