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Combined effects of strain and cooling path on hot deformation response and microstructure of low-carbon structural steel

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ABSTRACT

Purpose: The aim of the paper is to analyse the effect of thermomechanical process with different cooling paths on microstructure and mechanical properties of low-carbon structural steel.

Design/methodology/approach: The steel used for the investigation was subjected to two step deformation using a Gleeble 3800 simulator and then held at designed temperatures from 650°C to 800°C for different times. A final step included water cooling to room temperature to freeze the microstructure. Typical microscopic studies have been done. The analysis of the volume fraction of presented phases was carried out together with the measurement of grain size by means of image analysis. The last part of conducted research was hardness analysis of the steel after the different heat treatments.

Findings: It was found that the microstructure constitution and grain size are strongly dependent on the temperature of isothermal holdings. The microstructure of steel held at 800°C is composed of the mixture of bainite and two kinds of ferrite: globular and acicular. When the temperature was lowered by 50°C the ferrite shows the globular morphology. When the temperature drops to 700°C and below it, the microstructure is composed of ferritic-pearlitic mixture. It was observed that when the isothermal temperature was increased the grain size decreased and the opposite effect was observed for the holding time. The longer the time of the isothermal holding, the larger was the grain size.

Research limitations/implications: For better understanding of the phase transformation kinetics in this steel the dilatometric test are planned.

Practical implications: The knowledge of the microstructure evolution and hot deformation response of low-carbon structural steels is important from the industrial point of view.

Originality/value: The combined effects of hot deformation and different cooling paths give the useful information on a microstructure evolution.

Keywords: Structural steel, Low-carbon steel, Hot deformation, Thermomechanical process, Gleeble simulator, Cooling path

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MATERIALS

1. Introduction

Structural steels belong to the most often used steel grades in engineering applications. They are used in the manufacturing of wire rods, rebars, ribbed steel in coils and spools, reinforcements which are used for buildings, roads, bridges and other civil engineering applications. They are used also for the production of steel sheets, metal pipes, different profiles (for the construction manufacturing), road barriers (for all the types: roadside barrier, bridge barrier, median or work side barrier) and so on [1-4]. The microstructure of these steels is mainly composed of ferrite or ferrite and pearlite, which fraction depends mainly on a carbon content in the steel. This microstructure gives a good combination of strength and elasticity, which is enough for the above-mentioned applications. This high variation of different applications comes from its good weldability, low price and relatively good formability, which allows us to produce complex shape elements [5-8]. The other factor for the use of these steels is the possibility for obtaining a wide range of mechanical properties depending on deformation and heat treatment used. As the example the tempcore process can be shown [2]. Depending on the cooling rate, the product may have higher strength or plastic properties. The change in mechanical properties depends on the fraction of tempered martensite in the surface area of the bar and the fraction of ferritic-pearlitic structure in the centre. Increasing the cooling rate, the volume fraction of martensite increases together with the strength of the bar. Contrary reducing the cooling rate decreases the amount of martensite, which leads to a decrease in strength and corresponding increase in plasticity [1,2].

The properties of structural steels may be enhanced by the use of different microalloying elements, like Ti, Nb, B or V [3-6]. These micro additions increase the strength of steel by the grain refinement during hot rolling or forging processes and precipitation strengthening by different types of nitrides, carbides or carbonitrides. Moreover, the austenite grain refinement allows us to use higher austenitization temperatures during manufacturing process. Even at the higher temperatures the austenite grain remains smaller compared to the steel without microalloying elements. This approach may increase the mechanical properties of steels at low material cost [7,8].

The change in industrial demands leads to manufacturing numerous grades of high strength steels. Compared to the conventional structural steels, they have higher strength at similar elongation values. Manganese is an important element, which enables to modify significantly a final microstructure and mechanical properties [9,10]. Some technological problems (high hot deformation resistance, weldability, machining, coating, tooling costs) and increased alloying [11,12] are main reasons why conventional low-carbon structural steels are still used for the production of different products and constructions [13,14].

2. Experimental

The purpose of the work was to determine the effect of different cooling paths after hot deformation on a microstructure and properties of a low-carbon structural steel. The chemical composition of the analysed steel was 0.12% C, 0.4% Mn, 0.13% Si, 0.025% S and P, 0.2% Cr and Ni and 0.05% Al. The steel was subjected to different cooling paths after the hot deformation using the Gleeble 3800 simulator. Figure 1 presents the conducted tests for the steel together with the temperatures and time conditions. Material was heated up to 1200ºC and held at this temperature for 5 min, to homogenize the microstructure in the whole volume. After the austenitization the samples were cooled to 1100ºC. At this temperature the first deformation of 0.6 (true strain) was applied. The second deformation of 0.2 at 900ºC was given. Next, the samples were cooled (at a rate of 20ºC/s) to the different temperatures of isothermal holding. After the isothermal holding the samples were cooled to the room temperature with the use of water to "freeze" the microstructure directly after the performed holding.

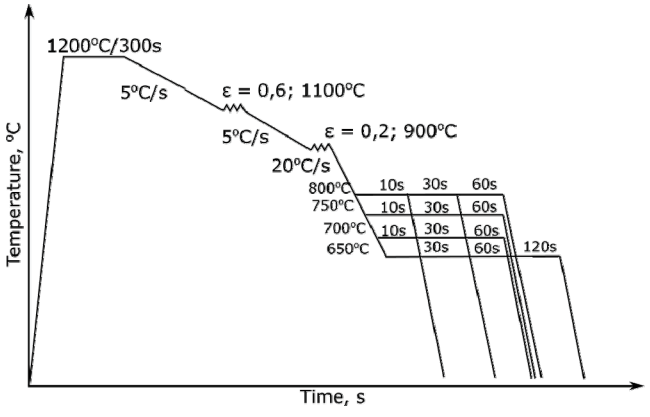

Fig. 1. The thermomechanicall process conducted for the steel

For the heat treatment following hot deformation four different temperatures and three different times were selected. The temperatures were changed from 800ºC

to 650ºC with the step of 50ºC and the times were changed from 10 s to 60 s. At 650ºC the isothermal holding time was prolonged to 120 s because of low diffusion rate of carbon at this temperature.

After the thermomechanical process the samples were prepared for metallographic investigations. For the purpose of grain size and phase fraction analysis the investigation were performed using the ImageJ software. The samples were cut and grinded by the use of different SiC based grinding papers of: 220, 500, 800 and 1200 gradation. After the grinding the samples were polished by the use of diamond paste and etched in 5% Nital.

The effect of the different heat treatments on the mechanical properties was assessed using hardness tests. They were carried out using the Vickers method. The load for the hardness was 9.81 N.

3. Results and discussion

3.1. Hot deformation resistance

During the thermomechanical process the samples were subjected to two strokes with different values of the strain. The first one was carried out at 1100ºC with the strain of 0.6. This was a simulation of rough hot rolling. The second one was applied at 900ºC with the strain of 0.2, which simulates the finishing rolling. The hot deformation response of the analysed steel is presented in Figure 2.

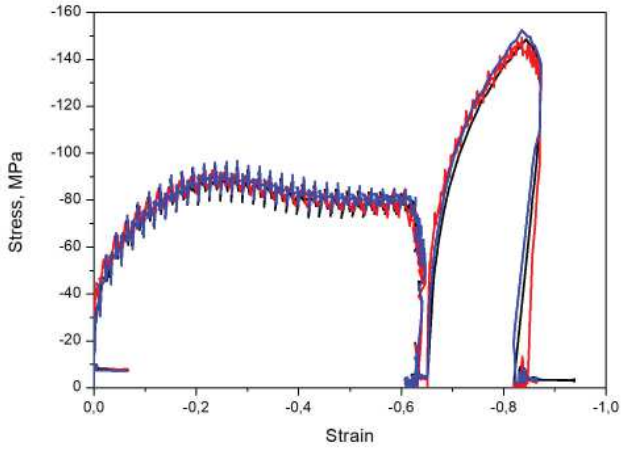

Fig. 2. A few representative stress-strain curves obtained for the analysed steel during two-step hot deformation

The presented stress-strain curves showed that during the first deformation at 1100ºC, the temperature and the strain level were enough for the occurrence of dynamic recrystallization. This phenomenon is indicated by the decrease of the slop in the first stress-strain peak. The temperature was enough for the occurrence of dislocation annihilation which leads to a decrease of the stress necessary to continuing the deformation. During the second deformation it can be seen that the temperature of the deformation was too low for the recrystallization. The evidence of the dynamic recovery is shown by a shape of the second curve. The lack of recrystallization leads to a higher dislocation density, which increases the amount of preferential places for the ferrite nucleation [4,7].

Moreover, the obtained curves are of the same character. This means that all the samples should possess the same microstructure (are fully homogenized during the austenitization step) before the heat treatment was conducted.

3.2. Microstructure evolution

The first step was to analyse the microstructure of the steel after performed the thermomechanical processing with various cooling conditions. A microstructure of the sample after isothermal holding at 800ºC is presented in Figure 3a. The microstructure is composed mostly of bainite/martensite and some granular and acicular ferrites. Decreasing the temperature of isothermal holding by 50ºC causes the amount of ferrite is increased (this time only globular ferrite) (Fig. 3b). A further decrease in the temperature to 700ºC and 650ºC induces mostly the ferritic microstructure with some fraction of martensite and pearlite (Fig. 3c) and pearlite (Fig. 3d). The reason for this kind of microstructure evolution in case of 800 and 750ºC is the change of intercritical temperature range, which according to the Andrews formula [15] is between 733ºC and 810ºC. A decrease in the temperature from 800 to 750ºC decreases the amount of austenite present during the isothermal holding, which transforms to bainite/martensite during cooling the steel to room temperature. At 800ºC the amount of austenite is higher compared to the 750ºC variant. That's why the amount of bainite/martensite is higher in this case. This effect is presented in Figure 4. In case of the 700 and 650ºC variants, the isothermal holding temperature is below A_{c1}, which means that all the austenite transforms to the pearlite during cooling the steel to the isothermal holding temperature.

The microstructures obtained for all the temperature variants with the longest duration of isothermal holding time are presented in Figure 5. It can be seen that in case of the 800ºC variant, the longer isothermal time influences the phase composition of the steel.

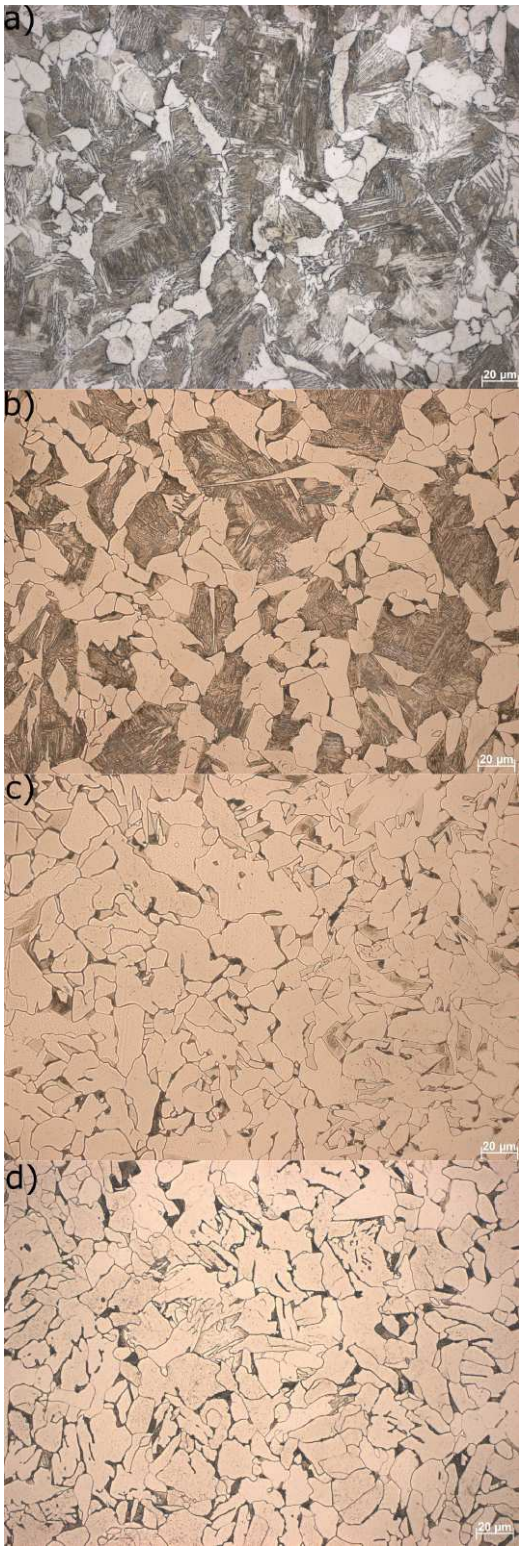

Fig. 3. Microstructure of the steel after isothermal holding for the shortest time at temperatures: a) 800ºC, b) 750ºC, c) 700ºC, d) 650ºC

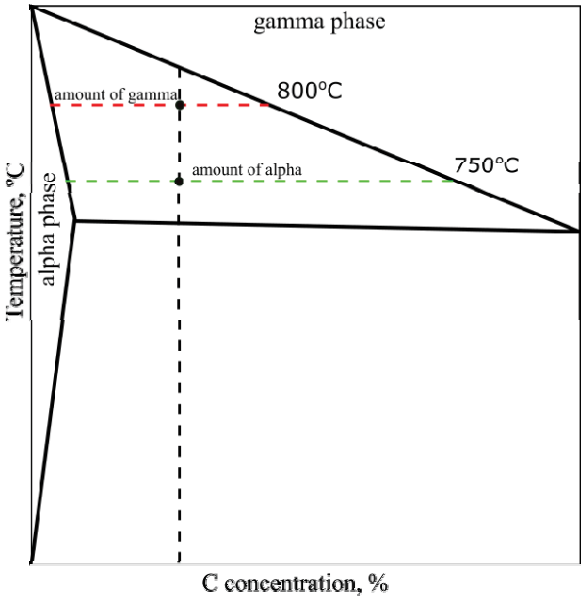

Fig. 4. Effect of intercritical region on the relative amounts of austenite and ferrite present during isothermal holding

Compared to the isothermal holding time of 10 s, in case of 60 s the amount of bainite/martensite islands decreases, together with acicular ferrite. For the rest of the variants, a decrease of the isothermal holding temperature does not lead to any changes in the structural composition of the steel. Moreover, what can be seen is that the prolonging the isothermal holding time affects the grain size of the phases. Compared to the 10 s variant the grain size in case of 60 s is larger at all temperatures.

The second step of the microstructure analysis was to determine the amount of the phases in the microstructure after the different thermomechanical processing together with the change of their grain size. This data was obtained by the use of the image analysis. The results of the phase fraction analysis are presented in Figure 6. The diagram presents the amount of ferrite fraction in the microstructure of the steel after different variants of the thermomechanical treatment. The rest of the microstructure is composed of bainite/martensite or pearlite islands. It can be seen that the amount of ferrite increases by 20 to 30% when the temperature of the isothermal holding decreases from 800 to 750ºC. A further decrease in the temperature to 700ºC leads to higher ferrite amounts compared to the higher temperatures (a similar increase in the ferrite fraction). There are no further changes in case of the ferrite amount, when the temperature is further decreased to 650ºC. There is only the change of the kind of the second phase (martensite, bainite or pearlite). These results are in good correlation with the microstructure analysis.

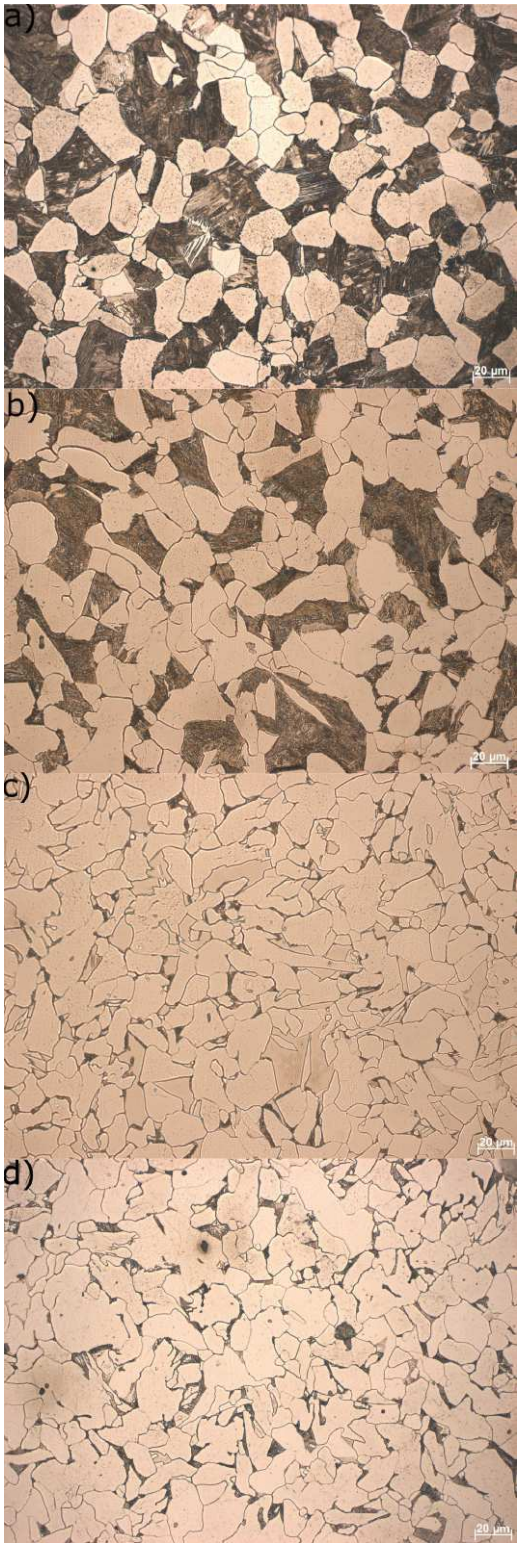

Fig. 5. Microstructure of the steel after isothermal holding for the longest time at: a) 800ºC, b) 750ºC, c) 700ºC, d) 650ºC

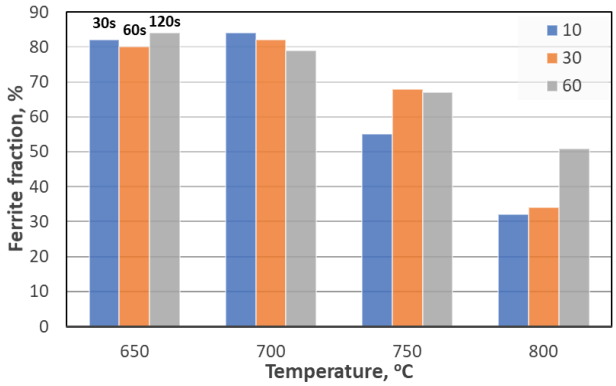

Fig. 6. The fraction of ferrite in the microstructure of the steel after different heat treatments

The effect of isothermal holding time on a ferrite fraction is temperature dependent. The highest change of the phase fraction with increasing time is shown at 800ºC. After 60 s the amount of ferrite increases by 20% compared to shorter times. In case of the lower temperatures the amount of ferrite is similar for all the selected times.

The change of ferrite grain size was determined by the similar means like in case of phase fraction. The image analysis was performed using the micrographs of 500x magnitude for better projection of digital image. For the determination of the grain size, 10 measurements of the size were performed for each variant of the thermomechanical processing. The results of this analysis are presented in Figure 7. The grain size of the phases is temperature and time dependent. The grain size increases together with decreasing the temperature of isothermal holding. The reason for this is the difference in cooling time (corresponding to the carbon diffusion time) to the isothermal holding temperature.

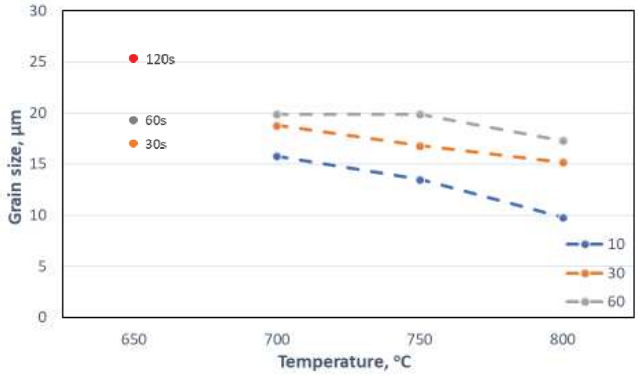

Fig. 7. Change of ferrite grain size depending on the temperature and time of isothermal holding

In case of 800ºC, the cooling time from the second deformation to the isothermal holding temperature is shorter compared to other temperatures. Because of this the time in which the temperature can influence a grain size is short. When the isothermal temperature is decreased, the time for the cooling to this temperature is longer. This is the major reason why the grain size increases together with decreasing isothermal holding temperature. In case of the isothermal holding time, the grain size increases for the longer times. The reason is similar like in case of the isothermal holding temperature. When the holding time is increased, the influence of the temperature on a grain size is prolonged leading to the larger increase in their size.

3.3. Hardness analysis

The last step of the work was the analysis of the hardness of the steel after all the heat treatment variants. The hardness was measured by the Vickers method. During the test, ten values were registered and the average was calculated. The results of this analysis are presented in Figure 8. The hardness of the steel increases as a function of higher isothermal holding temperature. Similar results were obtained in the work [1], where the conventional structural steel was subjected to various heat treatment variants. This is in good correlation with the presented microstructure composition. The highest hardness is shown by the 800ºC variant, which has a highest amount of hard bainite/martensite. Offor et al. [14] noted that increasing the isothermal holding temperature results in a decrease of plastic properties and notch impact toughness (because of higher amount of hard phases). Decreasing the holding temperature reduces the hardness due to higher ferrite fractions. The difference in hardness between 650 and 700ºC comes from a different grain size of the ferrite. At 700ºC the grain size is smaller what induces some hardness increase of the steel. The influence of isothermal holding time on the hardness depends on the holding temperature. In case of 650 and 700ºC, time does not affect the hardness significantly. The more evident changes can be visible for higher temperatures. The reason may be that in case of 750 and 800ºC, various amounts of bainite and martensite are present in the microstructure. The kind of the phase depends on a temperature-dependent diffusional enrichment of the austenite in carbon in the intercritical range (higher for the lower intercritical temperature). This results in different supersaturation of bainite/martensite in C and finally has an impact on the hardness.

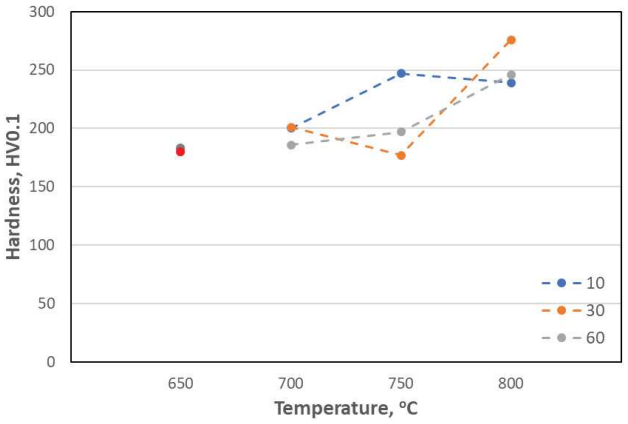

Fig. 8. Effect of the isothermal holding temperature and time on the hardness of the steel

4. Conclusions

The presented results indicated that the analysed steel is suitable to produce ferrite-based microstructures. The fine-grained ferrite-based microstructures are produced due to the combined effects of strain and cooling path on the austenite decomposition kinetics. The ferrite fraction is strongly temperature-dependent and less time-dependent. The ferrite fraction increases for lower isothermal holding temperatures. The second phase amount and type depend on the holding temperature and changes from martensite/bainite in a range of 800-750°C through martensite/pearlite at 700°C to pearlite at 650°C. The increase of in a temperature leads to a lower grain size of the ferrite. The difference in the grain size between 650 and 800ºC is around 8 μm. For longer cooling times the ferrite grain size increases.

The hardness increases together with an increase in the isothermal holding temperature due to the higher amounts of hard martensite and bainite. The isothermal holding time doesn't have much influence on the hardness in case of the lower temperature. For the higher temperatures some changes occur due to a mixed volume fractions of bainite and martensite and a corresponding different enrichment in carbon within the intercritical annealing temperature range.

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