INFLUENCE OF DEFORMATION CONDITIONS ON THE DYNAMICALLY RECRYSTALLIZED GRAIN SIZE OF THE MEDIUM CARBON VANADIUM MICROALLOYED STEEL 38MnSiVS5

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Abstract. *In forming processes such as hot forging of components for automotive industry, certain regions of the worked pieces are subjected to large straining and, as a consequence, dynamic recrystallization takes place in these points. In this work, the role of forging conditions on the microstructure evolution of a medium carbon vanadium microalloyed steel (38MnSiVS5) subjected to large straining was investigated by means of hot torsion tests. Isothermal tests were carried out over the strain rate and temperature ranges 0.1s^{-1} to 10s^{-1} and 900ºC to 1200ºC. The samples were quenched immediately after deformation and the average austenitic grains size were measured in order to analyze the dynamic recrystallized (DRX) microstructure. The flow stress curves determined indicated that this steel recrystallized during straining and the average austenitic grains size observed depends on the straining conditions. The influence of deformation conditions in the microestrutural evolution is discussed.*

Keywords*: Dynamic recrystallization; Large deformation; Microalloyed steel.*

1. INTRODUCTION

The recrystallization alters the characteristics of the material significantly during industrial processing. A deformed microstructure with high stored energy is substituted by a microstructure composed of fine grains with smaller dislocation density during the recrystallization. That process of formation of new grains usually happens for deformations larger than that imposed nominally in each deformation step of the industrial processes. Although, in the manufacture of components with complex shape as in the hot forging of crankshaft and other pieces for automotive industry, some areas are subjected to large straining due to the deformation heterogeneities. As a consequence, while some regions only soften by stactic recrystallization in the arrest time between deformations, the volume severely deformed recrystallizes during deformation.

It is well known that, during high temperature deformation, after certain amount of work hardening, materials with high staking fault energy soften intensely by dynamic recovery, while materials with low or medium staking fault energy soften by dynamic recrystallization. When carbon steels are deformed at constant temperature and strain rate, in the austenitic domain, the plastic flow stress increases with the deformation until reaches a maximum and decreases until reaches a steady state. In these materials, the dislocation density increase to a critical level (σ_C, ε_C) in which new grains nucleate and grow spontaneously during the deformation. The rapid elimination of dislocation during the new grains growth leads to a peak stress (σ_P, ε_P) and to a stress softening. This is followed by a steady state regime (σ_S, ε_S) in which a constant microstructure is maintained by the work hardening, recovery and dynamic recrystallization combination.

Both the required stress level to straining the material and the DRX grain size depend on the deformation conditions, i.e., strain rate and deformation temperature. The average grain size ($D\gamma$) has been related with the steady state stress through an equation of the type: $\sigma_S.D\gamma^m = k$, where m and k are constants (Derby, 1991). Also, a relationship of the form $Z.D\gamma^n = k$ has been proposed, where Z is the strain rate compensated temperature (Derby, 1991). Although the equations that relate the DRX grain size, the steady state stress and the deformation conditions are universal, it is necessary to know the parameter values of these equations for each material. The knowledge of the material behavior during deformation and in the arrest time between passes is fundamental to control microstructure evolution during industrial processing.

2. MATERIAL AND EXPERIMENTAL PROCEDURES

The material used in this work was a commercial medium carbon vanadium microalloyed forging steel - 38MnSiVS5 - used in the manufacture of automotive parts such as connecting rods and crankshaft, whose chemical composition is given in Table 1.

Table 1. Chemical composition of the steel tested (wt%)

C	Si	Mn	S	V	Al	N	Cu	Ti
0,38	0,62	1,35	0,055	0,11	0,025	0,013	Max	0,01

Mechanical tests were carried out on a computerized hot torsion machine. The samples, having a 12 mm length and 8 mm diameter in the reduced central gage section, were heated by means of an infrared furnace mounted directly on the testing machine. Chromel-alumel thermocouples were used to measure and control the temperature. To prevent oxidation, the sample was enclosed in a 2% hydrogen argon atmosphere surrounded by a quartz tube. Data were collected by means of a software program that imposes parameter tests such as temperature, strain and strain rate.

Isothermal continuous tests were carried out to determine the plastic flow curves at different temperatures and strain rates. Samples were heated from room temperature to the soaking temperature of 1200 °C, held at this temperature for 5 min, cooled to the test temperature at a rate of 2 °C/s, held for 1 min, and finally strained isothermally to $\varepsilon = 4.0$. These tests were carried out over a temperature range of 900 °C to 1200 °C, and at equivalent strain rates of 0.01, 0.1, 1 and 10 s^{-1}. Samples water quenched immediately after deformation was used to measure the average austenitic grains size.

Polished sections of the austenitized specimens were observed by optical microscopy after etching in saturate aqueous picric acid solution with some drops of surfactant at 80–100°C to determine austenite grain size. The grain size was measured in agreement with ASTM E 112.

3. RESULTS AND DISCUSSION

Some flow stress curves determined from samples of the 38MnSiVS5 steel are shown in Figure 1. These samples had, when reheated to 1200ºC, initial grain size (D_0) around 100 μm (Sousa, 1996). It is possible to see that during high temperature deformation the flow stress increases to a maximum and after this stress peak decreases to a steady state; the material soften for dynamic recrystallization.

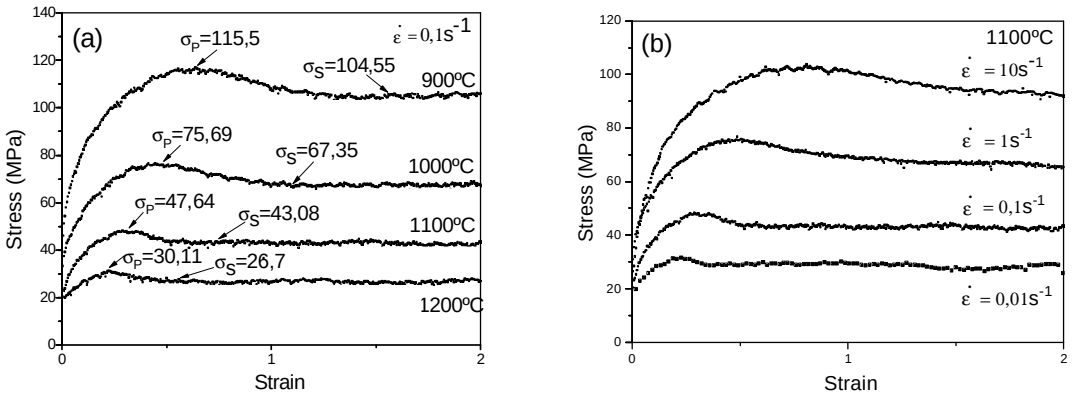

Figure 1. Flow stress curves determined under isothermal conditions with a strain rate of (a) $0,1s^{-1}$ and in (b) 1100°C.

The influence of deformation conditions (temperature and strain rate) on the steady state stress (σ_S) was observed in all of tested conditions. The σ_S values were larger in low temperatures and in high strain rates. This happens because lower strain rates and higher temperatures offer a long time to dissipate energy and high grain boundary mobility during nucleation and growth of DRX grains. Due to a pronounced increase in the dislocation density as the strain rate rises, there is an increase in σ_S.

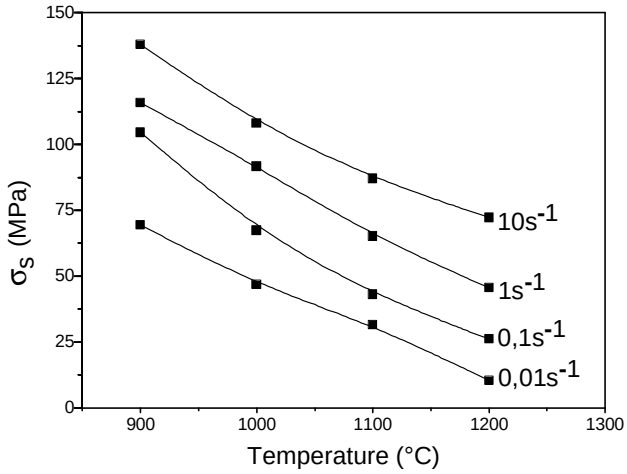

Figure 2. Influence of temperature on the steady state stress.

The literature shows that the relationship between the peak stress and the deformation conditions can be described through the equation proposed by Sellars and Tegart (1966):

$$Z = \dot{\varepsilon}.exp\left(Q_{def}/R.T\right) = A\left[sinh\left(\alpha.\sigma_P\right)^n\right] \tag{1}$$

where $\dot{\varepsilon}$ is the strain rate, σ_p is the peak stress, Q_{def} is the apparent activation energy for hot working, A, α, n and R are constants and Z the Zener - Hollomon parameter (1944), i. e., the temperature compensate by the strain rate. The parameters α and n were determined using the method proposed by Uvira and Jonas (1968) and the calculated value agrees with these found by Cho *et al.* (2001), Siciliano and Jonas (2000) and Stewart and Jonas (2004). The activation energy Q_{def} depends on the material and is calculated solving the equation:

$$Q_{def} = R.n\left(\frac{\partial ln\, sinh\left(\alpha.\sigma_P\right)}{\partial ln\left(1/T\right)}\right)_{\dot{\varepsilon}} \tag{2}$$

For 38MnSiVS5 steel, the apparent activation energy for hot working is 328kJ/mol. Taking into account the activation energy determined and the values of the other parameters of the Equation 1, the dependence of the steady state stress with the Z parameter was plotted, as shown in Figure 3. The steady state stress is higher for lower temperatures and higher strain rates. The relationship between σ_S and the Z parameter observed in the Figure 3 can be expressed through the equation:

$$Z = 5{,}06.\sigma_S^{\,6{,}59} \tag{3}$$

It is worth noticing that the relationship fits well experimental data, although a considerable deviation is observed in one point (experiment conducted at 900°C with strain rate of $10s^{-1}$). This spread can be associated with the critical condition of the test (lower temperature and higher strain rate). The σ_S exponent value (6,59) attained is in agreement with the literature, as found by Poliak and Jonas (2004) using a plain low C-Mn steel and Hotta *et al.* (2005) using a 9% Ni steel in as cast condition. In general, the value of the exponent for the DRX of metals and alloys are higher than 5 (Ohtakara, 1972).

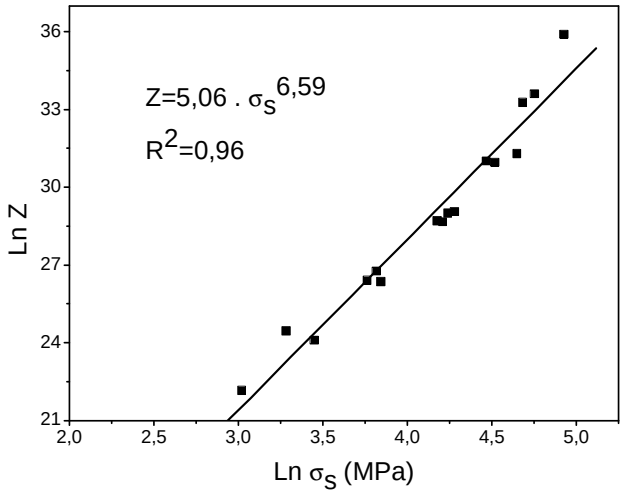

Figure 3. Dependence of steady state stresses on deformation conditions.

Figure 4 displays a micrograph set representing the microstructures observed in samples deformed at different temperatures and strain rates. The microstructure consists of a martensite matrix with images of the old austenite grain boundaries. In test accomplished at 900°C with strain rate of $1s^{-1}$, equiaxied grains with $D\gamma$ equal 8,6 ± 3,3 μm were measured. Taking into account that the average initial grain size was 100 μm (Souza, 1996) and the average final grain size was 19,8 ± 6,7 μm after deformation at 1100°C with strain rate of $1s^{-1}$, a significant grain refinement was observed even though the experiment has been carried out at high temperature. High standard deviation measured are due to the large spread in grain size; it can be seen in Figure 4(d) small grains (6,8 μm) along with larger grains (42,7 μm).

The influence of the temperature and strain rate on DRX grain size can be observed in the Figure 5 and 6. Increasing the temperature there is a considerable increasing in the grain size. This can be explained by the largest diffusivity presented at higher temperatures. Raising the strain rate there is a decrease in the DRX grain size. This can be associated with the dislocation density, which increases as the material work hardening (Sellars, 1980).

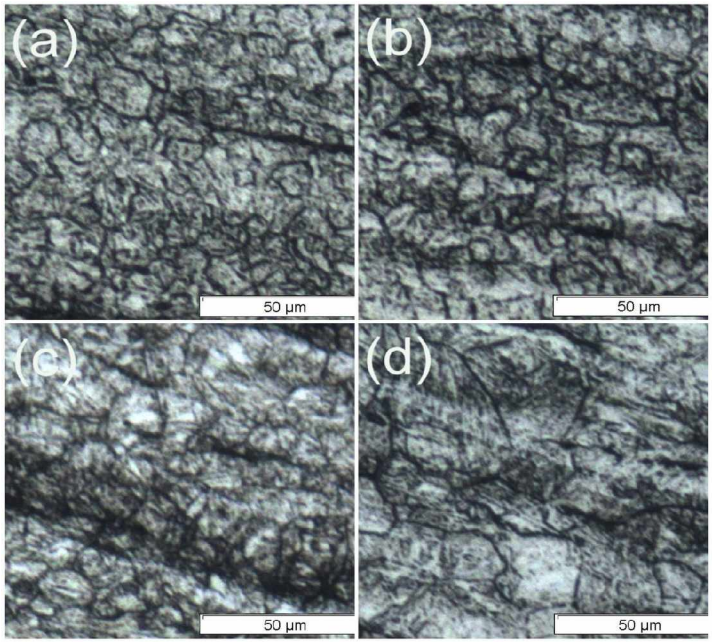

Figure 4. Microstructure observed in samples straining to steady state and water quenched. The deformation were conducted at (a)900°C and $1s^{-1}$; (b) 900°C and 0,1 s^{-1}; (c)1000°C and 1 s^{-1}; (d)1100°C and 1 s^{-1}

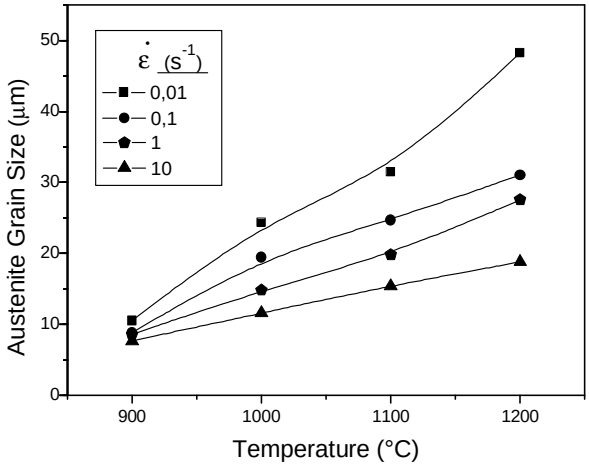

Figure 5. Influence of the temperature in the austenite grain size strained to the steady state.

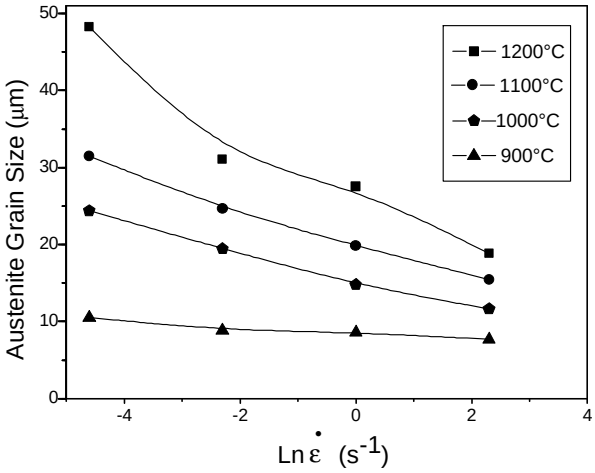

Figure 6. Influence of the strain rate in the austenite grain size strained to the steady state.

The dependence of the austenite grain size with the equivalent steady state stress is displayed in Figure 7. It can be seeing that more strength (σ_S) the material in steady state smaller the recrystallized grain size. Since higher values of σ_S are observed in experiments conducted at high strain rates and low deformation temperatures, greatest grain refinement can be attained in these conditions. It is well established that the average grain size in the steady state regime does not change with further straining (Luton and Sellars, 1969; Sandstrom and Lagneborg, 1975; Stuwe and Ortner, 1974). Furthermore, for a large range of materials the DRX grain size $D\gamma$ can be related to the steady state flow stress σ_S by a power law: $\sigma_S.D^m = K$ (Derby, 1990), where m and k are constant. Using regression analyses, the folioing relationship was attained:

$$\sigma_S = 1{,}04x10^3.D\gamma^{-0{,}98} \tag{4}$$

In a recent study, Liqiang *et al.* (2008), have obtained m equal 0,724 in a Nb-Ti microalloyed steels. The value of m = 0,98 found here is good agreement with the range of values observed in literature (0,4 <m <1,0) (Derby, 1990).

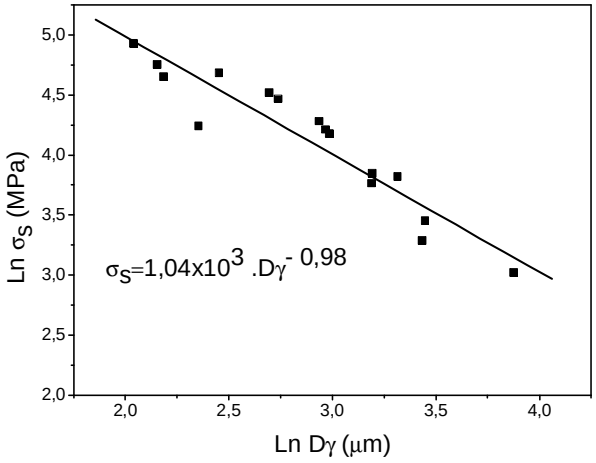

Figure 7. Dependence of austenite grain size with stress level in steady state.

It has been suggested (Sah, 1974) that the growth of the DRX grains is limited by work hardening within the grain, which is greater at lower temperatures and higher strain rates (i.e. at high *Z* values). Therefore, the microstructures of samples deformed under high *Z* conditions are finer than those of the samples deformed under low *Z* values. The DRX grain size ($D\gamma$) is often given as a power law function of the Zener–Hollomon parameter ($D\gamma = B.Z^{-k}$). The present work attained grain sizes following this relationship, as can be seeing in Figure 8. Once corrected to mean grain diameter values, there is a relatively good agreement between the present data and previous work (Ryan, 1990 and Salvatori, 2002) for different ranges of grain sizes and deformation modes (0,12< k <0,3). The following relationship was attained:

$$D\gamma = 8{,}26x10^{2} .Z^{-0{,}134} \tag{5}$$

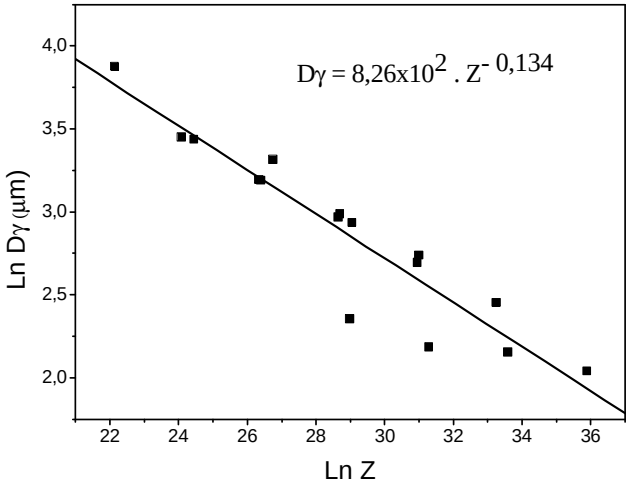

Figure 8. Dependence of average grain size in the steady state with deformation conditions.

In order to investigate the consistence of the data attained in this work, let's do an exercise. The grain size measured after deformation in the experiment conducted at 900°C with strain rate of $0{,}01s^{-1}$ was 10,5 μm. Applying Equations (3), (4) and (5) in these data a grain size equal 11,04 μm is obtained, which represent an error of 5,1%, which is a very small taking into account the spread observed in grain size measurement.

4. CONCLUSIONS

- The flow stress curves measured from samples of the 38MnSiVS5 steel have a typical shape of materials that softening by dynamic recrystallization. The apparent activation energy calculated was 328kJ/mol.

- The dependence of steady state stress with the temperature and the strain rate is described by the relationship $Z = 5{,}06.\ \sigma_S^{6{,}59}$.

- The average grain size is related to the steady state stress through the equation $\sigma_S = A.D\gamma^{m} = 1{,}04x10^{3}D\gamma^{-0{,}98}$.

- The equation that relates the DRX grain size with the parameter Z is $D\gamma = 8{,}26x10^{2}\ .\ Z^{-0{,}134}$.

5. ACKNOWLEDGEMENTS

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