INTENSIVE MULTI-AXIS HOT DEFORMATION OF LOW CARBON STEEL ON THE MAXSTRAIN II DEVICE

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Abstract

Using the sophisticated MAXStrain II unit, part of the HDS-20 simulator, the effect of intensive cumulative hot deformation on the final structural properties of non-alloyed low carbon steel was investigated. In the case of the MAXStrain II unit, the specimens are deformed by compression in two axes, which allows to achieve large cumulative strains. This fact, together with the possible course of suitable softening processes, represents a potential for research and development of materials with fine-grained structures. The microstructure of all samples of low-carbon alloy steel, deformed at MAXStrain II unit, was composed of a mixture of ferrite and pearlite; in the case of samples after accelerated cooling, hardening components were also detected in the microstructure (share up to 5 %). In all cases, during the MAXStrain II tests, the resulting ferritic grain of the steel under test was refined, with the finest microstructure showing an average ferritic grain size of 6.8 μm. The resulting ferritic grain size decreased with decreasing deformation temperature and, in the case of lower overall equivalent strain, also with longer interpass time. However, the chosen cooling rate had a dominant effect on the resulting ferritic grain size.

Keywords: Low-carbon steel, MAXStrain II unit, multi-axis hot deformation, microstructure, grain refinement

1. INTRODUCTION

The mobile conversion unit MAXStrain II, which company DSI developed as a tool for developing materials with ultra-fine grain structure, is one of the specialised units attachable to Gleeble simulators. In the case of the MAXStrain II, the material (prismatic specimen) under test is deformed by two anvils and rotated along its longitudinal axis by 90° between each deformation, allowing it to be cyclically deformed in the other two directions. The advantage of this sophisticated device is the ability to load the material under test with large strains while precisely controlling the temperature and strain rate. The specimen can be deformed by compression in a maximum of 80 passes with a minimum interpass time of approx. 0.6 s (given by the time to rotate the specimen by 90°). For the MAXStrain II unit, the maximum anvil speed is 700 $mm \cdot s^{-1}$, the maximum static force load in compression is 196 kN, and the maximum dynamic force load in compression is 80 kN. The temperature of the deformed specimen is measured by thermocouples which are led (through a drilled hole) to the deformed part of the specimen. This ensures accurate sample temperature measurement even with large cumulative strains [1-4].

The MAXStrain unit has been used, for example, to investigate the controlled microstructure evolution, or to investigate the possibility of grain refinement in Al [5,6], Mg [7] and Ti [4,8] based alloys and also in the case of intermetallic alloys [9]. This technique has also been used to investigate of the grain refinement possibilities

of microalloyed steels [3,10-13]. Although the MAXStrain unit has the potential to be also used for physical simulations of hot forming processes of steels (e.g. continuous rolling of bars or wires), only a minimum of works dealing with this issue or verification of the possibilities of refinement of the final grain of steels after their cumulative hot deformation can be found in the literature [12,13]. It is well known that grain refinement leads to an increase in the mechanical properties of the materials under investigation, and this relationship can be expressed, for example, by the Hall-Petch relation [5,14]. In hot forming, besides the forming thermomechanical parameters, the final grain size is mainly influenced by the recovery or recrystallization processes and the phase transformations occurring during the cooling of the steel [15-17].

The aim of this work was to study the influence of thermomechanical forming conditions during multi-axial intensive deformation on the MAXStrain II unit on the microstructure evolution (respectively refinement of the final ferritic grain) of unalloyed low carbon steel.

2. EXPERIMENT DESCRIPTION

For the purpose of the present work, an unalloyed low carbon steel was selected which contained 0.14 % C; 0.51 % Mn; 0.13 % Si; 0.034 % P; 0.022 % S; 0.20 % Cr; 0.13 % Ni; 0.001 % Al and 0.017 % Mo; (all in wt. %). The investigated steel, used for structural purposes, was supplied in hot rolled bars with a square cross-section of 20 x 20 mm. The initial structure of the investigated steel was a mixture of ferrite and pearlite, with a minority of pearlite (see **Figure 1**). The mean diameter of the ferritic grain was determined using the QuickPHOTO INDUSTRIAL software using the linear method. The ferritic grain of the investigated steel was highly inhomogeneous in terms of size, with a mean ferritic grain diameter of 13.5 μm (with a mean error of 1.07 μm).

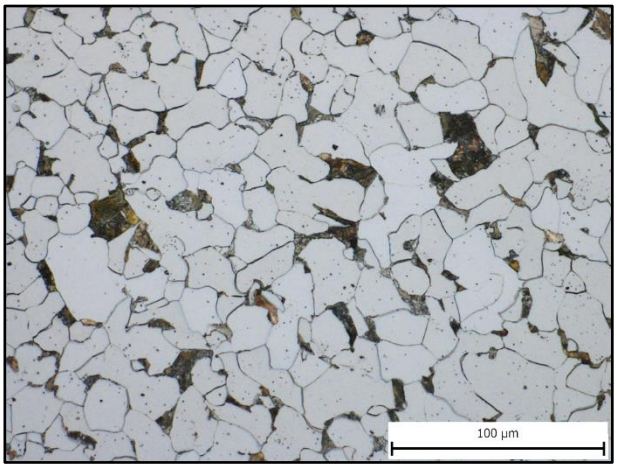


Figure 1 Initial structural state of investigated steel

A cylindrical samples with a diameter of 6 mm and a length of 86 mm was first made from the investigated steel and then was used for the dilatometric determination of the Ac_1 and Ac_3 phase transformation temperatures. For this purpose, an optical non-contact dilatometer was used, equipped with a simulator HDS-20, which is installed on Faculty of materials science and technology VŠB-TU Ostrava [17]. The prepared sample was electrically resistively heated at a rate of 0.167 °C·s^{-1} up to a temperature of 1,000 °C. By analysis of the measured dilatation curve the temperatures of phase transformation during heating of the investigated steel Ac_1 = 712 °C and Ac_3 = 851 °C were determined. Based on the determined Ac_3 temperature, the deformation temperatures for compression tests in the MAXStrain II unit were then selected.

The tests with intensive compression deformation of the investigated steel were carried out on the MAXStrain II unit connected to the HDS-20 simulator. For this purpose, two types of prismatic samples were made from the investigated steel (see **Figure 2**). Both samples had a deformed section length of 12 mm and an initial deformed cross-section of 10 x 10 mm. The used samples differed mainly in the design of their head sections, by which are fixed in the MAXStrain II unit. The head sections of the first

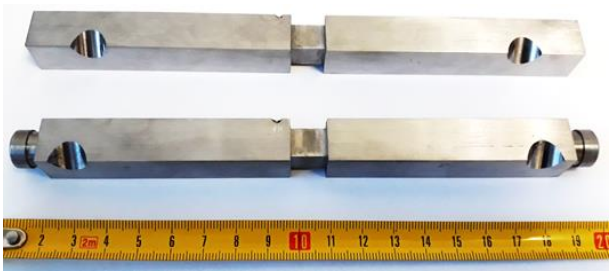


Figure 2 Initial shape of the samples for compression tests in MAXStrain II unit

type of sample were solid, and the overall length of the sample was 195.6 mm. In the case of the second type of sample, the head sections were hollow (a hole was drilled in them respectively) for install a nozzles, which can be used to cooling the sample by accelerated manner with compressed air or with water. The total length of the second type of sample was 191.8 mm. The head sections of both sample types had a square cross-section of 15 x 15 mm, and both sample types were fitted with grooves to prevent the sample from sliding in the longitudinal direction during their deformation in the MAXStrain II unit.

The prepared prismatic samples were electrically resistively heated at a rate of 5 °C·s^{-1} directly to the selected deformation temperature. After a uniform 5 min holding time, they were deformed by compression alternately in two directions at isothermal temperature. To ensure that the deformation takes place in the single-phase austenitic region and at the same time to avoid grain coarsening in the interpass times, the deformation temperatures of 900 °C and 860 °C were determined (based on the evaluation of the dilatometric test). The aim was to investigate the possibility of refinement of the austenitic grain by the assumed static recrystallization (in the case of tests with an inter-pass dwell time of 5.6 s) and dynamic recrystallisation (in the case of tests with an inter-pass dwell time of 0.7 s). During the inter-pass dwell time, the sample was always rotated 90° along its longitudinal axis. All passes were performed at a uniform equivalent strain of 0.35, while total (cumulative) equivalent strain 2.1 or 10.5 of individual samples were varied. The total velocity of both anvils in each run was 600 mm·s^{-1}, which corresponds to a mean strain rate of 17 s^{-1} at the given equivalent strain. At the end of the deformation regime, the samples were cooled at the selected rate to a temperature of 100 °C. The full-head samples were used for the tests with a cooling rate of 2 °C·s^{-1}, with controlled cooling by heat dissipation through the clamping jaws. The hollow head samples were used for the 14 °C·s^{-1} cooling rate, with controlled cooling by a combination of heat dissipation through the clamping jaws and simultaneous blowing of the deformed part with compressed air. All tests were carried out under vacuum, and the temperature of the sample was measured throughout the test by using of thermocouples. All deformed samples were then subjected to metallographic analyses.

3. DISCUSSION OF RESULTS

In **Figure 3**, as an example, a photo of a sample deformed with a total equivalent strain of 2.1 at 860 °C with an inter-pass dwell time of 5.6 s (after cooling rate 2 °C·s^{-1}) is shown. Metallographic analyses were performed using traditional optical microscopy, always at the mid-height of the longitudinal section of the deformed part of the samples. Afterwards, the mean diameter of the resulting ferritic grain was determined using the QuickPHOTO INDUSTRIAL software by a linear method.

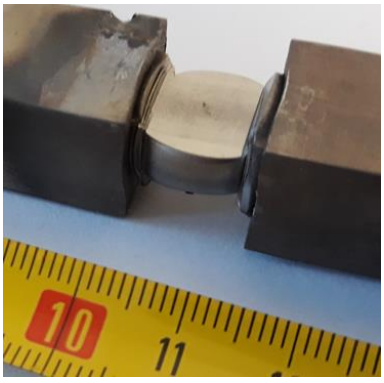
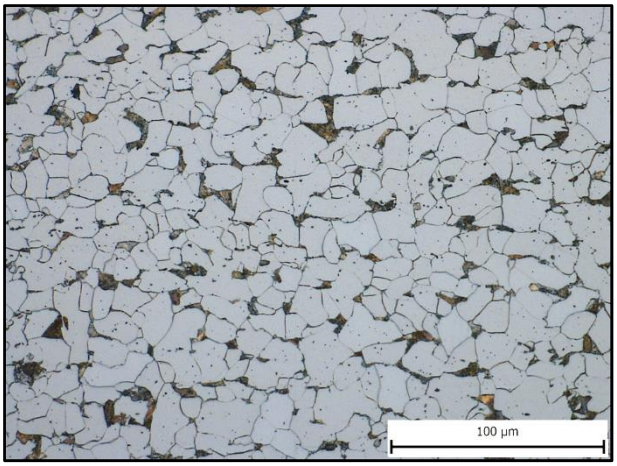
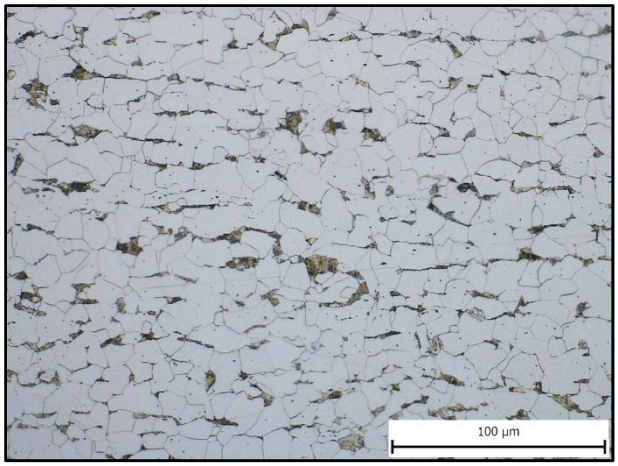


Figure 3 Sample after deformation in MAXStrain II

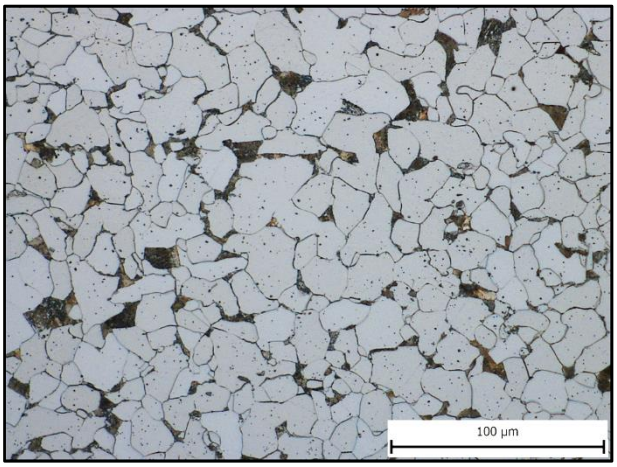
The microstructure of the samples deformed and controlled cooled at rate 2 °C·s^{-1} on the MAXStrain II unit consisted of a mixture of ferrite and perlite. In the case of the samples cooled after deformation at 14 °C·s^{-1}, their microstructure consisted of ferrite with a minor share of pearlite, bainite and martensite (share up to 5 %). In the microstructure of all samples, the share of ferrite was majority (see **Figure 4**). In terms of the resulting ferrite grains size, the microstructure of all samples cooled down at the rate 2 °C·s^{-1} was highly inhomogeneous (both very fine and relatively coarse ferrite grains can be found in the microstructure – see **Figure 4**). From the photo documentation of the microstructure (see **Figure 4**) and from the graphical dependence of the determined ferritic grain diameter on the deformation temperature (see **Figure 5**), it is clear that in all cases, the resulting ferritic grain of the tested steel was refined during the MAXStrain II tests. The finest microstructure of the samples deformed on the MAXStrain II unit showed a mean ferritic grain diameter of 6.8 μm, while in the initial condition, the steel under test had a mean ferritic grain diameter of 13.5 μm.



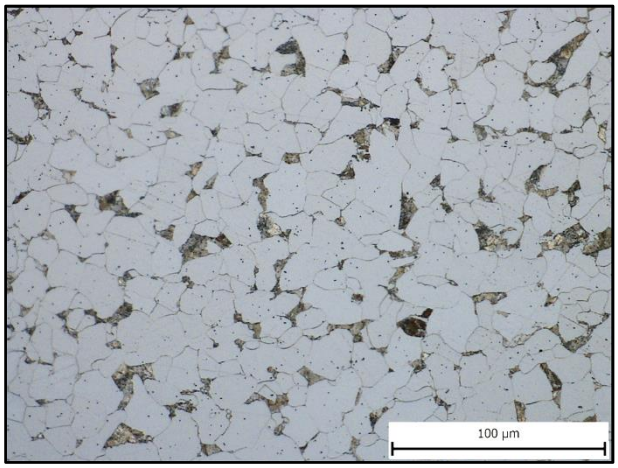
a) T_d = 900 °C; $e_{Eq(total)}$ = 2.1; inter-pass dwell time 5.6 s; cooling rate 2 °C·s^{-1}



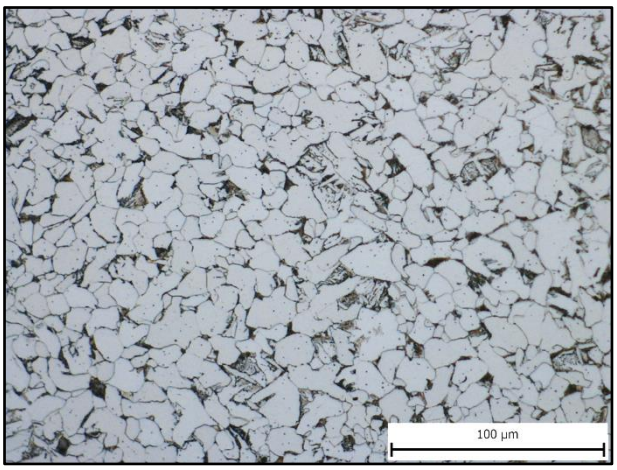
b) T_d = 860 °C; $e_{Eq(total)}$ = 2.1; inter-pass dwell time 5.6 s; cooling rate 2 °C·s^{-1}



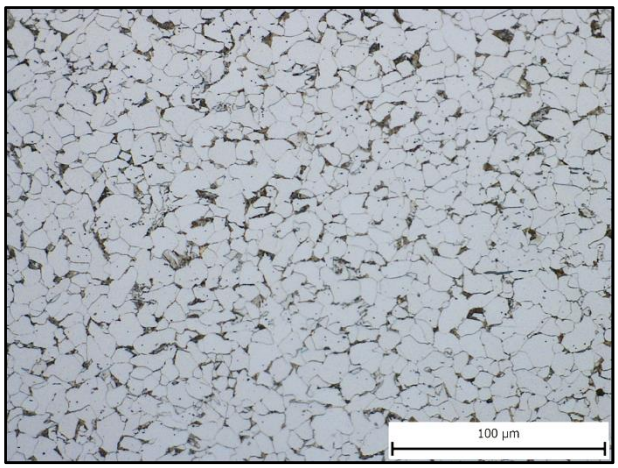
c) T_d = 900 °C; $e_{Eq(total)}$ = 10.5; inter-pass dwell time 0.7 s; cooling rate 2 °C·s^{-1}



d) T_d = 860 °C; $e_{Eq(total)}$ = 10.5; inter-pass dwell time 0.7 s; cooling rate 2 °C·s^{-1}



e) T_d = 900 °C; $e_{Eq(total)}$ = 10.5; inter-pass dwell time 0.7 s; cooling rate 20 °C·s^{-1}



f) T_d = 860 °C; $e_{Eq(total)}$ = 2.1; inter-pass dwell time 0.7 s; cooling rate 20 °C·s^{-1}

Figure 4 Microstructure of investigated steel intensively deformed in MAXStrain II unit (T_d is deformation temperature (°C) and $e_{Eq(total)}$ is total equivalent strain (-))

The resulting ferritic grain size decreased with decreasing deformation temperature and with longer inter-pass dwell time (only in the case of lower total equivalent strain) – see **Figure 5**, where the effect of static recrystallization had probably a positive effect. However, the 5.6 s inter-pass dwell time was not long enough to allow a perfect progression of static recrystallization of the austenitic grain from which the resulting ferritic grain transforms during cooling of the investigated steel. In the case of samples deformed with a large equivalent strain ($e_{Eq(total)}$ = 10.5) and with inter-pass dwell time of 5.6 s, the static recrystallization was probably incomplete, and at the same time, the austenitic grain was partially coarsened, which subsequently affected the size of the resulting ferritic grain. Thus, the inter-pass dwell times of 0.7 s were probably short for a perfect course of static recrystallization and, at the same time, probably not short enough for a perfect course of dynamic recrystallization to occur due to accumulated strain. However, at compression tests in the MAXStrain II, shorter inter-pass dwell time cannot be set in principle, because sample rotation between passes takes about 0.6 s. However, the dominant influence on the resulting ferrite grain size was the chosen cooling rate (see **Figure 5**).

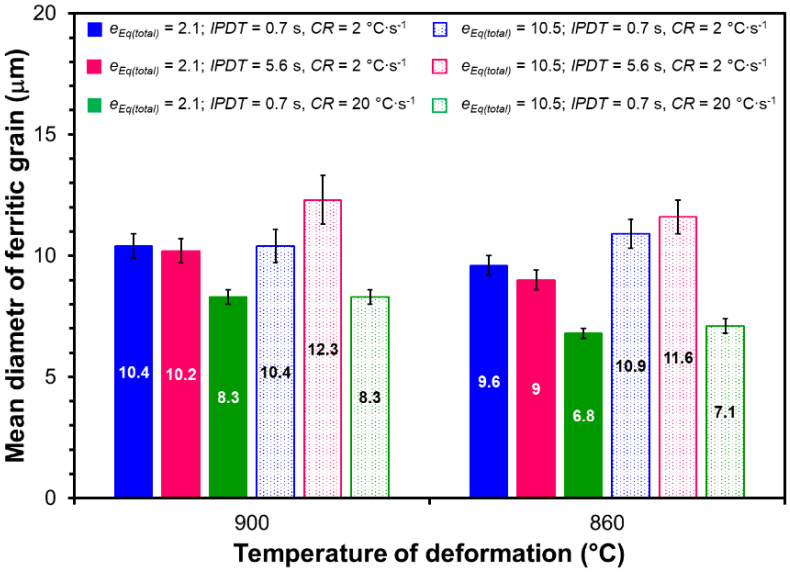


Figure 5 Mean diameter of the final ferritic grain (with mean value error) in the microstructure of investigated steel deformed in MAXStrain II unit ($e_{Eq(total)}$ is total equivalent strain (-); *IPDT* is inter-pass dwell time (s); *CR* is cooling rate (°C·s^{-1}))

4. CONCLUSIONS

Using the sophisticated MAXStrain II unit, which is part of the HDS-20 simulator, intensive hot deformation on the final structural properties of the non-alloyed low carbon steel was investigated.

The microstructure of all deformed samples consisted of a mixture of ferrite (majority fraction) and pearlite (minority fraction). In the case of the samples cooled after deformation by accelerated manner, hardening components were also detected in the microstructure (share up to 5 %). In all cases, during the MAXStrain II tests, the resulting ferritic grain size of the investigated steel under compression tests were refined (compared to the initial structural state), with the finest microstructure showing an average ferritic grain size of 6.8 μm. The resulting ferritic grain size decreased with decreasing deformation temperature and, in the case of a lower overall equivalent strain, also with a longer inter-pass dwell time. However, the chosen cooling rate had a dominant effect on the resulting ferritic grain size.

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