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MODELING OF FINAL STRUCTURE OBTAINED UNDER HIGH STRAIN-RATE DEFORMATION

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ABSTRACT- This paper discusses results of experimental research and a model implementation of the hot deformation process in the two-phase region under high strain rate. Hot compression tests were employed to determine the behavior of deformed microalloyed steel over a range of strain rates (1x10^-3 s^-1 - 2.5x10^3 s^-1) and temperatures (650°C-850°C). The thermomechanical history of the material is consequently integrated in the simulation and compared with the experimental results.

INTRODUCTION: The successful implementation of computer modeling and product innovations requires not only optimal planning of forming process schedules, but also understanding of the metallurgical mechanisms relevant to the microstructure development (i.e. recrystallization, grain growth and refinement, precipitation, and transformation kinetics). When the modern or new thermomechanical treatments of microalloyed steel, such as the deformation in the two-phase or ferrite region, are implemented, the computer simulation becomes an especially efficient tool. A typical final microstructure obtained as a result of hot deformation processes is a consequence of an inhomogeneous microstructure developed under such conditions. However, because of inhomogeneity of deformation parameters, unexpected local microstructure changes can be found. While strain rates of deformation in ranges up to 2 s^-1 are well known, the dynamic deformation conditions are not well understood and require more attention (Majta et al. [1997]). Analyses of dynamic problems are very interesting in the case of fracture behavior. Correct understanding of all microstructural phenomena in such conditions could improve the ductility of deformed steel, for example, in the forging process. Therefore, the analysis of the damage evolution should take place for the phase-changed microstructure, in particular, and not relative to the structure of the initial, pre-deformation material. The results presented here represent the first step of such analysis.

PROCEDURES AND RESULTS: The uniaxial compression tests of high-strength low-alloy (HSLA) steel were performed in a range of strain rates from 10^-3 s^-1 to 2.5x10^3 s^-1 using an Instron, a MTS testing machine, and a split Hopkinson pressure bar. Each experiment was performed in a range of temperatures corresponding to the austenite, two-phase, and ferrite regions. The thermomechanical history for these experiments is shown in Fig. below. The deformed samples were analyzed using optical microscopy. The objectives of theoretical work were threefold: (1) to improve the existing microstructural evolution models for the strain rate in the range of 10^-3 s^-1 - 2.5x10^3 s^-1, (2) to develop the thermomechanical and microstructure evolution models for the two-phase and
high strain-rate deformations, and finally, (3) to improve the existing model for mechanical properties in final products. The chemical composition of experimental steel is based on low carbon steel with a relatively high amount of niobium (see Table 1). The investigated steel was a typical industrial grade.

Table 1: Chemical Composition (in wt%) of the Steel Investigated.

<table>
<thead>
<tr>
<th>Designation</th>
<th>C</th>
<th>Mn</th>
<th>Si</th>
<th>Al</th>
<th>Nb</th>
<th>Ti</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>HSLA</td>
<td>0.067</td>
<td>1.30</td>
<td>0.34</td>
<td>0.037</td>
<td>0.076</td>
<td>0.024</td>
<td>0.0054</td>
</tr>
</tbody>
</table>

To reveal the effect of strain rate on developing of the final microstructure it is necessary to analyze separately the austenite-ferrite transformation phenomena especially in the case when deformation is proceeded in the two-phase region. It is well known that if the finish deformation is proceeded in temperatures below $A_r$, the processes of recovery and recrystallization occur in the ferrite phase to form a very refined structure with significant contribution of the substructure. This is due to the reduced extent of dynamic recovery occurring at the higher strain rates that in turn increase dislocation density and increase the driving force for recrystallization. On the other hand, the retained strain in the deformed austenite tends to increase transformation rate and temperature, which leads to the new inhomogeneous two-phase structure, even though deformation temperature is higher than $A_r$. However, this effect can be negligible for the higher cooling rates and finer austenite grain sizes. When the mechanisms described above operate at the same time (the case of deformation in two-phase region), we can expect very complex behaviors. The figure below contains results from low and high strain rate compression tests.

A typical dependence of flow stress on strain rates can be observed. It shows that the flow stress increases with increasing strain rate. This is due to the faster restoration process by dynamic recovery at lower strain-rates. The highest flow stress values have
been obtained at low temperatures and at high strain-rates. The result of these conditions is that austenite supplies more driving force for transformation. The refinement in the ferrite structures that accompany deformation in austenite and two phase region with strain rate 50 s\(^{-1}\) are shown in the figure below. The ferrite structure produced by deformation in austenite region (TD=850°C) is relatively large, regular and homogeneous. When deformation temperature decreases, the microstructure consisted of polygonal grains and elongated deformed grains, the volume fraction of which increased steadily with decreasing temperature. It can be also generally stated that below TD=800°C we have effects of ferrite refinement. It is widely recognized that ferrite nucleation occurs preferentially at grain boundaries, twin boundaries and deformation bands in deformed austenite. The grain boundaries are the most effective in nucleating ferrite grains because of their high energy. However, the presence of deformation bands, substructure of new nucleated ferrite grains, presence of Nb-precipitates, and pinning the interphase interface that occurs in steel deformed in the two-phase region, leads to much finer but inhomogenous, final structure (see Manohar [1996]). Deformation bands are not always uniformly distributed. Because some grains are unfavorably oriented for the formation of deformation bands, they contain no or very few deformation bands in their interiors. The average distance between effective boundaries and deformation bands is much smaller for fine structures. The specimens deformed in the two-phase region have a microstructure consisting of equi-axed, soft ferrite grains and hard grains containing substructure. Additionally, the nature of grains that were nucleated at the beginning of transformation is different, depending on the degree of restoration, ranging from recrystallized to as-deformed ferrite. All of these phenomena strongly depend on time and temperature. When loading time decreases, i.e. strain rate increases, there is no time for restoration process, transformation start temperature increase, and finally, a very inhomogeneous ferrite structure can be expected. The modeling process employed in the present work effectively links the advanced finite element approach that simulates metal flow and heat transfer during hot plastic deformation with the equations describing microstructure
development and strengthening mechanisms (Majta et al. [1996]). The thermomechanical part of modeling, simulating the metal flow and heat transfer, is based on the finite element approach described in detail in Pietrzyk et al. [1991]. The model uses a rigid-plastic flow formulation for the calculation of all mechanical events, including the determination of effective strains, shear strains, strain rates, and stresses.

The influence of high strain-rate on the final microstructure was analyzed differently here. The following aspects are included:
- transformation kinetic,
- recrystallization and precipitation kinetics,
- ferrite grain size description, and
- strengthening mechanisms.

Examples of calculations in the figure directly above clearly show the high inhomogeneity of ferrite structure obtained after deformation in the two-phase region. However, to improve the model another approach should be made to link the nucleation rate of ferrite with austenite-ferrite transformation and ferrite refinement kinetics.

CONCLUSIONS: For a given finishing temperature and deformation, the Nb-steel exhibits strong influence of strain rate on the final structure. The experimental results show that dynamic conditions do not produce any difference in flow stress curves. It can also be observed that significant differences exist in the level of structure homogeneity after deformation in austenite and two-phase regions. This tendency is also observed in calculated results obtained using proposed modeling procedures.

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REFERENCES: