On the relationship microstructure/properties on yield strength of a Fe-C-Mn steel

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Abstract. Fe-C-Mn steel was produced by the electric arc furnace, vacuum degassing, ladle treatment and continuous casting route followed by a hot rolling schedule, water quench and tempered. Then, after evaluation of the microstructure and mechanical properties of the steel, a relationship between microstructure and mechanical properties was presented focusing on the impact of the different strengthening mechanisms on the resulting yield strength.

1. Introduction

To improve the stringent requirements of steels for several industries such as oil and automotive, technologies for steelmaking and plate rolling have been improved to make economically feasible the production of steels for critical applications. Steelmaking technologies have allowed the production of clean steels by the electric arc furnace, vacuum degassing, ladle treatment and continuous casting route [1]. Steel production has involved the control of constituents, reduction of sulfur and phosphorous contents, the control of inclusion morphology by Ca-treatment and soft reduction during the continuous casting process to minimize the central segregation [2]. Concerning rolling technologies, thermomechanical controlled rolling of steel slabs followed by suitable heat treatment of plates has provided production of plates with a good combination of strength, toughness and weldability [3]. Also, improvements in properties have been associated with the control of the different strengthening mechanisms, including solid solution strengthening, grain refinement, strengthening by controlling transformations, precipitation hardening and strain aging [4,5]. In this sense, the present work reports result in terms of the contribution of the different strengthening mechanisms to the resulting yield strength of an HSLA steel.

2. Experimental procedure

The steelmaking of steel was produced in a Mexican steel industry an involved melting of 100% sponge iron into an electric arc furnace followed by ladle treatment, including vacuum degassing, secondary refinement, and then continuous cast. The resulting chemical composition of the steel slab is shown in table 1. Hot rolling was performed on a Fenn reversible mill (0.127 m roll, 25 tons of load and 0.166 m/s of rolling speed and an average strain rate of 2.8 s⁻¹), from 1150 °C to 870 °C in 10 passes, reaching 63 % of total deformation as shown in figure 1, and then, the resulting plate was water quench from
940°C to room temperature and tempered at 520 °C and air-cooled. The Microstructure was observed under an electron microscope Stereoscan 440 and a transmission electron microscope Jeol 2100, both microscopes were equipped with EDAX microanalysis. The flat tensile (ASTM E-8) test was conducted on an Instron 1125 (10 tons) test machine at a strain rate of 5x10^{-3} s^{-1}. An optical microscope coupled with an image analysis was used for the quantitative determination of grain size, which was carried out by measuring 10 fields per sample at 100X. This accounted for a total analyzed area of about 6 mm² per specimen.

**Table 1.** Chemical composition of the steel under study (in wt. %).

|   | C   | Mn | Si  | P   | S   | Cr  | Nb  | Ti  | N   |
|---|-----|----|-----|-----|-----|-----|-----|-----|-----|
|   | 0.065 | 1.10 | 0.21 | 0.010 | 0.0028 | 0.35 | 0.06 | 0.026 | 0.0038 |

**Figure 1.** Heating, soaking, rolling of slabs and cooling of plates.

**3. Results and discussion**

**Table 2.** Mechanical properties of steel under study after being thermo-mechanically treated, water quenched and aged.

|                     | 0.2 % Yield Strength | Ultimate Tensile Strength | Elongation |
|---------------------|----------------------|---------------------------|------------|
|                      | (MPa)                | (psi)                     | (%)        |
| 585.6               | 84,934.1             | 670.0                     | 97,175.3   | 30 |

**Figure 2.** Microstructure of steel after quenching and tempering of plate.
Figure 2 shows the resulting microstructure of the steel under study in the quenching and tempering condition which corresponds to tempered martensite with an average grain size of 10 µm. The resulting room temperature mechanical properties are shown in table 2.

As has been mentioned [6], a state of the art HSLA steels need a minimum yield strength of 550 MPa (79,770.80 psi) where strengthening mechanisms for micro-alloyed steels involve grain size, solid solution hardening, dislocation hardening, precipitation strengthening and transformation hardening [4, 7] according to equation (1) [8]:

\[
\sigma_{ys} = \sigma_{\text{base}} + \sigma_{\text{dis}} + \sigma_{\text{ppt}} + \sigma_{\text{trans}}
\]  

where \(\sigma_{ys}\) is the yield strength of steel. And the terms \(\sigma_{\text{base}}, \sigma_{\text{dis}}, \sigma_{\text{ppt}}\) and \(\sigma_{\text{trans}}\) are strengthening mechanisms due to: 1) \(\sigma_{\text{base}}\) = solid solution strengthening by interstitial and substitutional elements plus refinement of grain size, 2) \(\sigma_{\text{dis}}\) = work hardening, 3) \(\sigma_{\text{ppt}}\) = dispersion strengthening, including lamellar and random dispersed structure; 4) \(\sigma_{\text{trans}}\) = strengthening by phase transformation.

The base yield strength (\(\sigma_{\text{base}}\)) is given in equation (2):

\[
\sigma_{\text{base}} = \sigma_0 + \left[ 15.4 - 30C + 6.094 / (0.8 + Mn) \right] \alpha_{\text{ferrite}}^{1/2}
\]

where \(\sigma_0 = 63 + 23Mn + 53Si + 700P\). The base yield strength was calculated for the steel sample taking into account a final grain size of 10 µm (0.010 mm), measured in the rolling direction and the corresponding C, Mn, Si and P element content (in wt. %). The resulting \(\sigma_{\text{base}}\) contributed to 272.9 MPa (39,580.7 psi) to the \(\sigma_{ys}\) as shown in table 3.

| C   | Mn | Si  | P      | \(\sigma_0\) (MPa) | \(\sigma_{\text{base}}\) (MPa) |
|-----|----|-----|--------|-------------------|-----------------------------|
| 0.065| 1.10| 0.21| 0.010  | 106.4            | 272.9                      |

Regarding work hardening contribution, \(\sigma_{\text{dis}}\), it was calculated using equation (3) [9]:

\[
\sigma_{\text{dis}} = \alpha M G b \rho^{1/2}
\]

where \(\alpha (=0.3 \text{ for iron})\) is a correction factor specific to the material, \(M (=3 \text{ for bcc crystals})\) is the average Taylor factor for polycrystals, \(b (=0.248 \text{ nm})\) is the magnitude of the Burger’s vector, \(G (=81.6 \text{ GPa for iron [10]})\) is the shear modulus and \(\rho\) the dislocation density. This last term presented an average value of \(\rho = 9.0X10^{13} \text{ dislocations/m}^2\), where the number of dislocations was measured in thin regions of the transmission electron microscopic foils of the quenched and tempered sample as shown in figure 3. It was obtained a dislocation hardening contribution of 172.7 MPa (25,048.0 psi) as shown in table 4.
Precipitation hardening contribution was calculated according to equation (4) [9]:

$$\sigma_{\text{ppt}} = (0.538 \ G \ b \ f^{1/2} / X) \ln(X/2b)$$

(4)

where \(f\) is the volume fraction of \(\text{Cr}_2\text{C}_6\) precipitates and equal to \(0.51\times10^{-3}\) in the as-quenched and tempered condition (figure 4) where an average diameter of precipitates \((X=10\ \text{nm})\), giving a precipitation hardening contribution of \(114.1\ \text{MPa (16,548.8 psi)}\) as shown in table 5.

| \(\sigma_{\text{ppt}}\) (from equation 4) | (MPa) | (psi) |
|------------------------------------------|-------|-------|
|                                          | 114.1 | 16,548.8 |

Figure 4. Precipitates of \(\text{Cr}_2\text{C}_6\) in steel after quenching and tempering

To estimate the contribution of tempered martensite hardening, it was derived according to the equation (1) because there is not a direct equation for this mechanism. Feeding the values for the grain size strengthening plus solid solution hardening, dislocation hardening and precipitation hardening
mechanisms into the equation (4), it was obtained a value of 26.2 MPa (3,799.9 psi) for the tempered martensite transformation hardening contribution. Therefore, it is presented that the estimation of the contribution of the main strengthening mechanisms for steel is not simple. However, the relationship between the microstructure and the yield strength can be expressed by equation (1). From the analysis, it was noticed that the predominant strengthening mechanisms are a solid solution by interstitial and substitutional elements together with grain refinement. \( \sigma_{\text{base}} \), quantifying a contribution of 46.6%, while work hardening strengthening \( \sigma_{\text{dis}} \) contributed to 29.4%, to the experimental yield strength value. The remaining 24% is attributed to precipitation and phase transformation.

As was presented, the yield strength of the steel can be expressed as the sum of two terms: 1) The first group which includes strengthening of solid solution elements and grain size and 2) the second group considers only work hardening strengthening, in agreement with the work of Carretero et. al. [11].

4. Conclusions
1. Thermomechanical processing and heat treatment applied to the steel under study responded positively allowing to reach target properties equivalent to a steel HSLA X-80 5L grade.
2. Evaluation of the impact of the different strengthening mechanisms on the yield strength property indicates a contribution of 46.6% for interstitials and substitutional elements plus grain size, while work hardening contribution corresponded to 29.4%. Precipitation and phase transformation mechanisms contribute together with 24%.
3. Results from experiments and modeling show a good correlation. The model indicates that solid solution, grain size and work hardening have the most impact on the strength given a technological consequence to control microstructural features via thermomechanical controlled processing of slabs and cooling of plates.

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References
[1] Takeuchi I, Fujino J, Yamamoto A and Okaguchi S 2003 Pipes and Pipelines Int. 48 33.
[2] Mendoza R, Huante J, Lugo G, Alvarez-Fregozo O and Juarez-Islas J A 1999 J. Mater. Eng. Perform. 8 549.
[3] De Meester B 1997 ISIJ Int. 37 537.
[4] Fallahi A 2002 J. Mater. Sci. 32 451.
[5] Fonstein N 2015 Advanced High Strength Steel (Switzerland: Springer International Publishing) p 1.
[6] Charleux M, Poole W J, Militzer M and Descamps A 2001 Metall. Mater. Trans. A 32 1635.
[7] Brown L M and Ham R H 1971 Int. Conf. on Strengthening Methods in Crystals ed A Kelly and R B Nicholson (New York: John Wiley & Sons) p 9.
[8] Gosh S K, Bandyopadhyay P S, Kundu S and Chatterjee S 2011 Mat. Sci. Eng. A 528 7887.
[9] Misra R D K, Nathania H, Hartmanne J E, Siciliano F 2005 Mater. Sci. Eng. A 394 339.
[10] Garcia C I, DeArdo A J, Raykin E, Defilippi J D 1995 Proc. Int. Symp. on High-Performance Steels for Structural Applications (Cleveland, OH: ASM) p 155.
[11] Carretero V, Bliznuk V, Sanchez N, Thibaux P, Kestens L A I, Petrov R H 2014 Mater. Sci. Eng. A 604 46.