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Review Article

Investigation of Mechanical Properties of AISI 304 Stainless Steel Depending on Cold Deformation Rate, Phase Quantity and Heat Treatment Processes

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Abstract

Stainless steels have a wide range of uses in the industry due to their high corrosion resistance and high formability capabilities. Stainless steel flat materials are produced with hot rolling process after casting, annealing and cold rolling. After these processes, stainless steel prepared for service lines by annealing and surface passivation. In this study, after the tensile tests of the materials of different thicknesses after rolling the AISI 304 stainless steels in different deformation ratios before and after solution annealing, true yield and tensile strengths were calculated based on engineering tensile and true tensile strengths. Using of these calculated values, the strength constant and deformation hardening base values of the materials subjected to cold working in the mill were theoretically tried to be calculated, and the relationship between these values and the hardening ability formed by the alloy elements that make up the material were investigated.

Introduction

Cold rolling is the cold forming process of the materials that intervenes with the effect of the pressing force of at least two rolls. Cold rolling is made in order to bring different mechanical properties to the material and reduce it to the final usage thickness after continuous casting, hot rolling and annealing-pickling process in the production of stainless steel sheet. Sendzimir rolling mill (Figure 1) consist of twenty-rolls, ten rolls above and ten rolls below. The low diameter of the work rolls reduces the contact area on the material surface, it provides easier to rolling of alloy such as stainless steel.

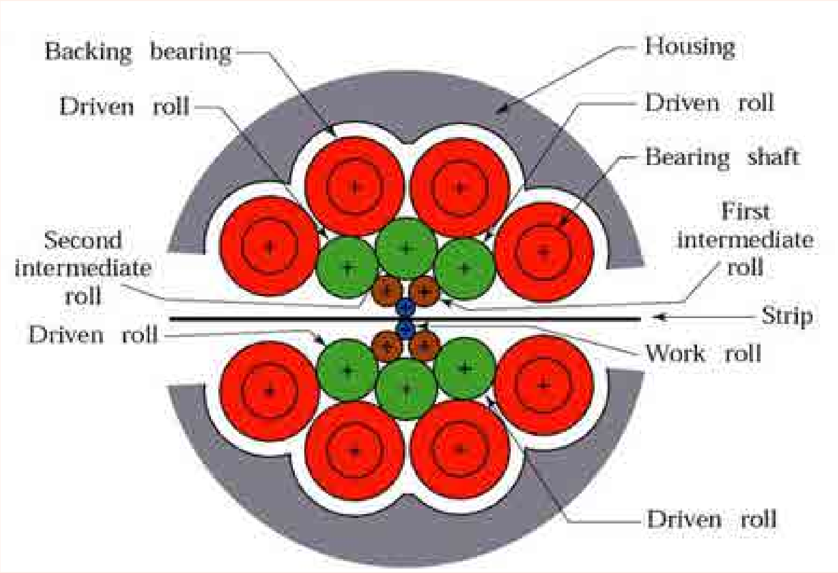

Figure 1: Representation of Sendzimir Rolling Mills.

During cold forming of metallic materials, grain growth generally occurs towards the rolling direction. This situation causes a certain increase in strength. In some materials, due to the high pressure force during cold rolling, grain elongation, grain breakage and phase transformation are observed together. This is a common situation especially in austenitic stainless steels [1,2]. In AISI 304 austenitic stainless steels, this phase conversion takes the form of austenite to Alpha-martensite [2]. One of the factors determining the conversion rate and conversion energy after deformation is the chromium and nickel equivalents of the alloy. High nickel equivalence, in particular, reduces the free energy of martensitic transformation [3]. It also affects the deformation rate, mechanical properties and martensitic conversion rates of the material. Chromium and nickel equivalence ratios are calculated with the first and second equations as shown [4].

$C_{reş}$ = %Cr + %Mo + 1,5.%Si + 0,5.% Nb (1)
$Ni_{eş}$ = %Ni + 30.% C + 30.% N + 0,5.% Mn + 0,4.% Cu (2)

Solution annealing is applied to AISI 304 stainless steels after the cold rolling process. The purpose of the annealing process is converting the martensite to austenite phase by removing the material to austenite conversion temperature, to eliminate internal stresses, to dissolve metal carbides deposited to the grain boundary, to disperse the dislocations formed, to bring the material to its final condition.

Experimental

3 mm thick stainless steel sheets, all of which are hot rolling products, are used to obtain the material constants. These sheets are rolled to different thicknesses with using different deformation rates. Samples were taken from the rolled to the final thickness materials before the annealing and pickling process was applied and tensile and hardness tests were carried out. After the annealing and pickling process of the same materials, samples were taken and tensile and hardness tests were carried out in the same way. As a result of the findings, material constants were theoretically calculated and modeled. In (Figure 2), the experimental process is schematized.

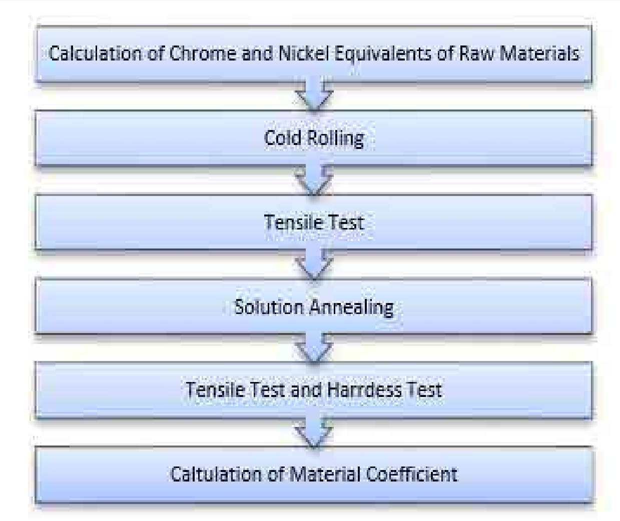

Figure 2: Experimental process.

Process studies were carried out with Trinox Metal Corlu factory production machines. Rolling operation was done on Sendzimir machine, annealing operation was done on Atlas machine. Tensile test and hardness results were measured in the Trinox Metal quality control laboratory. Hardness tests were carried out with Emcotest DuraScan 10 brand device. The Hardness Test Machine is as shown in Figure 3. Tensile tests were also carried out with MTS brand Alliance RT/100 brand device. The Tensile Test Machine is as shown in Figure 4.

Figure 3: Emcotest DuraScan 10 Hardness Test Machine.

Figure 4: MTS Alliance RT/100 Tensile Test Machine.

Calculation of material coefficient

The formulations used in calculating the material constants are as follows;

$$\sigma = \frac{F}{A} \quad (3)$$

$$e = \frac{\left(L - L_o\right)}{L_o} Vi = Vo \quad (4)$$

$$Vi = Ai \times Li = Ao \times Lo \quad (5)$$

$$e = \frac{\Delta L}{L_o} = \frac{Li - L_o}{L_o} = \frac{Li}{L_o} - 1 \quad (6)$$

$$\frac{Li}{L_o} = 1 + e \quad (7)$$

$$\varepsilon = \int_{\varepsilon_0}^{\varepsilon_i} \frac{dL}{L} = \ln \frac{Li}{L_o} \quad (8)$$

$$\frac{Li}{L_o} = 1 + e \quad (9)$$

$$\varepsilon = \ln \frac{Li}{L_o} = \ln\left(1 + e\right) \quad (10)$$

$$\sigma t = \sigma_e \left(1 + e\right) \quad (11)$$

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$$\sigma_{true\ yield} = \sigma_{engineering\ yield}(1+e) \tag{12}$$

$$\sigma_{true\ tensile} = \sigma_{engineering\ yield}(1+e) \tag{13}$$

$$\sigma_{true\ tensile} = Kx\varepsilon^{n} \tag{14}$$

$$n = \frac{\log\left(\frac{\sigma_{true\,tensile}}{\sigma_{true\ yield}}\right)}{\log(500x\varepsilon)} \tag{15}$$

$$K = 500^{n}\sigma_{true\ yield} \tag{16}$$

$$SC = \left(\frac{Ni_{es}}{Cr_{es}}\right)\times 100 \tag{17}$$

$$DR = \frac{(t_0 - t_i)}{'}\% \tag{18}$$

$$EDR = SC \times DR \tag{19}$$

Terms and abbreviations in equations are at follows; σ: Engineering Tensile Stress, σT: True Tensile Stress, σe: Engineering Tensile Stress A: Area, e: Engineering Strain, ε: True Strain, Lo: Length (t=0), Li: Length (t=i), n: Strain Hardening Coefficient, K: Material Factor

Experimental Results

As a result of the experiments, the yield strength, tensile strength and elongation amounts of the materials were reached. Material constants, true elongation, true yield and true tensile strengths were calculated using experimental test results. The data obtained as a result of the calculation was analyzed and the relations between them were examined.

Experimental results before annealing process

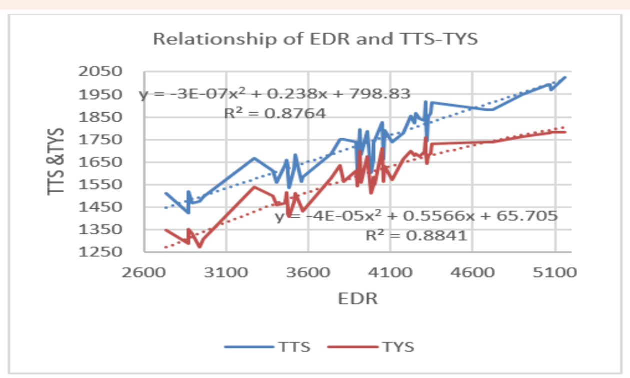

Figure 5: The relationship between Effective Deformation Ratio (EDR) with True Tensile Strength (TTS) and True Yield Strength (TYS).

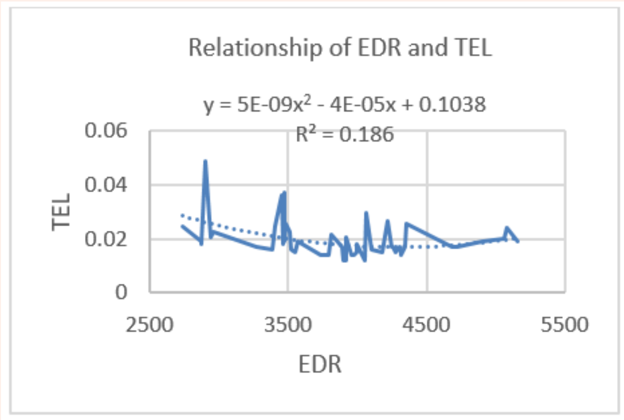

Figure 6: The relationship between Effective Deformation Ratio (EDR) with True Elongation Length (TEL).

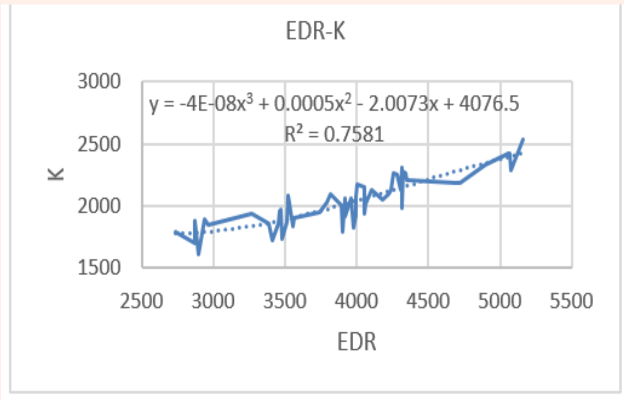

Figure 7: The relationship between Effective Deformation Ratio (EDR) with Strength Coefficient (K).

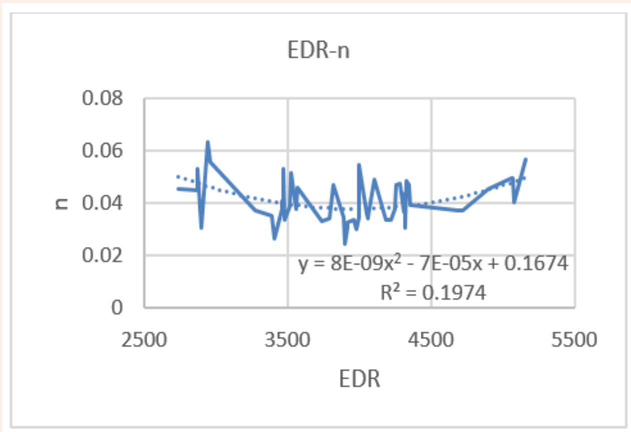

Figure 8: The relationship between Effective Deformation Ratio (EDR) with Strain-Hardening Exponent (n).

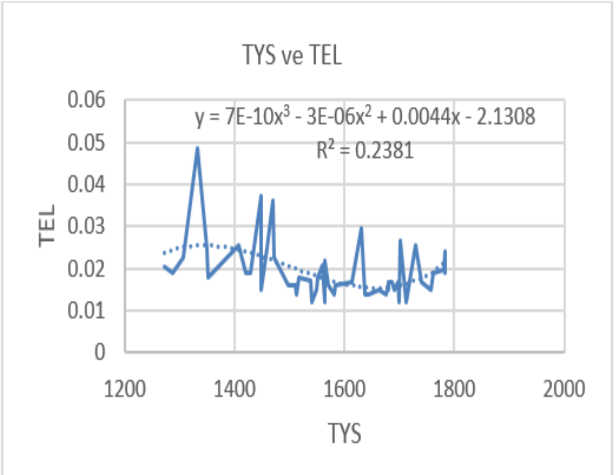

Figure 9: The relationship between True Yield Strength (TYS) with True Elongation Length (TEL).

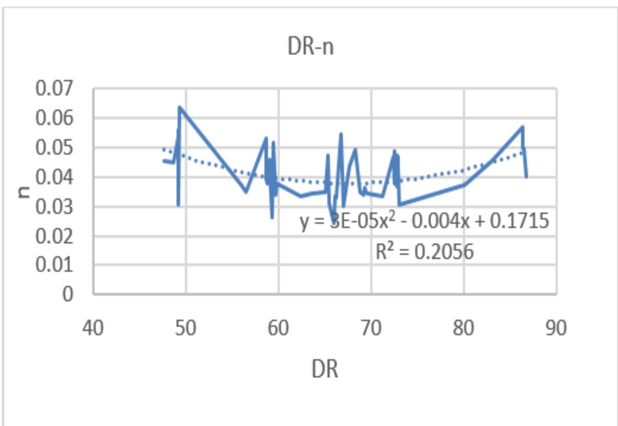

Figure 10: The relationship between Deformation Ratio (DR) with Strain-Hardening Exponent (n).

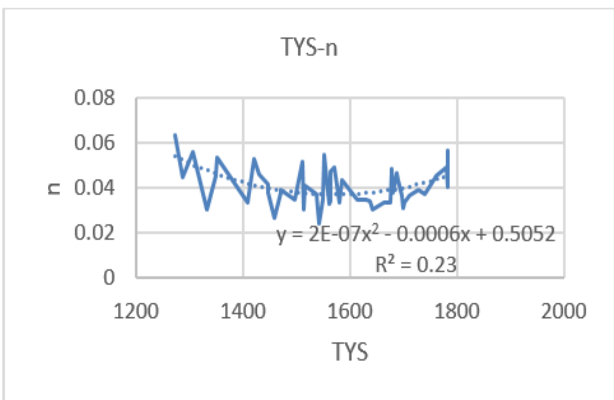

Figure 11: The relationship between True Yield Strength (TYS) with Strain-Hardening Exponent (n).

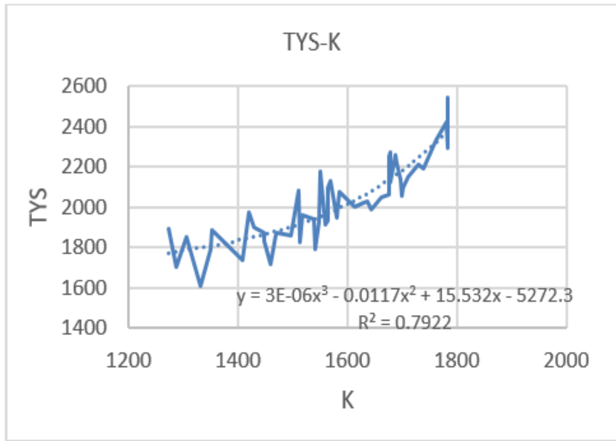

Figure 12: The relationship between True Yield Strength (TYS) and Strength Coefficient (K).

Experimental results after annealing process

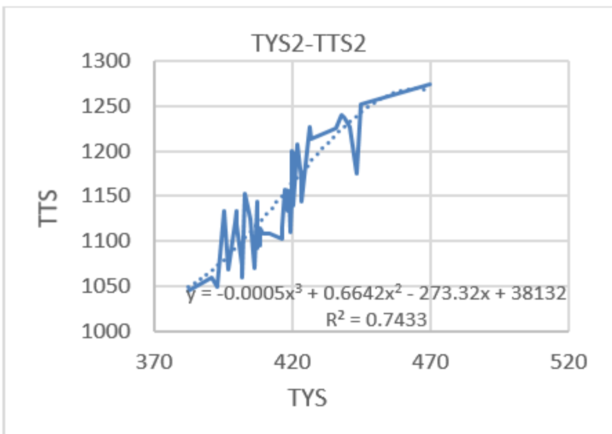

Figure 13: The relationship between True Yield Strength (TYS) with True Tensile Strength (TTS) after annealing.

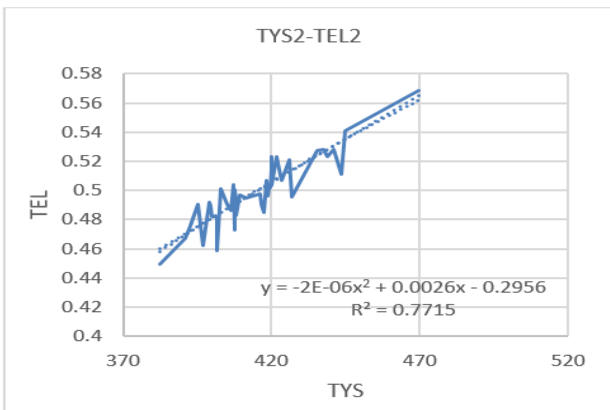

Figure 14: The relationship between True Yield Strength (TYS) with True Elongation Length (TEL) after annealing.

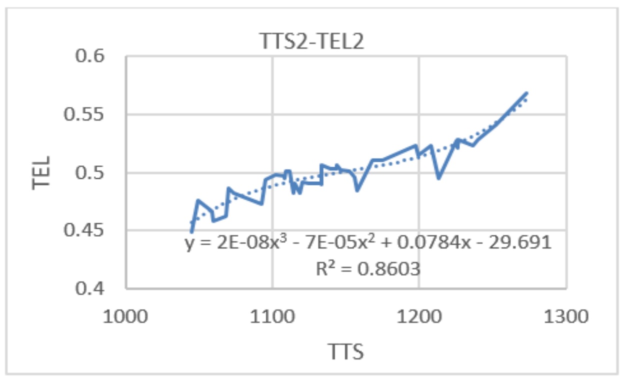

Figure 15: The relationship between True Tensile Strength (TTS) with True Elongation Length (TEL) after annealing.

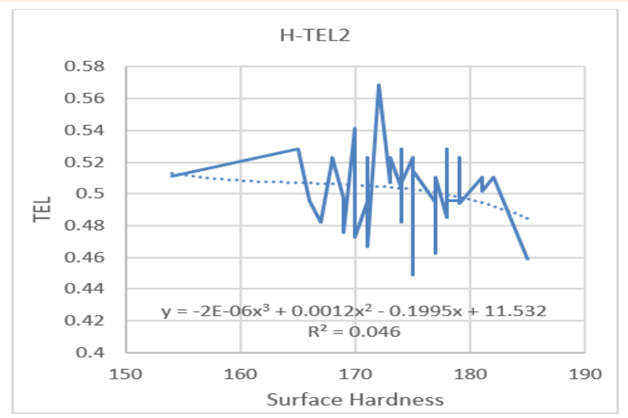

Figure 16: The relationship between Surface Hardness (H) with True Elongation Length (TEL) after annealing.

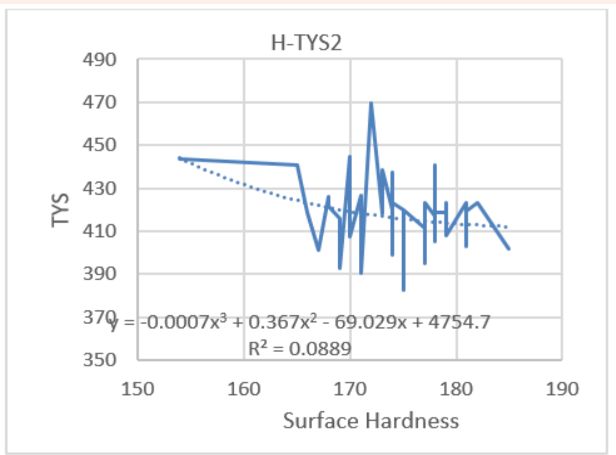

Figure 17: The relationship between Surface Hardness (H) with True Yield Strength (TYS) after annealing.

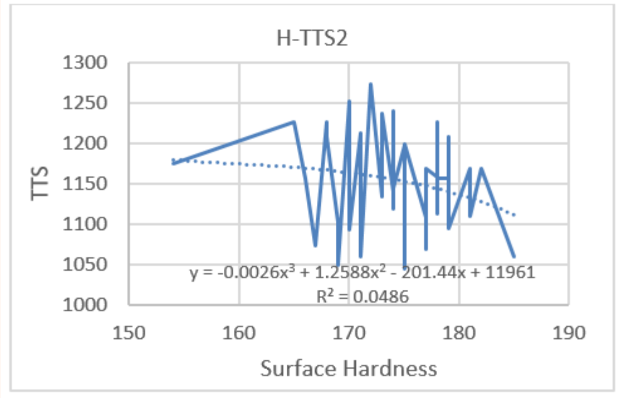

Figure 18: The relationship between Surface Hardness (H) with True Tensile Strength (TTS) after annealing.

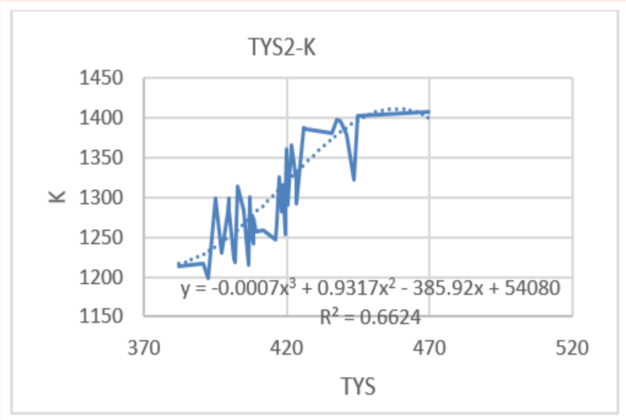

Figure 19: The relationship between True Yield Strength (TYS) with Strength Coefficient (K) after annealing.

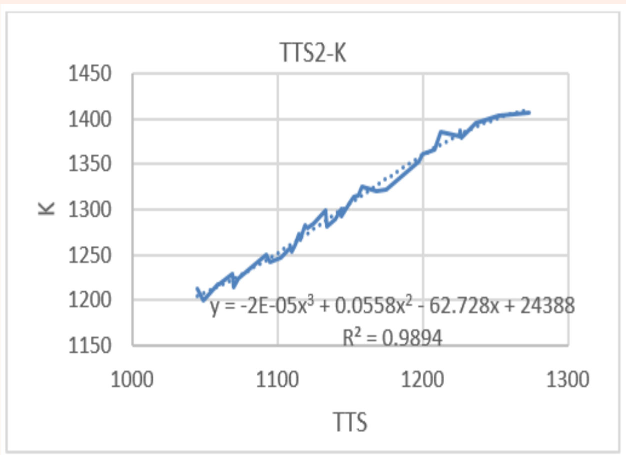

Figure 20: The relationship True Tensile Strength (TTS) with Strength Coefficient (K) after annealing.

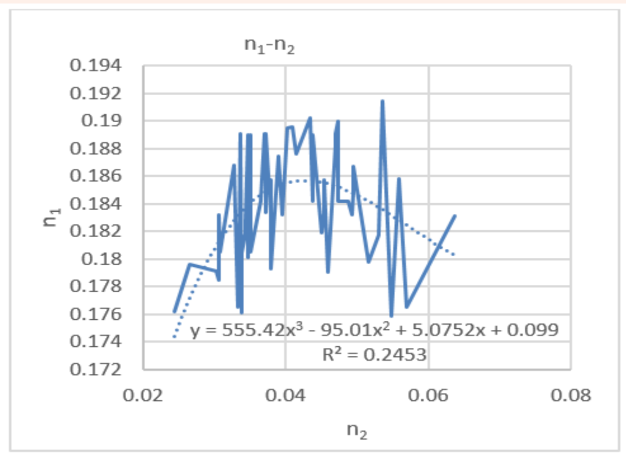

Figure 21: The relationship between Strain-Hardening Exponent (n) before and after annealing.

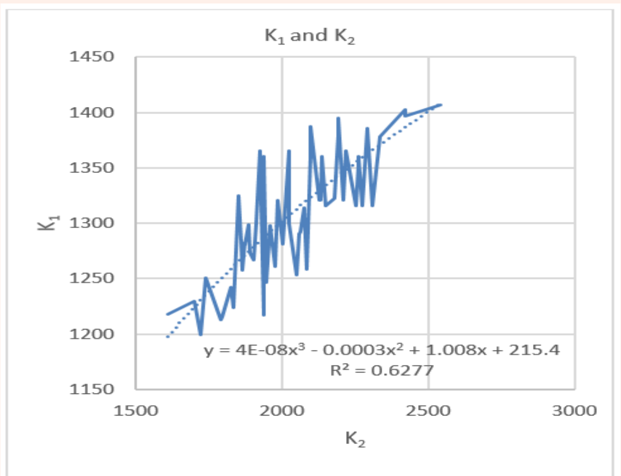

Figure 22: The relationship Strength Coefficient (K) before and after annealing.

Discussion

When the mechanical properties of the samples taken before heat treatment are examined numerically, it is observed that there is a strong correlation between the effective deformation rate and yield strength and tensile strength (Figure 5). Especially with the increase in the rate of effective deformation, it was determined that the data overlap between the yield and tensile strengths (Figure 5). While the yield and tensile strengths increase with the increasing effective deformation rate, it is clearly seen that there is no relation with elongation (Figure 6). It is thought that the increase in the deformation rate and the increase between the tensile and elongation values are due to the phase transformations occurring in the internal structure after the plastic forming process applied to the material and the increasing dislocation rate. AISI 304 stainless steel is a deformation hardenable steel, as it is included in the TWIP (Twinning inducity plasticity) steel group. After the plastic forming process applied, the grains were twinned, intertwined and the austenite phase turned into Alpha-martensite phase [3]. The dislocations that occured did not only create a brittle structure, but also caused an increase in many of the mechanical properties of the material. Another reason for this increase in yield and tensile strength may be the Alpha-martensite phase in the boundary regions of the anisotropic austenite phase. This formed phase is tetragonal volume centered and creates hard zones inside the cubic surface centered structure, preventing the grains from slipping on each other. In such a case, an increase in flow and tensile strength of the material is expected while a decrease in elongation values is expected. No relation was found between the effective deformation rate and elongation (Figures 6-10). The primary factor affecting the mechanical properties of the material before heat treatment is dislocation formation and martenetic transformation, no elongation relation has been established on the material. Also, when the data are examined, it is seen that the elongation values are very low. The most important point here is the serious reduction in elongation with deformation.

There was no statistical relationship between deformation hardening exponent and yield strength and effective deformation rate (Figures 11,12). After heat treatment, it can be seen that a relationship can be established between true tensile and true yield values (Figure 13). It is seen that the relationship between tensile and elongation is higher than the relation between yield and elongation (Figures 14-16). No relation was determined between the hardness values, yield, tensile and elongation values (Figures 16-18). In this case, hardness is not a value that will require the material to be included in the strength indicators. There was no significant relationship between yield strength and strength coefficient after heat treatment (Figure 19), but a strong relationship can be established between tensile strength and strength coefficient (Figure 20). When n and K values were compared before and after heat treatment, no significant relationship could be established between these values. However, the relationship between the values of K before and after heat treatment was found to be stronger than the values of n before and after heat treatment (Figures 21,22).

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