International Journal of Technology (2016) 3: 500-508
ISSN 2086-9614 

# KINETICS OF STRAIN AGING BEHAVIOR OF API 5L X65 AND API 5L B STEEL TYPES ON LONG-TERM OPERATIONS

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(Received: December 2015 / Revised: January 2016 / Accepted: February 2016)

## ABSTRACT

The kinetics of strain aging behavior of API 5L X65 and API 5L B steel types on long-term operations were studied. Pre-strain was applied to the two steel types and the process was continued with the aging process at various temperatures and over various time periods. Mechanical properties data were used to determine activation energy levels. The results showed that API 5L B steel has a lower activation energy level than API 5L X65 steel through the identification of yield strength value, which is 13.7 kJ compared to 24.87 kJ, which means that API 5L B steel is more susceptible to strain aging than API 5L X65 steel. Predictions of long-term mechanical properties which are verified through tensile testing showed that the appropriate parameters to observe and predict the strain-aging behavior are implemented by evaluating the changes in yield strength, which gives the minimum value for the average margin of error for API 5L X65 steel and API 5L B steel, i.e. 0.3% and 0.45%, respectively. On the other hand, prediction value parameters, such as elongation, toughness and the Vickers hardness have an average margin of error range between 2.6 to 5.06%.

*Keywords:* Kinetics; Long-term operation; Pipeline steels; Pre-strain; Strain-aging

## 1. INTRODUCTION

Strain aging in carbon steels is a strengthening phenomenon occurring when steel is plastically pre-strained and then aged for a certain period of time. Interactions between dislocations and interstitial atoms increase the resistance to the steel's deformation (Richards et al., 2011). Strain aging degrades the mechanical properties of the steel pipe, mainly resulting in a decrease in ductility and toughness of the steel material (Ğunduz, 2008). A decrease in ductility and toughness of the pipe material is undesirable because it can reduce the strain capacity and increase the susceptibility to failure. Aging at relatively low temperature can occur at long intervals, such as monthly or yearly, so strain aging can occur in a long-term operating pipeline (Baron, 2012; Kotrechko et al., 2004). The role of the interstitial atoms to strain aging at relatively low temperature needs to be studied, considering the conditions of manufacturing process, construction, and operation of the pipeline that occur when the steel is exposed to pre-strain and aging temperatures. Elements such as carbon and nitrogen interstitial atoms have a very important influence on the behavior of the strain aging, due to their high mobility at relatively low temperature (~200°C) (Richards et al., 2011). In the present study, kinetics of

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Permalink/DOI: http://dx.doi.org/10.14716/ijtech.v7i3.2812

strain aging behavior will be studied for two different types of HSLA steel, i.e. API 5L X65 and API 5L B steel at temperatures below 150°C.

## 2. EXPERIMENTAL PROCEDURE

Steel types used in this study are in accordance with the specifications of API 5L X65 and API 5L B steel. Their respective chemical composition is shown in Table 1. The tensile tests were carried out parallel to the rolling direction of the steel plate. Tensile test specimens for both steel types have a gage length of 50 mm and a width of 12.5 mm. The thicknesses of the specimens were 8.8 mm for X65 grade and 8.2 mm for B grade. Before aging, tensile test specimens were plastically pre-strained at 5%. Aging was then carried out in an oven furnace at temperatures of 90, 115 and 140°C, respectively with aging times of 1, 6, 12, 24, 48, 72, 96, 120, 144 and 168 hours. After aging, tensile and hardness tests were performed on the specimens in order to obtain the changes in mechanical properties, such as yield strength, elongation, hardness and toughness. Toughness was calculated based on the area under the stress-strain curve by using numerical methods. The test results were used to determine the activation energy and the aging time equivalent which were then used to study the kinetics of the strain aging behavior of the steel types. Aging at 40°C for 168, 336 and 504 hours (or 7, 14 and 21 days) was also carried out to verify the results of the kinetic studies.

Table 1 Chemical composition of the steels (%wt)

| Steel | C | Si | Mn | P | S | N | Cu | Ni | Cr | V | Ti | Fe |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| API 5L X65 | 0.074 | 0.254 | 1.045 | 0.0074 | 0.0015 | 0.0045 | 0.164 | 0.217 | 0.145 | 0.046 | 0.003 | Bal. |
| API 5L B | 0.168 | 0.168 | 0.681 | 0.103 | 0.031 | 0.049 | 0.026 | 0.014 | 0.017 | 0.004 | 0.002 | Bal. |

## 3. RESULTS AND DISCUSSION

Figures 1-4 show the relationship between aging and the resultant properties change, i.e. yield strength, hardness, elongation and toughness for API 5L X65 and API 5L B steel types, respectively. It is shown that the higher the temperature and aging time, the higher the increase in properties change. In the figures, it is also seen that API 5L B steel shows a significant change in properties more than those of API 5L X65 steel.

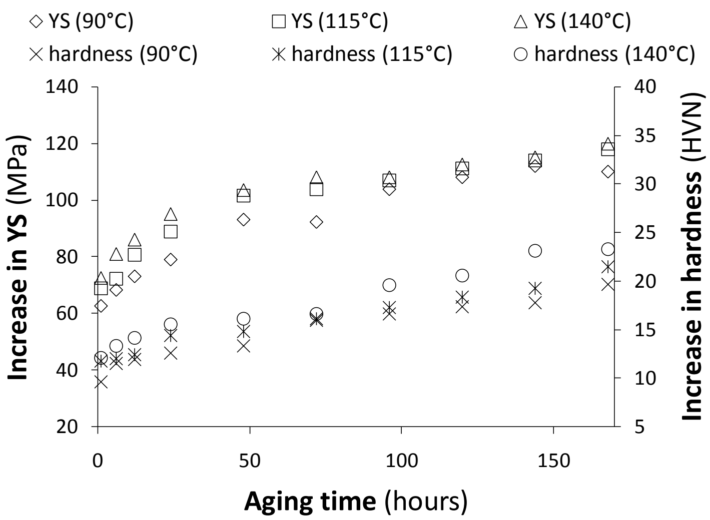


Figure 1 Comparative changes in yield strength and hardness after pre-strain and aging for API 5L X65 steel

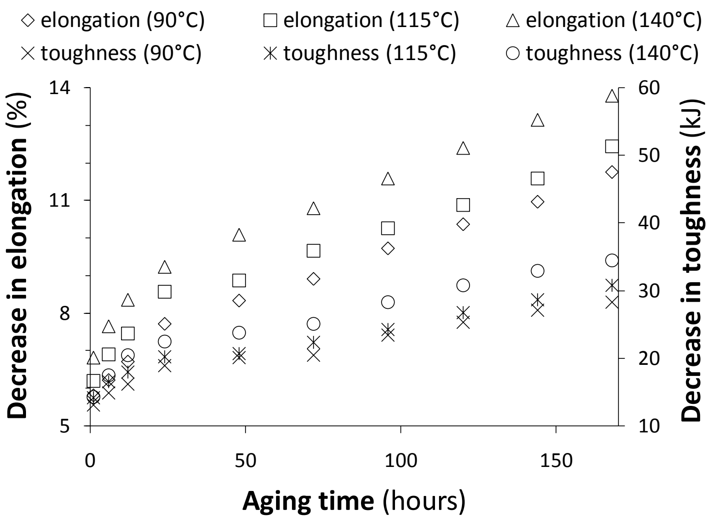


Figure 2 Changes in elongation and toughness after pre-strain and aging for API 5L X65 steel

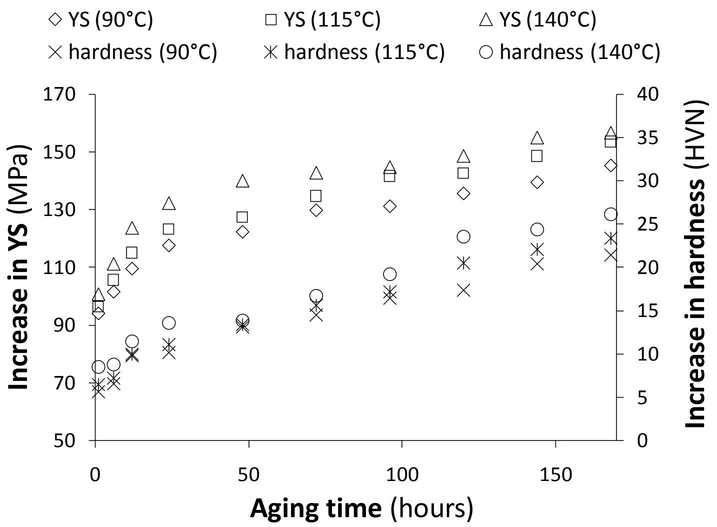


Figure 3 Changes in yield strength and hardness after pre-strain and aging for API 5L B steel

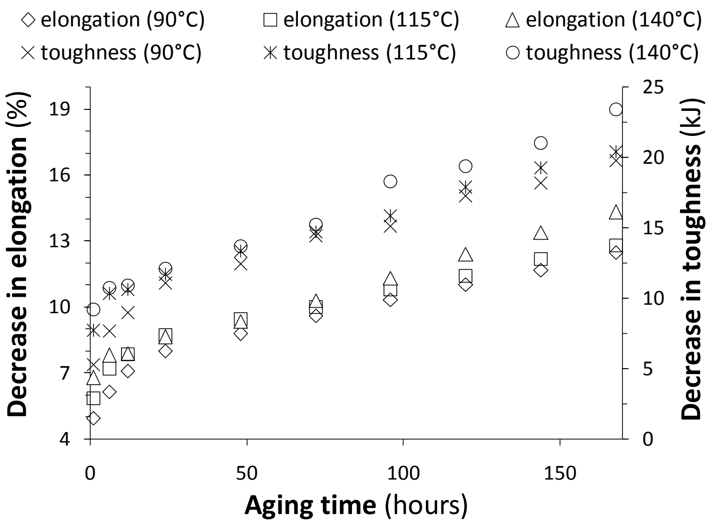


Figure 4 Changes in elongation and toughness after pre-strain and aging for API 5L B steel

The kinetics of the aging can be analyzed using Equation 1 as shown below (Palosaari & Manninen, 2012):

$$W = \frac{\Delta Y}{\Delta Y_{max}} = 1 - \exp[-(kt)^n] \quad (1)$$

where $W$ is the aged volume fraction, $\Delta Y$ is the increase in the yield strength after pre-strain and aging, $\Delta Y_{max}$ is the maximum stress increment value, $t$ is the aging time at constant temperature, $k$ is the rate constant and $n$ is the time exponent. $\Delta Y$ and $\Delta Y_{max}$ can be modified with other properties such as elongation, hardness and toughness. Using Equation 1 and the data obtained from the experiments, ln (ln[1/(1-$W$)]) against ln $t$ plots can be obtained for the tested steel samples as shown in Figures 5 and 6. The values of $n$ and ln $k$ are shown in Table 2.

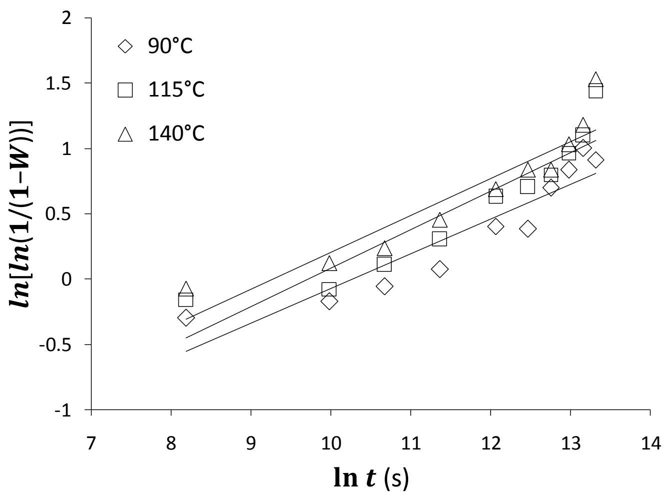


Figure 5 ln (ln[1/(1-$W$)]) versus ln $t$ plots for API 5L X65 steel (for YS change)

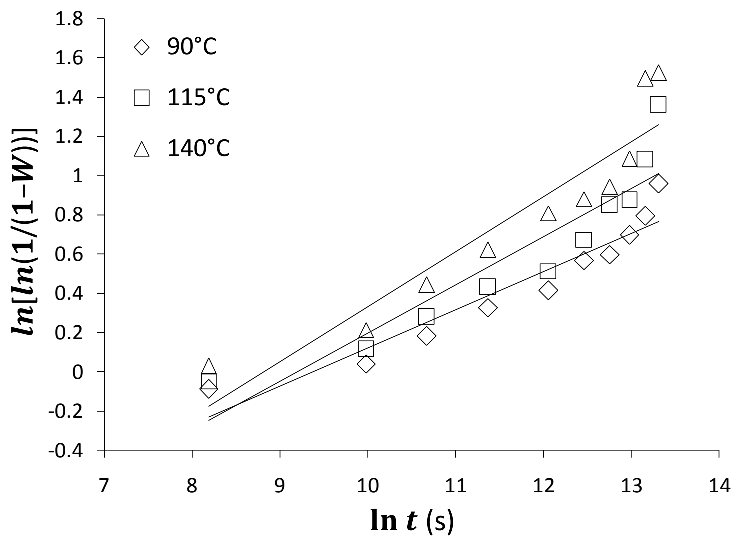


Figure 6 ln (ln[1/(1-$W$)]) versus ln $t$ plots for API 5L B steel (for YS change)

Table 2 Values of the time exponent *n* and ln *k* for the tested steels (for YS change)

| *T* (°C) | API 5L X65 steel | | | | API 5L B steel | | | |
|---|---|---|---|---|---|---|---|---|
| | 1/*T* ($K^{-1}$) | *n* | *n* ln *k* | ln *k* | 1/*T* ($K^{-1}$) | *n* | *n* ln *k* | ln *k* |
| 90 | 0.00275 | 0.2671 | -2.7451 | -10.28 | 0.00275 | 0.1941 | -1.8191 | -9.37 |
| 115 | 0.00258 | 0.2951 | -2.8697 | -9.72 | 0.00258 | 0.2464 | -2.2667 | -9.20 |
| 140 | 0.00242 | 0.2834 | -2.6302 | -9.28 | 0.00242 | 0.2803 | -2.4715 | -8.82 |

Activation energy of the steels can be obtained using the Arrhenius equation as follows in Equation 2, (Palosaari & Manninen, 2012):

$$k = k_0 \exp\left(\frac{-Q}{RT}\right) \tag{2}$$

where $k_0$ is pre-exponential factor, $Q$ is activation energy (J/mol), R is the gas constant (8314 J/mol.K) and $T$ is the aging temperature (K).

The activation energy can be obtained from the slope of the Arrhenius plots as shown in Figure 7. The activation energy for the increments of yield strength, elongation, hardness and toughness are summarized in Figure 8. In the figure it is shown that the activation energy of API 5L B steel is lower than API 5L X65 steel. In addition, it appears that the use of the yield strength parameter results in lower activation energy values than the use of other properties. Activation energy values obtained in this study were lower than previous researchers' values (Palosaari & Manninen, 2012; Kemp et al., 1990; Hämmerle et al., 2004). Low activation energy values in API 5L B steel indicate that the steel is more susceptible to strain aging compared to API 5L X65 steel. This is due to the content of carbon and nitrogen interstitial atoms in API 5L B steel that is higher than in the API 5L X65 B steel.

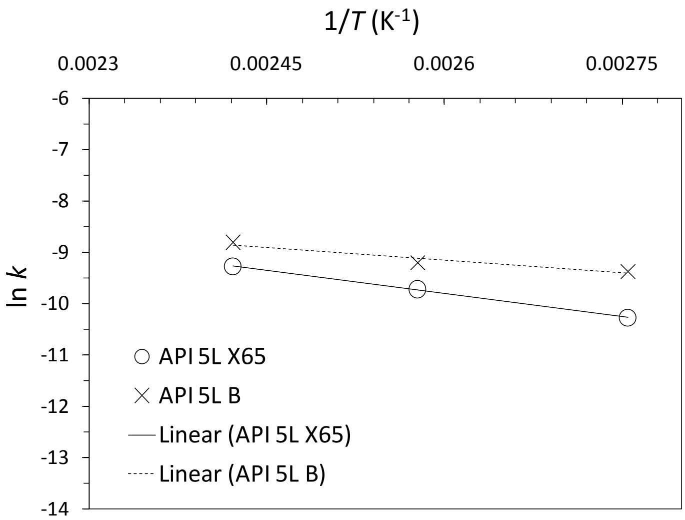


Figure 7 ln *k* versus 1/*T* plots for API 5L X65 and API 5L B steels (for YS change)

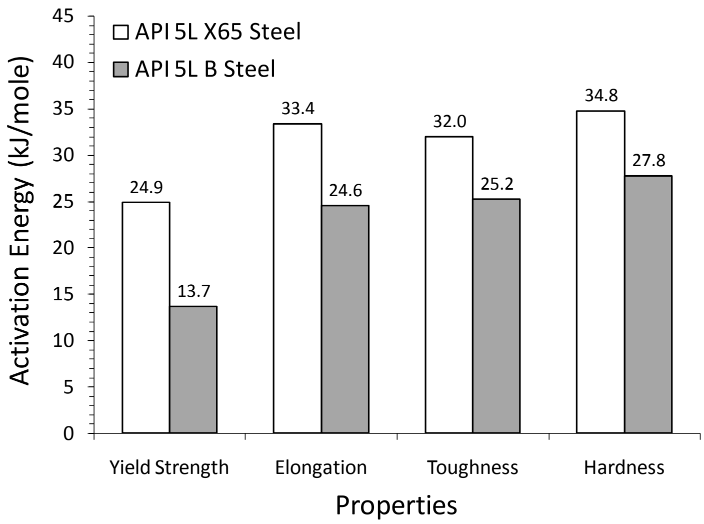


Figure 8 Activation energy for the tested steels

Temperature, aging time and activation energy data obtained and shown in Figure 8 are used to predict the properties changes of the pipeline steel due to strain aging in long-term use. The prediction is performed using the substitution of Equations 1 and 2 to obtain the aging time equivalent equation as follows in Equation 3:

$$\ln\left(\frac{t_1}{t_2}\right) = \frac{Q}{R}\left(\frac{1}{T_1} - \frac{1}{T_2}\right) \tag{3}$$

where $t_1$ is the pipeline operation time, $t_2$ is the aging time, $T_1$ is the pipeline operation temperature and $T_2$ is the aging temperature.

Figures 9-12 respectively show the relationship between the aging time and the prediction of yield strength, hardness, elongation and toughness for API 5L X65 and API 5L B steel types for pipelines operating at temperatures of 40°C. The graphs in fact can be extended on the horizontal axis to show a condition of long-term pipeline operation.

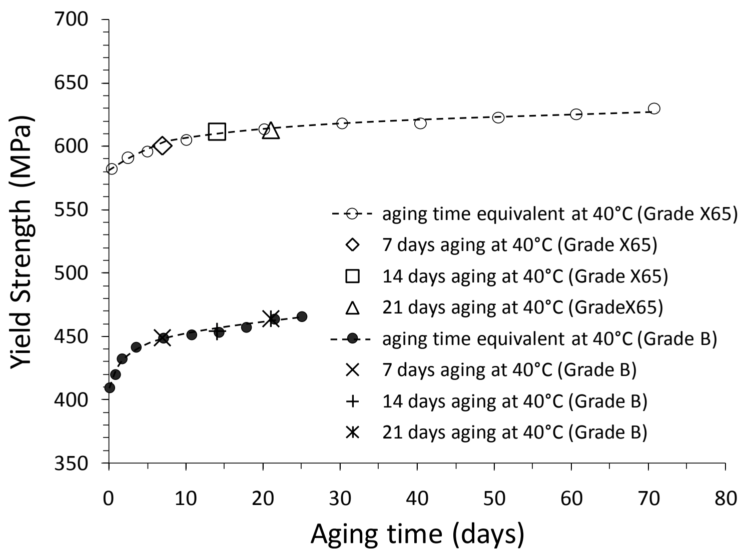


Figure 9 Relationship between the aging time and the yield strength prediction for the steels at aging temperatures of 40°C

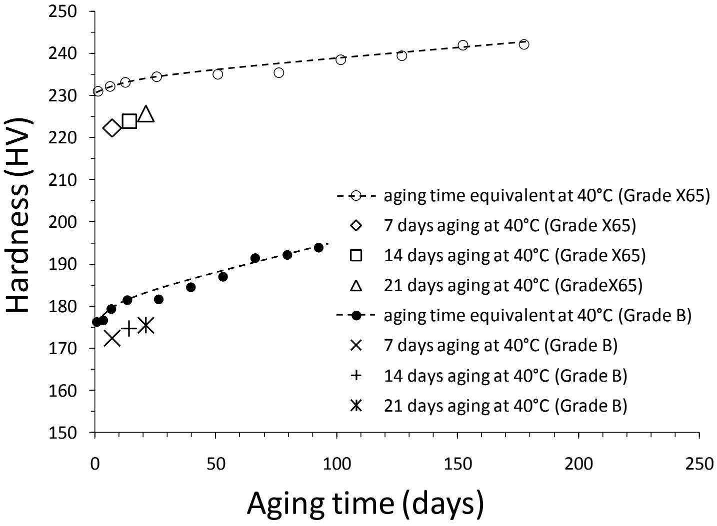


Figure 10 Relationship between the aging time and the hardness prediction for the steels at aging temperatures of 40°C

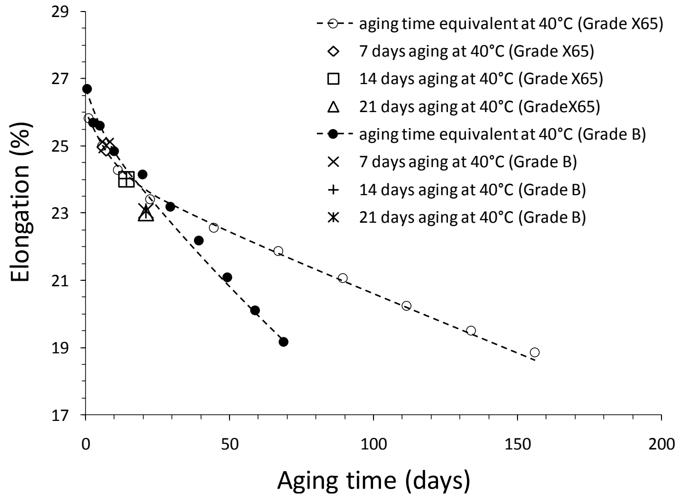


Figure 11 Relationship between the aging time and the elongation prediction for the steels at aging temperatures of 40°C

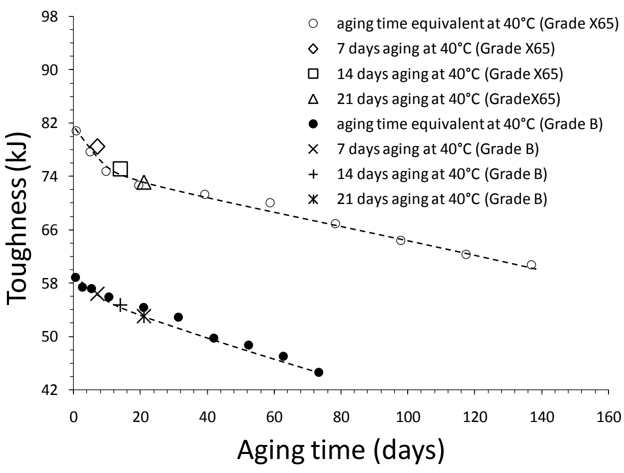


Figure 12 Relationship between the aging time and the toughness prediction for the steels at aging temperatures of 40°C

In Figures 9-12 above, it is shown that in general the prediction of mechanical properties at aging temperatures of 40°C gives appropriate conformance, except for the hardness prediction result. The accuracy of the prediction for the various mechanical properties at an aging temperature of 40°C is summarized in Figure 13. From the figure, it is seen that the prediction of mechanical properties using the yield strength parameter gives the best results, followed by the use of elongation, toughness and hardness parameters, respectively. It shows that the yield strength parameter is the most appropriate parameter to be used to study the kinetics of strain aging rather than other parameters.

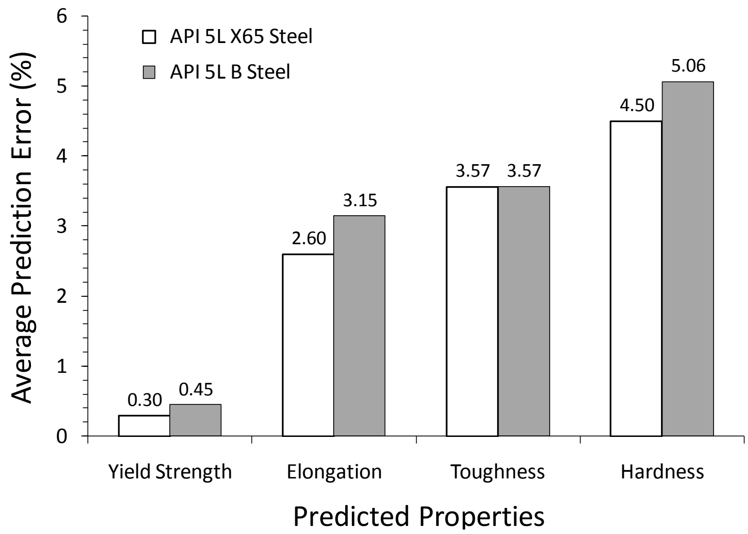


Figure 13 Accuracy of the mechanical properties prediction for the tested steels at an aging temperature of 40°C

## 4. CONCLUSION

In this work, API 5L B steel has a strain aging activation energy lower than API 5L X65 steel due to its higher carbon and nitrogen content, therefore this condition makes it more susceptible to strain aging. The yield strength parameter is the best parameter to be used in studying the kinetics of strain aging.

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