Influence of warm working parameters on deformation behavior and microstructure of AISI 1015 carbon steel

Carmen Medrea-Bichtas¹, Gavril Negrea² and Serban Domsa²

¹ Technological Education Institute of Pireaus, Department of Physics, Chemistry and Materials Technology, 250, Thivon & P. Ralli Street, 12244 Aigaleo, Athens, Greece
² Technical University of Cluj-Napoca, Department of Materials Science and Engineering, Muncii Avenue 103-105, 3400 Cluj-Napoca, Romania

ABSTRACT

This paper presents the influence of warm working parameters (temperature and strain rate) on deformation behavior, microstructure and hardness of a low carbon steel (AISI 1015). Samples were subjected to torsion tests at different temperatures from 550 to 700 °C, in order to determine their resistance to deformation, deformability, microstructure and hardness. Based on deformation behavior of the steel, the optimal deformation regime appears to be situated in the range 625 – 675 °C. The microstructure obtained after warm working is much finer compared with the as-supplied microstructure of the steel (normalized condition). The results obtained in this study show that warm working offers a viable alternative to cold and hot working.

Corresponding author: Professor Serban Domsa, e-mail: sdomsa@zeus.east.utcluj.ro

I. INTRODUCTION

Plastic deformation is one of the most important technological processes involved in the steelmaking industry and in the manufacturing of many consumer goods. To be competitive, the basic task of the producer is to improve the properties of the final product while keeping the production costs as low as possible. Development of new plastic deformation techniques, capable to confer superior properties to the processed material, can contribute to the achievement of this goal. Such techniques should be simple, requiring no significant changes to the production line and should provide high productivity. To a large extent, these requirements can be fulfilled by warm working process which allows for production of engineering components with improved mechanical properties, manufactured with low energy costs, reduced materials quantities and efficient labor costs.

At steady-state conditions, the plastic deformation process is greatly influenced by operating temperature. For a low carbon steel, the influence of temperature on resistance to plastic deformation and deformability is shown in Fig. 1. Although, an increase in the deformability (plasticity) of the steel would be expected with increasing temperature, in fact, the deformability shows some important fluctuations. For instance, in the temperature range 250-300 °C, a sudden increase in the resistance to plastic deformation - which means a sudden decrease in the deformability - is often observed. This phenomenon is due to the precipitation of the cementite at the ferrite grain boundaries (“blue brittleness”). Another decrease of the plasticity is observed during the transition of the ferrite into austenite. Finally, a decrease of the plasticity is also observed near the melting temperature of steel. Based on such data, the temperature range for a particular plastic deformation process can be set such as to avoid unnecessary high energy consumption and to allow for high deformation values to be achieved.
In principle, the working process can be accomplished at hot, warm and cold temperatures /1/,/2/. Hot working process requires low deformation energy and can provide high deformation ratio and high strain rates. The main disadvantages of this process consist of significant oxidation and decarburization phenomena that occur at high temperatures. Oxidation can lead to important material losses (up to 20% for steels) and causes difficulties for the surface finishing. Decarburization also affects the surface properties and often requires material removal with negative impact on costs. To minimize the effects of oxidation and decarburization, several methods are used in industrial processes. A common solution is to heat the material in a controlled atmosphere, but this method is not usually viable for carbon steels due to high operational costs. Another method is to use direct electrical heating, a technique with many advantages, but its application is limited to small and medium sized semi-finished products which is characterized by low productivity due to piece-by-piece operation.

Cold working found broader commercial applications, yielding products of good surface quality and very low tolerances as opposed to hot working process. This method requires high deformation energy and can be successfully applied only to materials with high plasticity. In practice, this process is conducted in multiple stages, with intermediate annealing treatments, a factor that also increases production costs.

Warm working, which is conducted in a temperature interval situated above the recrystallization threshold and below A₁, combines the advantages of hot and cold processes. Compared to hot working, this method yields superior surface quality and higher dimensional control of the products. In addition, warm working is an energy efficient process and leads to reduced oxidation and decarburization phenomena /3/. Compared to cold working, the warm working requires lower deformation energy, can be applied to a broader range of steels, and provides higher deformation ratios as well as lower hardness variations across the section of the product /4/.

There are several studies dealing with warm working of steels /5/,/6/ but many aspects of this process have not been thoroughly investigated. For instance, the optimum temperature range, specific to each material and working process (rolling, drawing, forging etc.) and material properties obtained under certain operating conditions are not well defined yet.

In this paper, the influence of temperature and strain rate on deformation behavior (resistance to deformation and deformability), microstructure and hardness of a warm worked low carbon steel is presented. The advantages of warm working compared to hot working are also assessed.

II. EXPERIMENTAL DETAILS

The experiments were conducted on AISI 1015 carbon steel. The samples, with the geometry presented in Fig. 2 (deformation zone - φ 8 x 36 mm), were cut from normalized hot-rolled bars and subjected to torsion testing at different temperatures from 550 °C up to
700 °C (the temperature was increased in steps of 25 °C). To compare the deformation behavior in the warm and hot temperature ranges, several torsion tests were also performed at 1000 °C. The samples were heated by induction to desired temperature. All the tests were carried out on a home-build machine which allows for precise measurements of the sample temperature, torque, rotation angle and axial force. The microstructure of the samples was investigated by optical microscopy and their hardness was measured by Vickers method.

The variation of the deformation shear stress is calculated from the equation. (1):

\[
\tau_d = \frac{M_t(3 + m)}{2\pi R^3}
\]

where, \(\tau_d\) is the deformation shear stress [N/mm²],
\(M_t\) – torque [N·mm],
\(R\) – radius of the sample [mm],
\(m\) – a coefficient that takes into account the non-uniformity of the strain rate along the sample axis, which is a function of temperature \(t_d\) and characterizes the visco-plastic behavior of the material. This coefficient takes the following values /7/:

- \(m = 0.1\) for \(t_d < 700 \, ^\circ C\);
- \(m = 0.2\) for \(700 \leq t_d < 1000 \, ^\circ C\);
- \(m = 0.3\) for \(t_d > 1000 \, ^\circ C\).

To study the influence of the strain rate on the plastic behavior of the samples, the tests were performed at two rotation speeds \((n)\) at each temperature step between 550 and 700 °C: 120 [rpm] for a high deformation rate and 22 [rpm] for a low deformation rate. These values are situated in the normal deformation rate range. In addition, a series of tests were performed at a given temperature (625 °C) for different rotation speeds between 22 and 250 [rpm].

The deformability of the material was assessed from the number of torsion of the sample until breaking \(n_t\). However, for a more precise assessment of the deformability, a correction was made to take into account the normal stress \((\sigma)\) which is also generated in the sample during torsion testing /7/:

\[
n_{tc} = n_{te} \cdot \left(1 + c \frac{\sigma}{\tau}\right)
\]

where, \(n_{tc}\) is the corrected number of torsion until breaking;
\(n_{te}\) – the effective number of torsion until breaking;
\(c\) – a coefficient with values in the range 2.5 – 3.0 /1/ (c = 2.5 was selected);
\(\tau\) – the shear stresses determined by eq. (1);
\(\sigma\) – the normal stress determined by the following equation:

\[
\sigma = \frac{F}{\pi R^2}
\]

where \(F\) stands for the axial force.

The torsion speed at the sample surface is given by the equation /7/:

\[
v = \frac{\pi Dn}{L}
\]

where, \(v\) is the torsion speed at the sample surface [s⁻¹];
\(D\) – diameter of the sample [mm];
\(n\) – rotation speed of the testing machine [s⁻¹];
\(L\) – sample length [mm].
For example, by replacing the sample dimensions and the two main rotation speeds in Eqn. (4), the following torsion speeds at the sample surface are obtained: 0.25 and 1.39 s⁻¹.

III. RESULTS AND DISCUSSION

The influence of temperature and torsion speed on deformation behavior (resistance to deformation ($\tau_d$) and deformability ($n_{tc}$)) is shown in Fig. 3. By increasing the temperature from 550 °C to 675 °C, the shear stress decreases by a factor of almost 2, from 115.53 N/mm² to 65 N/mm². The reduction of the resistance to deformation is more pronounced in the temperature interval 550 - 625 °C due to completion of recrystallization process. If at 550 °C the sample structure is just restored, at 700 °C the structure is completely recrystallized. The small increase of the resistance to deformation at 700 °C is due to the fact that the actual average temperature of the sample exceeded A₁ temperature.

Note: The reference temperature reported throughout the text represents the initial temperature of the sample. The actual average temperature of the sample during the tests was found to be higher than initial value by 26 - 34 °C, depending on initial temperature and rotation speed.

By increasing the torsion speed, in other words - the strain rate, the resistance to deformation increases significantly. However, compared to hot working at 1000 °C, the resistance to deformation at 675 °C is two times higher (65 N/mm² and 31.2 N/mm², respectively), but it is incomparably lower than the resistance to cold working /8/.

The deformability of the sample, as assessed by the number of torsions before breaking (Eqn. 2), increases with increasing temperature and torsion speed. For a given temperature, both, resistance to deformation and deformability, increase by increasing the strain rate as shown in Fig. 4.
The warm working leads to a finer microstructure, characterized by a globular aspect with perlite homogeneously distributed in the ferrite matrix. In the case of warm working at 550 °C, the resulting microstructure has very fine grains but it is strain hardened, with less defined grain boundaries (Fig. 5 a). Increasing the working temperature to 600 °C allows for simultaneous evolution of strain hardening and recrystallization processes. The grains are very fine, partially recrystallized (Fig. 5 b). After warm working at 650 °C, the microstructure is completely recrystallized and has a very fine and uniform aspect (Fig. 5 c). A further increase of the initial temperature of the sample to 700 °C resulted in a slight increase of the grains, but the microstructure remained essentially fine and uniform.

The microstructure of the samples after warm working is much finer compared to the initial microstructure of the steel in the as-supplied condition (normalized, Fig. 5 d), suggesting that the mechanical properties of the steel after warm working are also superior to those obtained after normalizing.

The hardness of the samples after warm working decreased with increasing the deformation temperature as shown in Fig. 6. It can be seen that in the temperature range 550 – 675 °C, the average hardness varies from 153 to 134 HV which is about 10 to 30% higher than the initial hardness (119 HV) /8/,/9/. Considering the deformation ratios to which the samples were subjected, this relatively small increase of the material hardness during warm working confirms that strain hardening and recrystallization processes are taking place simultaneously.

Figure 4. The influence of torsion speed on the resistance to deformation and deformability at 625 °C.

Figure 6. Influence of the initial temperature on the hardness of the sample after torsion tests.
IV. CONCLUSIONS

Based on the torsion tests carried out in the temperature range from 550 to 700 °C on AISI 1015 carbon steel, the following conclusion can be drawn:

1. The optimal deformation temperature is 625 to 675 °C. In this temperature range, the warm working requires smallest deformation energy and allows for maximum deformation ratios to be achieved.

2. The strain rate has a significant influence on plastic behavior of the material. Both, resistance to deformation and deformability, increase with increasing the strain rate.

3. The microstructure obtained by warm working is much finer compared to the microstructure obtained by normalizing the material after hot rolling, with advantageous consequences on the mechanical properties.

4. The results obtained in this study show that warm working offers a viable alternative to cold and hot working processes.

References


Mailing addresses of the authors:

Dr. Carmen Medrea-Bichtas
Technological Education Institute Piraeus
Department of Physics, Chemistry and Materials Technology
250, Thivon & P. Ralli Street
12244 Aigaleo, Athens, Greece
e-mail: cbichtas@yahoo.com

Dr. Gavril Negrea
Technical University of Cluj-Napoca
Faculty of Materials Science and Engineering
Muncii Avenue 103-105, 3400 Cluj-Napoca, Romania
Tel. + 64 415051 ext. 161 Fax. +64 415054
e-mail: gnegrea@zeus.east.utcluj.ro

Professor Serban Domsa
Technical University of Cluj-Napoca,
Faculty of Materials Science and Engineering,
Muncii Avenue 103-105, 3400 Cluj-Napoca, Romania
Tel. + 64 415051 ext. 161 Fax. +64 415054
e-mail: sdomsa@zeus.east.utcluj.ro