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Simulation of the Hot Flow of C80 Steel intended for the AISI1080 Strength Rank Bar

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Abstract*— The objective of this study is to provide data on the mechanical properties of high-carbon C80 steel intended for the manufacture of working tools and to develop a comprehensive understanding of their microstructural evolution in terms of deformation parameters. This steel is known for its wear resistance and toughness, and is also ideal for manufacturing bearings and other wear parts produced in industrial processes. More specifically, the main objective is to develop a material with a better balance of properties from unalloyed steel in order to expand production to AISI 1080 grades using the same chemical composition. To this end, empirical tests, including hot tensile testing (within range of strain rates), were carried out to simulate the rolling sequences of the industrial process. The results of these experimental protocols have highlighted the significant effect of deformation parameters on the evolution of the final microstructure, and therefore on the mechanical properties of the steel studied. This has also led to technological proposals for obtaining high grades for this type of AISI 1080 rolled steel. The prediction of the evolution of the austenite microstructure during hot deformation, a key step in modelling phase transformations, has also been developed to more accurately predict grain size as well as the associated critical strains and stresses. These various investigations will allow us to develop flow property prediction approaches based on analytical aspects and microstructural observations in order to determine quantitative relationships between macroscopic constitutive laws while describing the physical phenomena underlying rheological behaviour. Hot working simulation tests were performed by uniaxial tensile testing in order to obtain the stress-strain flow curve for C80 is a high carbon rolled steel. This will be validated by comparing its predicted load-elongation curves with the experimental results of the tensile tests. Subsequently, a numerical model validated using the JMat Pro software was used to analyze the load distribution between the samples in roughing mill at various temperatures (1000˚C, 1050˚C, 1100˚C) and under strain rates (0.001, 0.01, 0.1, 1, 10 s-1). This approach made it possible to predict the deformation mechanisms and the progression of hot plastic deformation leading to the final on determines the flow stress at constant strain rates C80 steel. The aim of this work is to study the combined influence of temperature, and strain rate on the hot rheological behavior of C80 steel and the mechanisms that govern them.

***Keywords*—Hot Flow Stress, Hot tensile test, C80 steel, Profile, Rheologic behavior, JMat Pro software.**

I. INTRODUCTION

Improving the mechanical properties of these steels can be achieved through various mechanisms that can occur during deformation and/or after normalizing treatment (structural hardening, grain refinement, and/or fine precipitation). It follows that controlling the microstructure of materials and understanding the associated metallurgical and mechanical behavior (rheology) is one of the important and necessary factors in achieving these properties. It is well known that any metallurgical and rheological study of these alloys is closely linked to the evolution of mechanical properties as a function of deformation parameters (applied stress, imposed

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strain, strain rate, and temperature). The main objective is to determine the rheological behavior of high-carbon steels through analytical resolution in order to arrive at a behavior law that includes structural and mechanical evolution during industrial processes. Deformation of metals and alloys at temperatures above 0.5 Hot deformation processes may encounter different softening mechanisms like Static Recrystallization (SRX), Dynamic Recrystallization (DRX). This report is based on the investigation of hot deformation behavior of our Steel by constant strain rate Compression Tests. Flow curves at different operating parameters (Temperatures (1000˚ C, 1050˚ C, 1100˚ C) and Strain Rates (0.001, 0.01, 0.1, 1, 10 s-1) were obtained by isothermal continuous uniaxial compression tests [1, 2].

Deformation of metals and alloys at temperatures above 0.5 Tm is a complex process in which mechanical working interacts with various metallurgical processes such as dynamic restoration including recovery and recrystallization, and phase transformation for polymorphous materials. The essential rheological characteristics of metals are obtained from the results of conventional mechanical tests such as tensile testing. In general, resistance to plastic deformation is a function of the deformation rate. However, in the case of intercrystalline sliding, the resistance is relatively independent of the rate (except at very high rates).Any mechanical analysis involves two quantities: the yield strength and the coefficient of friction. The objective of mechanical tests is to provide their values under real or near-real conditions of the forming operation. Conversely, if we want to know the state of a specific material during and after the operation, it is necessary to simulate a thermomechanical treatment on test specimens.

We attempt to present the conventional assumptions and simplifications that allow us to model this behavior. At low temperatures, the deformation of a metal occurs with work hardening; the yield stress increases. At high temperatures (temperature T > 0.5T_{melting}), the work hardening phenomenon competes with recovery (softening). We can say that the structure and the yield stress are very sensitive to the strain rate. An increase in temperature is equivalent to a decrease in this stress.

We introduce an assumption that forms the basis of the theory of plasticity.

- Regardless of the path taken, the material remains isotropic.
- The yield stress will only be a function of the quantity invariant under a change of axis (generalized strain and strain rate).

Three constitutive laws are used:

a) Pure cold working:

The general law is: $\sigma_0 = f(T, \varepsilon)$

b) Pure viscous behavior (hot):

The general law: $\sigma_0 = g(T, \varepsilon)$

c) Viscoplastic behavior:

The general law: $\sigma_0 = j(T, \varepsilon, \varepsilon)$

To use test results from literature or your own tests without risk of error, two main rules must be observed:

- only work with data presented as stress-strain-strain rate-temperature.
- carefully determine the reference conditions of the tests (same process temperature, same mechanical treatment, etc.).

Rheology is the study of the deformation of matter. Its main objective is the general study of continuous media between viscous liquids and rigid solids. In our case, we will primarily study the rheology of metals and the different classification criteria. We will begin by presenting the rheological characteristics of metals and their influence on forming. Then, we will provide an overview of the most commonly used rheological laws in forming. Many studies assume that the behavior is perfectly plastic. It is important to examine more closely the various causes of deviation from this perfect model. As a general rule, the yield strength increases with deformation. This is the phenomenon of work hardening. In fact, the term work hardening encompasses all the changes undergone by the mechanical properties of a material as a result of plastic deformation. The material can become anisotropic. This is the phenomenon of anisotropic work hardening. Large, permanent deformations generate an orientation effect on the crystalline grains. A polycrystal whose grains were initially randomly oriented, thus creating isotropy in the material, will see them orient themselves according to the applied stresses. The most concrete example is the rolling of sheet metal.

Under these conditions, it is observed that the yield stress of a tensile test specimen is a function of the direction in which the sample is taken from the material. In practice, standardized sheet metal acceptance tests require samples to be taken in both the longitudinal and transverse directions. This will subsequently lead us to a model of anisotropic plastic behavior.The hardening phenomenon also encompasses the asymmetry sometimes observed in tensile and compression tests. In general, the compressive behavior is similar to the tensile behavior, but for some materials (such as cast iron), the elastic limit exhibits different values. This is referred to as kinematic hardening.

To enable the experimentally observed hardening, while maintaining a threshold surface beyond which the representative point cannot move, displacement or deformation mechanisms have been considered: the threshold function is parameterized by introducing hardening variables.The tensile test is very incomplete from a thermal perspective. In practice, it is assumed that the specimen undergoes isothermal evolution and that the test takes place at a constant temperature. In reality, the second law of thermodynamics shows us that the irreversibility of the plastic deformation process results in heat transfer. A blacksmith can "heat" a piece through the repeated action of his hammer (and possibly a drop hammer). Furthermore, it should be noted that many shaping processes take place at high temperatures.

Therefore, it is important not to neglect the effects of heat.

Hot deformation processes may encounter different softening mechanisms like Static Recrystallization (SRX), Dynamic Recrystallization (DRX), Meta-dynamic Recrystallization (MDRX), Continuous Recrystallization (CRX), Continuous Dynamic Recrystallization (CDRX) and Dynamic Strain Induced Transformations (DSIT). Each softening mechanisms operating inthe microstructure evolution depends on the chemical composition, prior machining procedures and the deformation parameters. Flow behavior and microstructural studies in our steel reported the occurrence of processes like work hardening, DRV, DRX and DSIT. This report is based on the investigation of hot deformation behavior of SIMP Steel by constant strain rate Compression Tests. Flow curves at different operating parameters (Temperatures and Strain Rates were obtained by isothermal continuous uniaxial compression tests.

In the Fig.1 (a), we can see the major processes occurring at various stages of a typical single peak flow curve. Typically DRV occurs at all levels of strain greater than 0.1 and is a principal mechanism for the reduction of flow stress σ and strain hardening rate (ϴ=ɗσ/dε). DRX is an important softening mechanism which occurs at some critical strain and refinement of grains occur and equiaxed grains are observed in the microstructure upon completion of DRX. The strain at which dynamic recrystallization (DRX) is initiated is of considerable importance in the modeling of hot rolling mills [3-5]. The major experimental difficulty in detecting the onset of DRX is that attainment of the critical stress σc(εc) does not reveal itself in the flow curve, which remains smooth prior to and beyond the critical point. For this reason, the presence of stress peaks in constant strain rate flow curves is often considered as the sole reliable indication of the initiation of DRX. But flow curves without welldefined stress peaks are generally believed to pertain to mechanical behavior with dynamic recovery (DRV) as the only restoration mechanism Fig1. (b). Nevertheless, DRX takes place in many materials even though no clearly defined stress peaks are observed in laboratory flow curves.

Other examples of such materials include Nb microalloyed low carbon and austenitic stainless steels. Flow curves obtained for SIMP steel deviated from the conventional single-peak flow curves at higher Zener-Holloman Parameter (Z). When deformed in compression, no peaks can be seen in the flow curves at all at higher Z values. The occurrence of DRX in such steels, if this is to be identified solely from stress peaks, is therefore often questioned. Previous studies suggested the non-occurrence of DRX under no-peak condition but microstructural studies validated the occurrence of dynamic recrystallization in samples deformed under high Zener-Holloman parameter value. Critical points for the onset of DRX were obtained using Poliak-Jonas methods [9].

Higher order polynomials were used to fit the flow curves which didn’t show any well-defined peaks; those polynomials upon further differentiations gave us the accurate inflection points on strain hardening rate ϴ against stress σ curves or equivalently from minima of (ɗϴ/ɗ σ) - σ curves. It is shown that the present technique can be used to establish the occurrence of DRX when this cannot be determined unambiguously from the shape of the flow curve. The application of constitutive equations for determination of hot working constants was critically discussed. The impact of DRX on high temperature mechanical behavior has been best understood and quantified for constant strain rate compression. At sufficiently high temperature, DRX is initiated at some critical stress σc attained at a critical strain εc. As a flow softening phenomenon, DRX leads to a decrease in flow stress with increasing strain. Beyond this critical point, the stress continues to increase until the softening due to the progress of DRX balances the continuing strain hardening in the unrecrystallized parts of the material. This balance is manifested by the peak stress σp attained at the strain εp. Typically, when

DRX takes place in a constant strain rate test, stress–strain curves such as that of Fig. 1(a) are obtained but it is not always true [8, 9].

Understanding the mechanical behavior of materials used to manufacture various structures is essential. Mechanical testing provides this necessary data. First and foremost, it is crucial for developing forming processes. Indeed, while for a long time empiricism and experience were sufficient to carry out deformation operations (rolling, drawing, extrusion, forging, machining, etc.), the increasing demands for quality and precision necessitate detailed calculations of these various operations. Clearly, these calculations cannot be performed without a precise understanding of the laws governing the mechanical behavior of materials, which involve the rate of loading and temperature, as well as the interactions between mechanical properties and the evolution of the microscopic structure [10, 11].

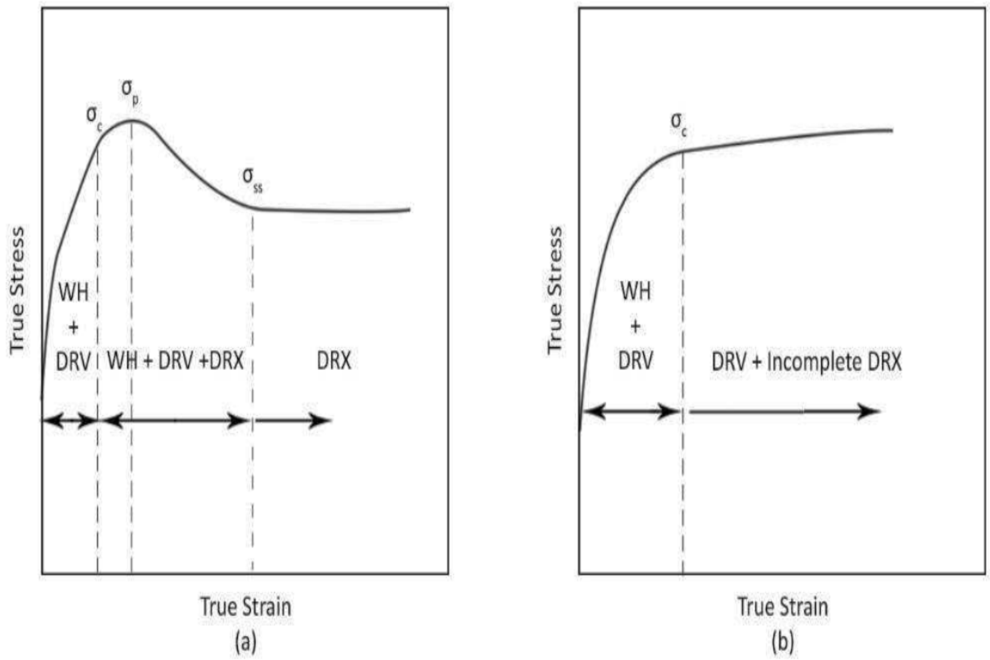

Fig. 1(a) Typical single-peak true stress and true strain curve for hot deformation depicting various viable processes at different stages of the flow curve, (b) Monotonously increasing flow curve with no distinctive peak depicting viable processes at different stages.

II. METHODOLOGY, RESULTS AND DISCUSSION

The main objective of our study is the modification of the mechanical properties of type construction steels (raw steel billets in table 1), namely "AISI1080", from which it is proposed to optimize the range of heat treatments. To simulate the rolling conditions of C80 steel in the roughing mill for large diameter steel bars, we have chosen the following key conditions (according to to industrial rolling) [6-7]. For Steels, pass strains and strain rates of 0.001 and $1s^{-1}$ were applied, respectively. The effect of roughing passes was omitted for simplicity. Deformation temperatures used were 1000, 1050, and 1100 °C for the respective steels, all at least 50°C above their ortho-equilibrium Ac_3 temperatures. Thermodynamic analysis was conducted using the JMatPro simulation software (version 7.0). The typical conditions ranges at roughting rolling stages are (industrial manufactory): Temperature range: 1000-1100°C, Speed range: 0.1-1 m/s, True strain range : 0.2-0.4, Strain rate range : 0.9-10 S-1. The hot compression tests are divided according to three solutions temperature regimes of 1000-1100 °C.

TABLE 1
CHEMICAL COMPOSITION OF STUDY STEEL

Content in chemical element in% by mass									
C	**Mn**	**Si**	**P**	**S**	**V**	**Al**	**Cu**	**Cr**	**Mo**
0.78	0.7	0.38	0.016	0.025	0.02	0.057	0.08	0.2	0.25

The isothermal investigation gives us Different phases of the non-alloyed carbon steel C80, The presence of different phases in the two samples (from the cast (C) and rolled (L)) is studied by XRD analysis. Global scanning XRD patterns (2theta = 10–110) indicate that α-Fe and cementite (Fe3C) peaks were reported. (Fig. 2).

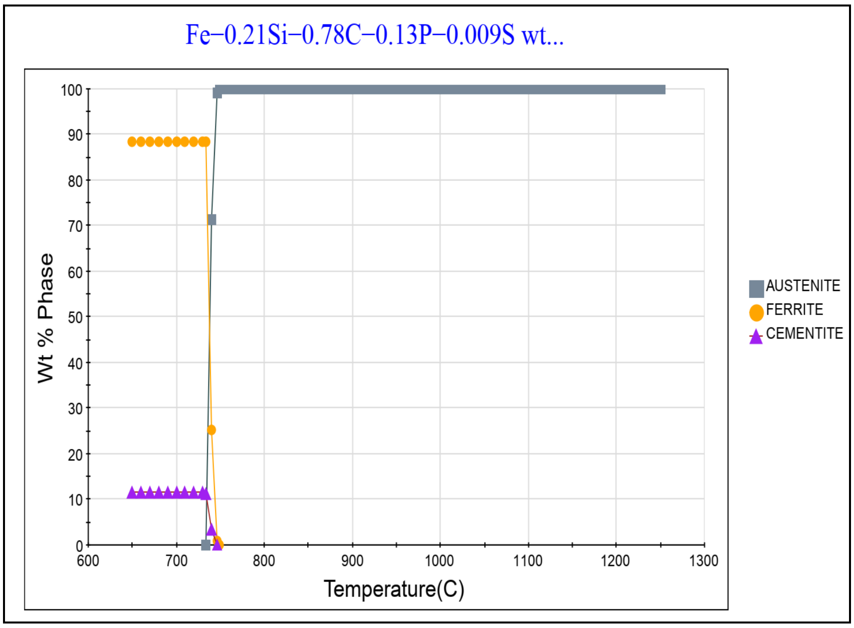

Fig.2.1 Different phases of the non-alloyed carbon steel C80 by isothermal investigations.

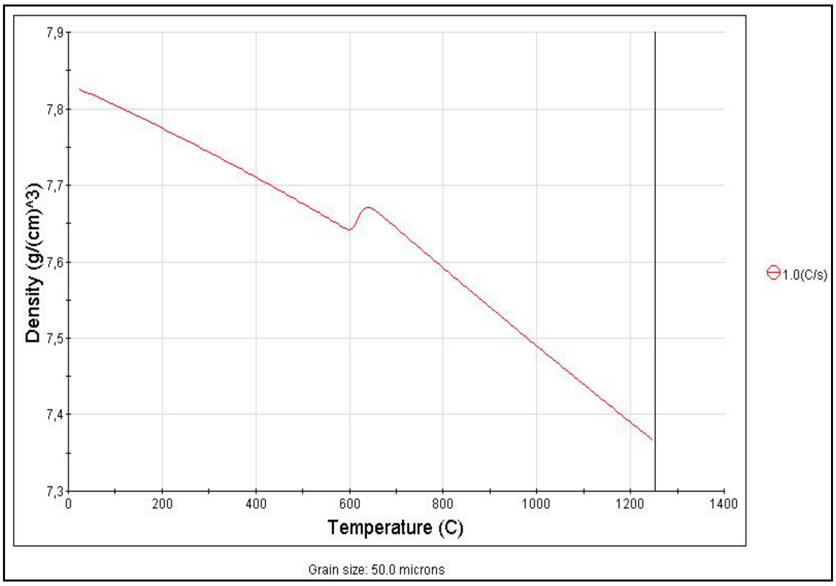

Fig.2.2 evolution of the density with hot temperatures

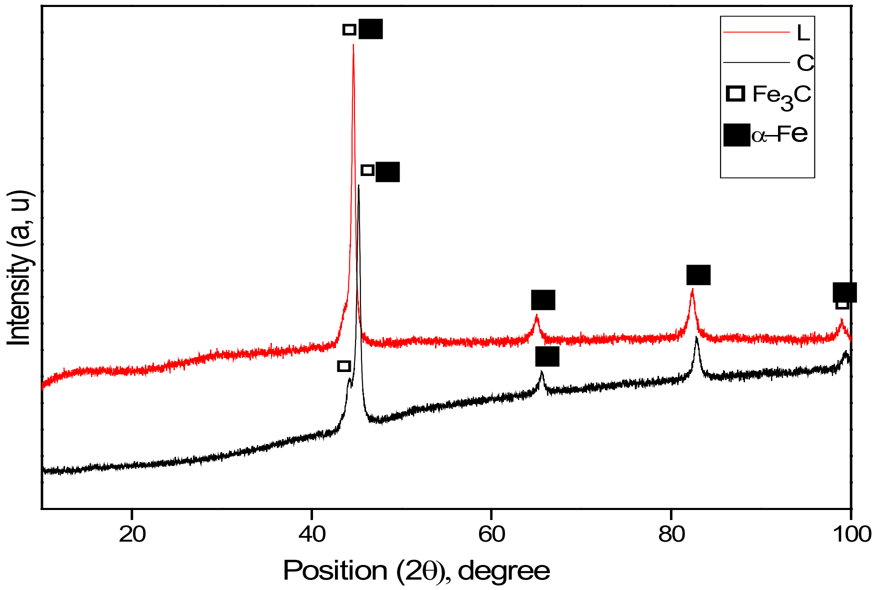

Fig.2.3. XRD spectrum of casting and rolled laminate samples. L : rolled sample, C : casting sample.

III. FLOW CURVES AT DIFFERENT DEFORMATION CONDITIONS

To simulate the rolling conditions of C80 steel in the roughing mill for large diameter steel bars, we have chosen the following key conditions (according to to industrial rolling). Full experimental details are available in Refs. [6-7]. For Steels, pass strains and strain rates of 0.001 and 1s⁻¹ were applied, respectively. The effect of roughing passes was omitted for simplicity. Deformation temperatures used were 1000, 1050, and 1100 °C for the respective steels, all at least 50°C above their ortho-equilibrium Ac3 temperatures. Thermodynamic analysis was conducted using the JMatPro simulation software (version 7.0). The typical temperature, strain and rate ranges at roughting rolling stages are (industrial manufactory):

- Temperature range :1000-1100°C
- Speed range : 0.1-1 m/s
- True strain range : 0.2-0.4
- Strain rate range : 0.9-10 S-1

The hot compression tests are divided according to three solutions temperature regimes of 1000-1100 °C and are presented in Table 2 (after reheating temperature of 1250 °C, initial grain size 50 µm (Fig. 3).

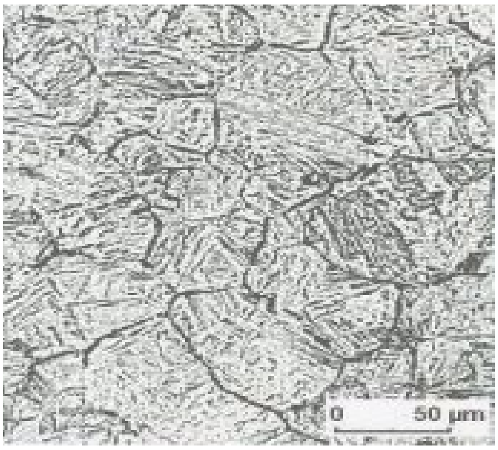

Fig. 3 Microstructure of austenite formed at a temperature of 1250 °C (100% austenite)

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TABLE 2

STRAIN RATE AND DEFORMATION SCHEDULE AFTER REHEATING TEMPERATURE OF 1250 °C, INITIAL GRAIN SIZE 50 µM

Strain rate (s-1)	**Temperature (°C)**		
	1000	**1050**	**1100**
0.001	x	x	x
0.01	x	x	x
0,1	x	x	x
1	x	x	x
10	x	x	x

After removal of the elastic portion, each flow curve was corrected for friction and then was smoothed in order to eliminate the irregularities and fluctuations. True Stress-True Strain Curves at different temperatures and strain rates are shown in Fig. 4.

The first steel, plain C80 carbon steel, contains minimal austenite-stabilizing alloying elements. For this steel, a flow stress was calculated reaching for example the 45.46 and 46.6 MPa for C80 at 1100°C respectively with 0.1s-1 strain rate and 71.94 and 96.04 MPa at 1000°C with 1s-1. Based on the investigations carried out and the corresponding simulations, we can deduce that as the temperature increases, the flow stress decreases [8, 9]. The strain rate has a constraining effect; it varies proportionally with the max stress. The deformation capacity (in percentage) increases significantly (Fig. 5). These critical values are associated with dynamic metallurgical phenomena including phase transformation, recrystallization, and recovery. They can be determined from the stress-strain curves by applying the well-known double differentiation method developed by Poliak and Jonas [9, 10, 11].

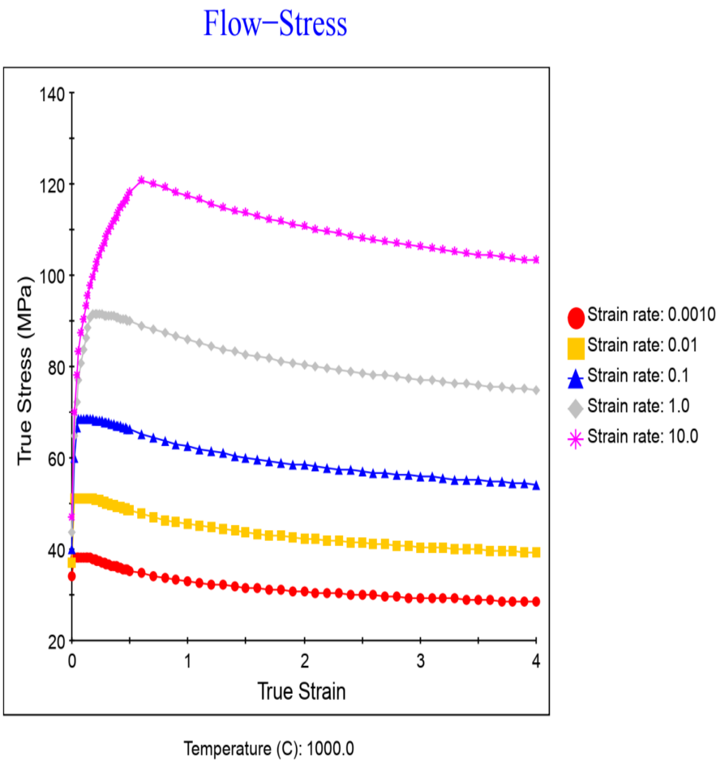


Fig. 4.1 The hot deformation behavior of the non-alloyed carbon steel C80 investigated by isothermal continuous uniaxial compression tests under the condition of $\dot{\varepsilon}$=0.001-10 s^{-1}; T=1000°C.

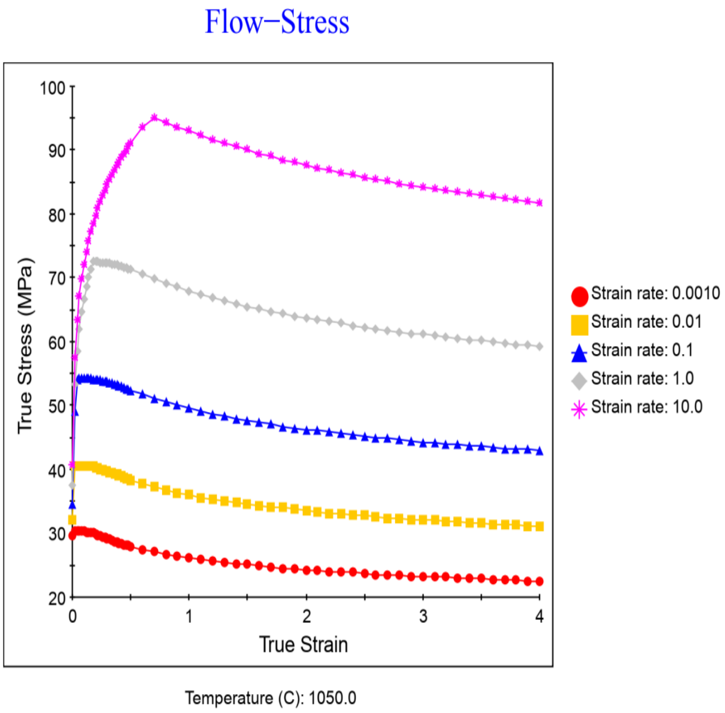


Fig. 4.2 The hot deformation behavior of the non-alloyed carbon steel C80 investigated by isothermal continuous uniaxial compression tests under the condition of $\dot{\varepsilon}$=0.001-10 s^{-1}; T=1050°C.

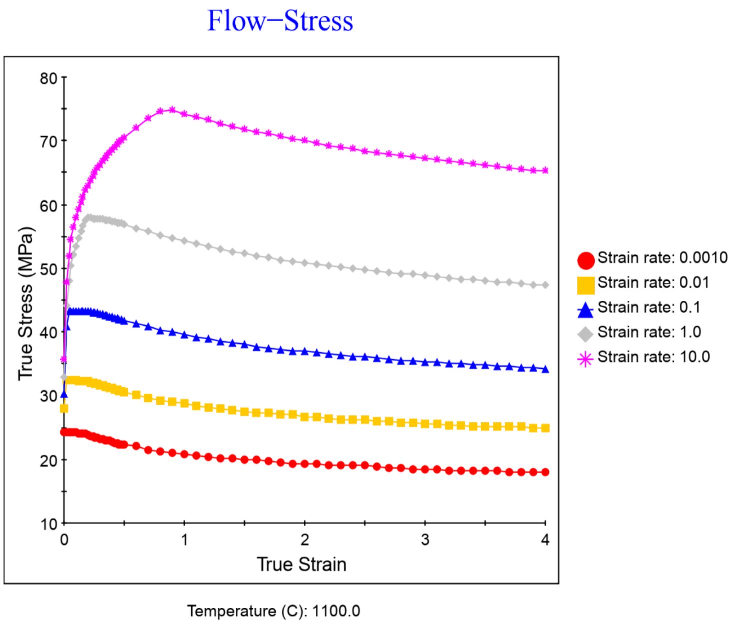
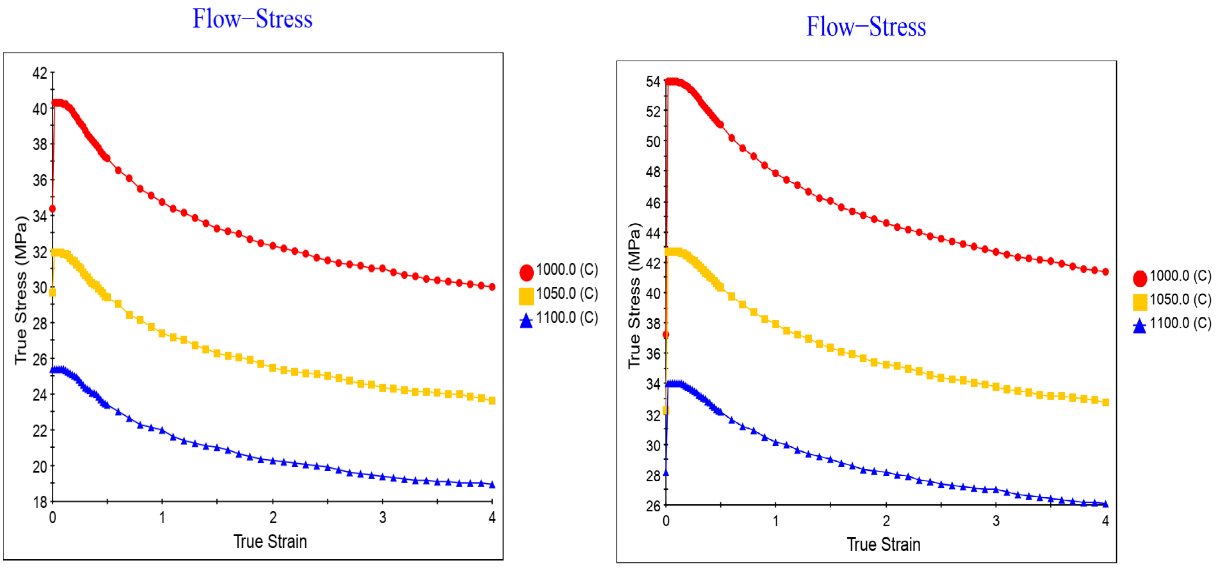


Fig. 4.3 The hot deformation behavior of the non-alloyed carbon steel C80 investigated by isothermal continuous uniaxial compression tests under the condition of $\dot{\varepsilon}$ =0.001-10 s^{-1}; T=1100°C.

TABLE 3

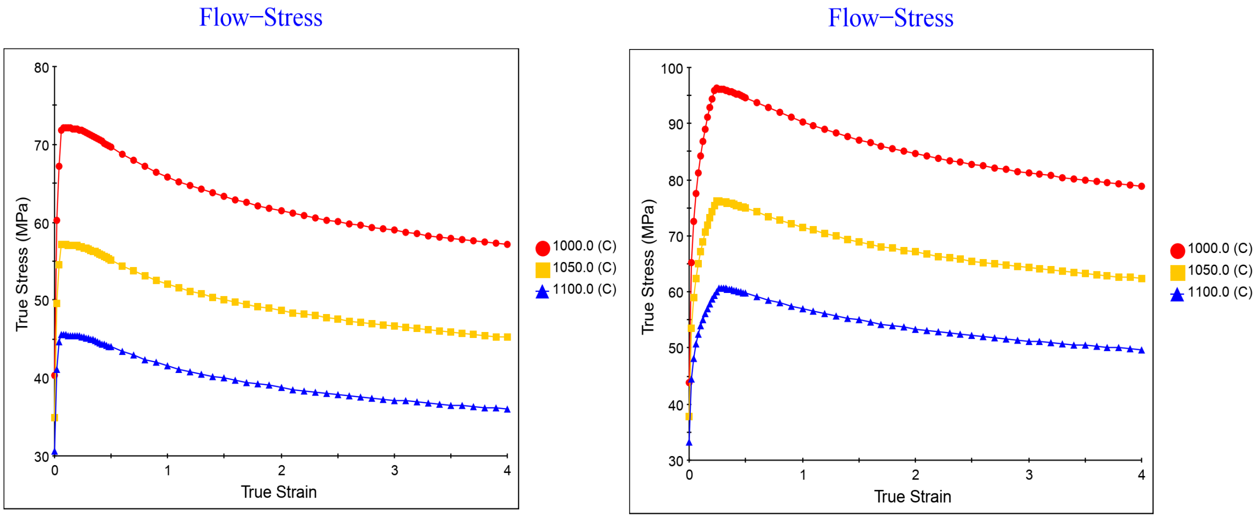
RESULTS OF MAXIMAL STRESS AND DEFORMATION

T °C	MPa /%	1000	1050	1100
$\dot{\varepsilon}_{0.001s-1}$	σ_{max}	40.63	31.92	25.24
	ε_{max}	0.02	0.02	0.02
$\dot{\varepsilon}_{0.01s-1}$	σ_{max}	54.34	42.68	33.77
	ε_{max}	0.02	0.02	0.02
$\dot{\varepsilon}_{0.1s-1}$	σ_{max}	71.94	57.0	45.46
	ε_{max}	0.08	0.08	0.08
$\dot{\varepsilon}_{1s-1}$	σ_{max}	96.04	76.04	60.50
	ε_{max}	0.24	0.26	0.32
$\dot{\varepsilon}_{10s-1}$	σ_{max}	126.34	98.58	77.36
	ε_{max}	0.8	0.8	0.9



Strain rate: 0.0010

Strain rate: 0.01



Strain rate: 0.1

Strain rate: 1.0

Fig. 5 Effect of stain rate on the hot deformation behavior of the non-alloyed carbon steel C80

IV. CONCLUSION

This study contributed to the understanding of the hot plastic deformation mechanisms of high-carbon steels. Through experimental simulation tests, including hot tensile testing under a range of strain rates and temperatures, the rheological and microstructural behavior of these steels was reviewed. The results of these investigations highlighted the significant influence of deformation parameters (strain rate, temperature) on the evolution of the structure and the associated plastic flow, which are essential for simulating rolling sequences at the industrial process level. The steel's behavior will thus be modeled by a viscoplastic constitutive law derived from hot tensile tests, taking into account the effects of thermal and mechanical coupling on the evolution of the strain stress. Flow curves at low strain rates and High Temperature (> 950 ° C) shows a distinct peak whereas flow curves at high strain rates and high temperatures shows a monotonously increasing curve without any peak. Beyond the critical point, the stress continues to increase until the softening due to the progress of DRX balances the continuing strain hardening in the unrecrystallized parts of the material. This balance is manifested by the peak stress σ_p attained at the strain ε_p. Both ε_p and σ_p decrease in a similar manner with rising temperature and declining strain rate. But the absence of peaks can be attributed to the secondary work hardening which proves to be a dominant process over other softening processes which not only retards the process of DRX but also contributes to the absence of peak. Softening process is prevalent till strains of 0.2-0.4 but after that, an increase in stress has been observed in all the curves. This increase in the stress can be attributed to the dominant effect of work hardening over softening mechanism taking place like DRX and DRV. Based on the investigations carried out and the corresponding simulations, we can deduce that as the temperature increases, the flow stress decreases. The strain rate has a constraining effect. The results found show that the key phenomena of the hot behavior of C80 steel is governed by that typical of figure 1 as Work hardening (WH), dynamic recovery (DRV) and dynamic recrystallization (DRX) [7-10].

This development also requires a more sophisticated approach to mechanical testing to provide the necessary data for engineers. Modern calculations also provide a means of better understanding the behavior of test specimens, and, thus reinforcing each other, experience and theory lead to an increasingly greater mastery of the mechanical strength of structures. Alongside traditional tests, specific tests have been developed that strive to provide intrinsic data, that is, data independent of the shape and dimensions of the specimens. In particular, advances in fracture mechanics have introduced a whole new range of tests. Faced with this array, engineers may find themselves unsure which test will provide the appropriate answer to the problem at hand. However, it is important to make this choice not only to arrive at unambiguous answers, but also for reasons of economy: some sophisticated tests are expensive. They should only be used if the data they provide is essential, and it is therefore important to resist trends. In many cases, traditional, proven, and cost-effective tests are perfectly adequate. From this perspective, it is important to distinguish between tests that provide usable quantities for calculating parts or processes, and that allow for precise dimensioning, and those that have a purely comparative value but allow for monitoring manufacturing and controlling the quality of a material or tracking the influence of a metallurgical factor. These latter tests have the advantage of simplicity; various correlations allowing the deduction of intrinsic constants from their results have been developed. Finally, it is necessary to determine the mechanical properties of materials to design structures in a way that avoids various failure modes [11].

Calculations require a correct evaluation of the stress and strain fields present in the components; therefore, a thorough understanding of the constitutive laws is necessary. Furthermore, it is essential to determine the limits that must not be exceeded to avoid failure: yield strength, breaking load, fatigue strength, etc. In recent years, advances in numerical computation, thanks to computers, particularly the finite element method, have made it possible to determine very accurately how parts behave [11, 12].

REFERENCES

[1] Clodualdo Aranas a, Fulvio Siciliano. Thermomechanical and thermodynamic behavior of deformed austenite in four different steel grades. journal of materials research and technology, 2021 ; 11 : 1911-1916, ttps://doi.org/10.1016/j.jmrt.2021.02.034

[2] Aranas C, Rodrigues SF, Ghosh C, Siciliano F, Jonas JJ. Recent developments in thermomechanical processing of steels. Iron Steel Technol 2020:1011. https://doi.org/10.33313/380/001.

[3] M. Rakhshkhorshid. Modeling the Hot Deformation Flow Curves of API, X65 Pipeline Steel, Int. J. Adv. Manuf. Technol., 2015, 77, p 203–210.

[4] Y.C. Lin and X.M. Chen. A Critical Review Of Experimental Results and Constitutive Descriptions for Metals and Alloys in Hot Working. Mater. Des., 2011, 32, p 1733–1759

[5] Indrajit Dey, Swarup Kumar Ghosh, Rajib Saha. Effects of cooling rate and strain rate on phase transformation, microstructure and mechanical behaviour of thermomechanically processed pearlitic steel. elsevier : Journal of materials research and technology,9;8(3):2685–2698, 2019 www.jmrt.com.br

[6] H. Mirzadeh and A. Najafizadeh. Hot Deformation and Dynamic Recrystallization of 17–4 PH Stainless Steel. ISIJ Int., 2013, 53, p 680–689.

[7] H. Mirzadeh. Constitutive Modeling and Prediction of Hot Deformation Flow Stress under Dynamic Recrystallization Conditions. Mech.Mater., 2015, 85, p 66–79.

[8] Chadha K, et al. Influence of strain rate on dynamic transformation of austenite in as-cast medium-carbon low-alloy steel. Materialia, 2018, p. 1:155e67.

[9] T. Sakai, A. Belyakov, R. Kaibyshev, H. Miura, and J.J. Jonas. Dynamic and Post-dynamic Recrystallization Under Hot, Cold and Severe Plastic Deformation Conditions. Prog. Mater. Sci., 2014, 60, p 130–207.

[10] Poliak EI and Jonas JJ. A one-parameter approach to determining the critical conditions for the initiation of dynamic recrystallization. Acta Mater, 1996; 44, p. 127e36. https://doi.org/ 10.1016/1359-6454(95)00146-7

[11] D. Berdjane and Al. Deformation behavior of a Nb-Ti-V microalloyed steel to achieve the HSLA X80 grade by simulation. Revue de Métallurgie 109, 465–475 (2012), EDP Sciences, 2013. www.revue-metallurgie.org (Metallurgical Research & Technology). doi: 10.1051/metal/2012042.
[12] Chadha K, et al, Influence of strain rate on dynamic transformation of austenite in an as-cast medium-carbon low-alloy steel, Materialia, 2018, p. 1:155e67.