Anisotropy in Microalloyed S355N Steel

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Abstract

Thermomechanical control process steel produced by rolling has a significant anisotropy. The elongated grains and inclusions formed during hot rolling of ferrite and low carbon HSLA steels directly influence the anisotropy of the steel's mechanical properties as a result of microstructural anisotropy. The present research deals with this anisotropy, and particular attention has been paid to the tensile and Charpy V-notched behavior and microscopic properties. The mechanical response of a 25 mm thick rolled plate of S355N steel was characterized. The results of Charpy tests of V-notched specimens of the through-thickness direction were found to be considerably temperature-dependent and also to vary in the longitudinal and the transverse directions. Marked anisotropy effects were observed, with the through-thickness orientation exhibiting a tensile response lower than that of the longitudinal and transverse ones. These experimental findings were rationalized using the correlation holding among inclusion distribution, reduction area percent, and banding of the microstructure.

Keywords: Anisotropy, S355N structural steel, Mechanical property, Nonmetallic inclusions.

1- Introduction

An isotropic material, by definition, is one which has the same properties in all directions. An anisotropic material in contrast is one which has unequal properties in at least two directions. Many hot-rolled, normalized, annealed, quenched, and tempered structural and pressure vessel steels are three dimensionally anisotropic to some degrees. Some are anisotropic to such an extent that their weldability is degraded in the through-thickness direction[1]. Thermomechanical-control process (TMCP) steels are widely used in steel constructions for their high qualities such as fine grain, high strength, and excellent weldability. However, it is found that during manufacturing, rolling causes anisotropy in the TMCP steel plate where material properties such as elastic constants as well as tensile and fracture strengths change in the testing direction [2,3]. Anisotropic properties of rolled steel plates are related to pancake inclusions in the rolling direction, residual stresses, and mechanical fibering [4-8].

S355N is a type of high strength and low-alloyed normalized steel. It is widely used in ship structures, bridge constructions, and offshore structures in which weldability is a more important parameter in the soundness of the construction. The Mousa Kalantari Causeway is being constructed over the Urumia Lake in north-west of Iran. Microalloyed S355N steel plates of a thickness range of 12-50mm are being widely used in its construction. Regarding the fact that anisotropy in thin plates is more noticeable in the event of complicated and detrimental defects or in lamellar tearing, a thin plate of 25mm was selected as a candidate material to study its properties in three directions and the results were compared with other anisotropic steel plates currently used in similar structures.

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2- Experimental Procedure

The chemical composition of the S355N steel used in this study is given in Table 1.

Table 1. The chemical composition of S355N steel.

C	Si	Mn	Al	V	Ti	Nb	S	Cr
0.2	0.5	1.15	0.02	0.12	0.03	0.05	0.017	0.3

Longitudinal and transverse tension and Charpy V-notch specimens were machined from the half width and half thickness location of a 25mm plate. The specimen's orientation is shown in Figure 1.

Standard tension specimens 12.5 mm in diameter and 60 mm in gage length were prepared according to E8-93. For making through-thickness tension and Charpy V-notch specimensother ASTM standards (A770/A770M) were used which describe the procedure for making Z-direction specimens from low thickness steel plates. The procedure used to make these specimens is shown in Figure 2 [9]. Through-thickness tension specimens were 6 mm in diameter with a total gage length of 45 mm.

However, the effective gage length of the through-thickness specimens was actually about 25 mm because the extensions welded to these specimens were part of the total 45 mm gage length. All the Charpy V-notch specimens had dimensions of 10*10*55 mm^3.

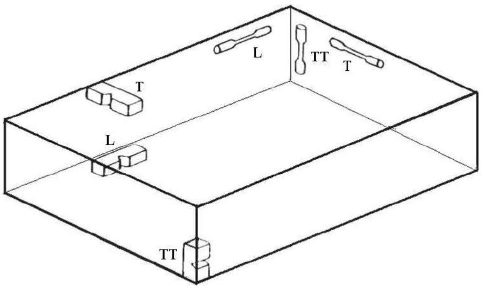


Fig. 1. Longitudinal, transverse, and through-thickness direction specimens of tensile and Charpy V-notched tests.

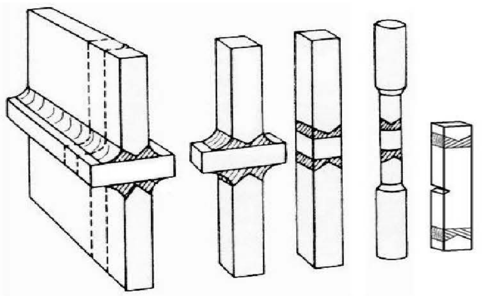


Fig. 2. The fabrication method of through-thickness tension specimens [9].

Tension tests were performed on an Instron 8502 hydraulic machine at ambient temperature using a 50 mm strain-gage extensometer for strain measurement of the longitudinal and transverse specimens and a 25mm strain-gage extensometer for strain measurement of the through-thickness specimens.

The tensile test specimens were strained at a crosshead speed of 2 mm per minute. Impact tests were conducted on Roell & Amsler machine over the temperature range of 25°C to -60°C. The specimens for light optical microscopy were mechanically polished to a 1 μm finish and etched using a 2% Nital solution. Microstructural images from the longitudinal, transverse, and through-thickness directions were prepared using an MPG3 type optical microscopy. A MV 2300 Cam Scan field-emission scanning electron microscopy (SEM) was used to evaluate the fracture surface of Charpy V-notch specimens. Volume fraction of inclusions as well as their size, morphology, and chemistry were analyzed in the longitudinal, transverse, and through-thickness sections by using image analysis and scanning electron microscopy. Real fracture strengths of the specimens were calculated using computer strength-strain data by dividing the maximum force by fracture area.

3- Results and Discussion

3-1- Microstructure

The microstructures of the steel in the longitudinal, transverse, and through-thickness directions are shown in Figure 3. The microstructure consisted of ferrite and pearlite, the latter being elongated in the rolling direction. These kinds of anisotropic structures formed of alternate layers of ferrite and pearlite are called banding. Banding may be caused in a hot-rolled steel by sever segregation of carbon and alloying elements, particularly manganese, during solidification and decomposition of austenite on cooling [10, 11]. The grain sizes of longitudinal, transverse, and through-thickness directions were 9.5, 8.5, and 8.5 μm, respectively.

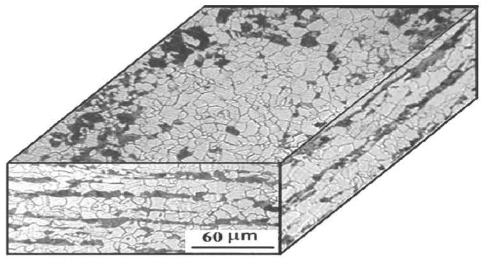


Fig. 3. Microstructures of the S355N steel in the longitudinal, transverse, and through-thickness directions.

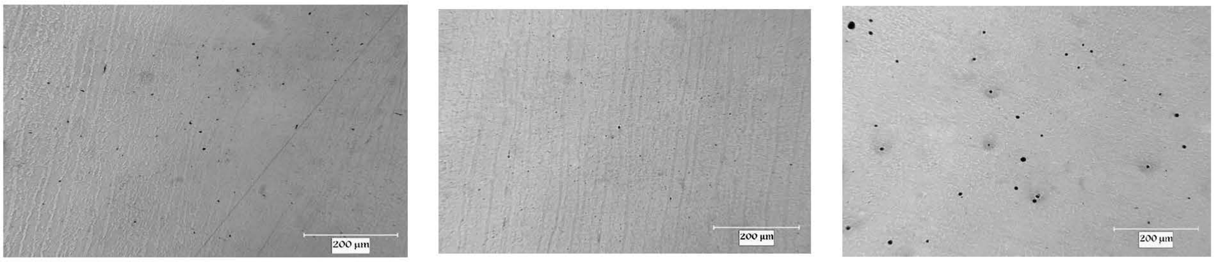
According to Bakkaloglu and Stanislaw zjac, the nonpancaked and equiaxed ferrite grains in the longitudinal, transverse, and through-thickness directions could be due to full recrystallization during normalization [12, 13]. Normalization, which can enhance grain elongation, only eliminates the crystallographic anisotropy but cannot influence mechanical fibering [8].

3-2- Inclusion

Figure 4 shows the microscopic distribution of inclusions with the same magnification. It is evident that inclusions are randomly distributed in all directions with the exception that inclusion size is the largest in the through-thickness direction but too small in the transverse direction. Given the detrimental effects of inclusions on mechanical properties, through-thickness direction is expected to be too weak.

Figure 5 shows these inclusions by SEM. At high magnifications, the globular morphology of inclusions is more important, which can explain the effect of such rare earth treatments as injection of calcium into liquid steel in order to reduce sulfur levels or to change inclusion morphology and composition. The rare earth inclusions are not ductile during hot-rolling and remain globular in the final products [10, 11, 14, 15].

Area percents and aspect ratios were determined for these inclusions in the longitudinal, transverse, and through-thickness directions using image analysis. The area percents of inclusion in the longitudinal, transverse and through-thickness directions were 0.14, 0.09, and 0.37%, respectively. As shown in Figures 4 through 6, the lowest inclusion area percent belongs to the transverse direction whereas its highest level is observed in the through-thickness direction. The aspect ratios of inclusions in the three directions range from 1 to 1.5 as shown in Figure 7.



Longitudinal Transverse Through-Thickness

Fig. 4. Inclusion distribution in the longitudinal, transverse, and through-thickness directions.

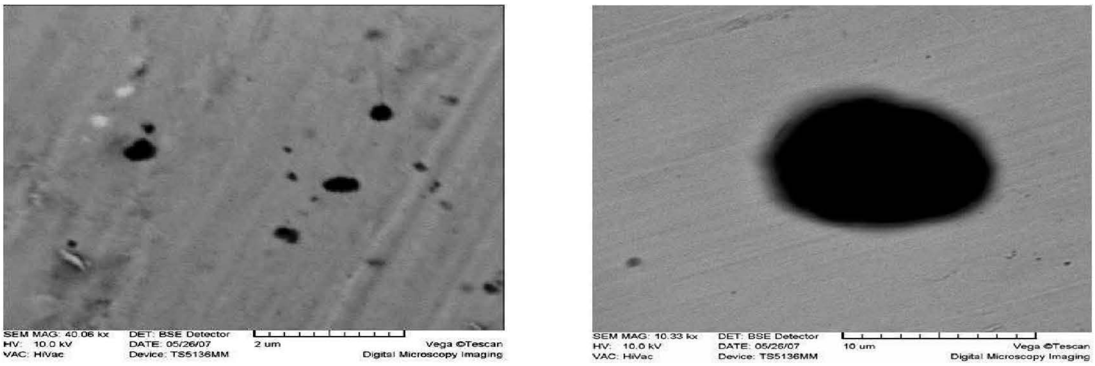


Fig. 5. Inclusion distribution and morphology of the longitudinal direction prepared by SEM.

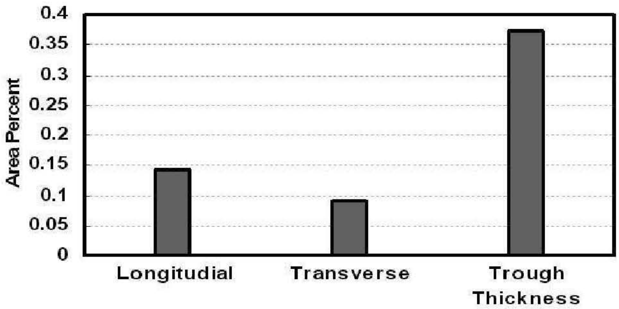
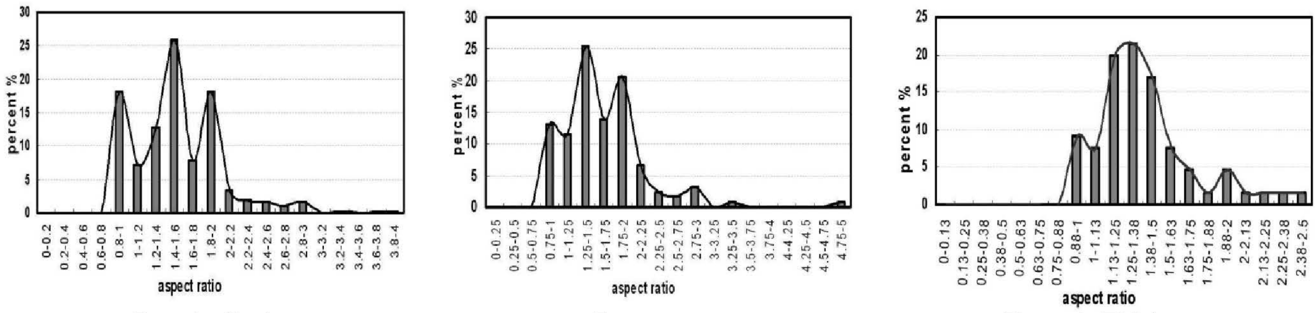


Fig. 6. Inclusion area percent in the longitudinal, transverse, and through-thickness directions.



Longitudinal Transverse Through-Thickness

Fig. 7. Inclusion aspect ratio in the longitudinal, transverse, and through-thickness directions.

Figure 8 illustrates the deleterious effect of sulfur level on through-thickness reduction of area in hot rolled and normalized C-Mn steels [14]. Reduction in area decreases linearly with increasing sulfur content. Nowadays, rare earth elements are used to control inclusion morphology in spite of high levels of sulfur in steels so that the reduction in area remains considerably high and does not decrease severely by increasing sulfur content. Even though S355N steel had a sulfur content of 0.017%, it was tougher showing the progress made in manufacturing modern fine grained and rare earth treated steels.

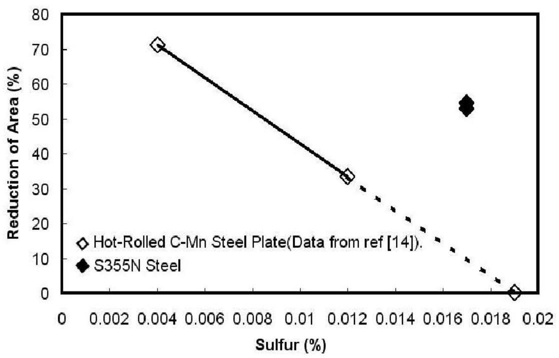


Fig.8. The effect of sulfur level on through-thickness reduction of area in the hot rolled and normalized C-Mn steels.

3-3- Tensile properties

Figure 9 shows the typical true-strain–true-stress computer-drawn curves up to the maximum load for the longitudinal, transverse, and through-thickness specimens. It is clear that toughness and elongation are greater in the longitudinal direction than in other directions and that there are apparent differences in the strength-strain properties such as uniform elongation and toughness among specimens taken from the longitudinal, transverse, and through-thickness directions.

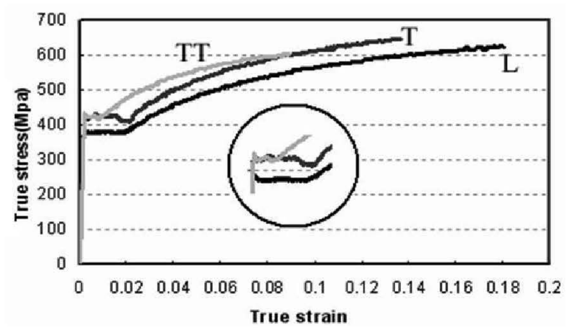


Fig. 9. Typical true strain-true stress curves up to maximum load for the longitudinal, transverse, and through-thickness specimens of S355N steel plate.

All the longitudinal and transverse direction specimens show clear Luders regions. The through-thickness specimens, however, show nearly continuous yield behavior because of their smaller effective gage-length-to-diameter ratio as compared to the longitudinal and transverse specimens (1.5 as compared to 4.8).

By as far back as the 1970's, steels were not clean and had considerable amounts of elongated inclusions [1]. Recent developments in steel processing have resulted in reduced inclusion levels and more controlled shapes of inclusion such as is observed in S355N steel. The elongated shape of inclusions had great detrimental effects on mechanical properties, especially in the through-thickness direction. Figure 10 shows the true-strain-true-stress curves of an anisotropic steel plate from three directions used in the 1970s. Comparison of these curves with those in Figure 9 reveals that the anisotropy in the latter steel's toughness and elongation is pronounced and, further, that the through-thickness mechanical property of the through-thickness specimen is too weak. However, modern clean steels such as S355N are more isotropic and have better mechanical properties in the through-thickness direction.

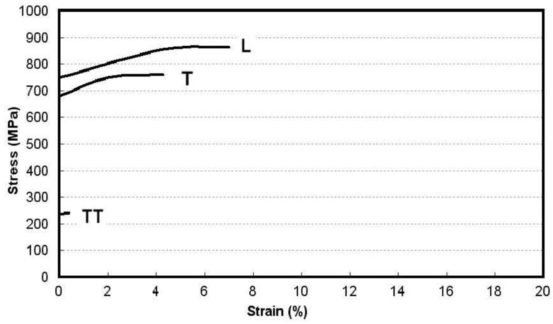


Fig. 10. The true strain - true stress curves of an anisotropic A514 steel plate used in 1970 from three directions [1].

Tensile ductility was the highest in the longitudinal direction specimens, which is in agreement with the lowest area percent of inclusions in the plane parallel to fracture surface (transverse section). On the other hand, the highest area percent of inclusions in the through-thickness tension specimens is associated with their lowest tensile ductility. Consequently, the area percent of inclusions must have an important influence on tensile ductility.

The strength values in the three directions are summarized in Table 2. The yield strengths of the longitudinal, transverse, and through-thickness specimens were 385, 424.3, and 415.5 MPa, respectively. The highest yield strength observed in the transverse direction and the lowest strength observed in the longitudinal direction are in agreement neither with the size and area percent of inclusions nor with the banding. Anisotropy in yield strength was 7%.

The tensile strength values for the specimens taken from the longitudinal, transverse, and through-thickness directions were 530, 567.5, and 540, respectively. Similar to the yield strength, the ultimate tensile strength was the highest in the transverse direction while its lowest value was observed in the longitudinal direction, which is not in agreement with inclusion size, area percent, and banding. Another interesting result was the anisotropy in the tensile strength which was again 7%.

The results show that anisotropy in the yield and ultimate tensile strengths is not evident. On the other hand, these strengths do not show the anisotropy of hot-rolled plates. Analysis of previous data in the literature [1, 14)] indicates that the yield and tensile strengths are independent of sulfur content, inclusion morphology, or tensile direction (Figure 11). So, ultimate tensile strength is directly related to carbon and pearlite contents and low anisotropy of this value is expected in different directions of a single steel. Fracture strength is, however, related to such microstructural properties as texture and inclusions that are capable of clearly showing the anisotropy [14, 15)].

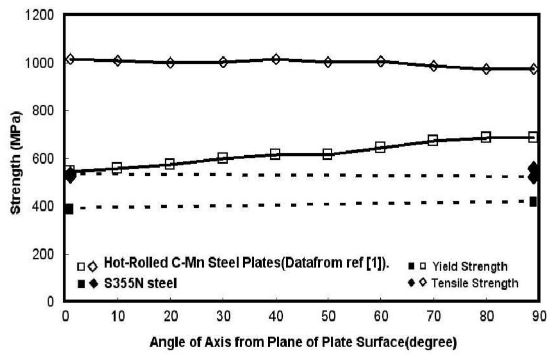


Fig. 11. Yield and tensile strengths are dependent on the orientation of hot-rolled steel plates.

The fracture strength behaviors were different from those of tensile and yield strengths. Anisotropy in the fracture strength of L, T, and TT directions was pronounced. Real facture strengths of specimens from the longitudinal, transverse, and through-thickness directions were 1388, 980, and 913 MPa, respectively. Anisotropy in real fracture strength was 34%.

The size and distribution of inclusions in the plane parallel to the fracture surface of the tensile specimen showed serious effects on fracture strength [14)]. Area percent of inclusions in the longitudinal, transverse, and through-thickness directions were 0.09, 0.14, and 0.37%, respectively. It can be seen in Fig.1 that the fracture surface of the longitudinal tensile specimen is parallel to that of the transverse direction while the fracture surface of the transverse tensile specimen is parallel to that of the longitudinal direction. Since the area percent of inclusions is the lowest in the longitudinal direction, the fracture strength of the transverse tensile specimen which has a fracture surface parallel to the longitudinal direction is, therefore, the highest. Along the same lines, the fracture strength of the through-thickness direction specimen is the lowest.

Engineering fracture strengths were 365, 511, and 460 in the L, T, and TT directions, respectively. It was maximum in the transverse direction and minimum in the longitudinal direction; the anisotropy in engineering fracturing strength was 30%. It was found that anisotropy could be accurately detected by fracture strength.

Area reduction (RA %), elongation (el), and fracture strain (ε_f) in the longitudinal, transverse and through-thickness directions are summarily reported in Table. 3.

Area reduction (RA%) in the longitudinal, transverse, and through-thickness directions were 73.3, 45.7, and 54, respectively. Reduction of area in the longitudinal direction was considerably high, which is in agreement with the low area percent of inclusions in the fracture surface (transverse section).

Anisotropy of uniform elongation was 49%, which was lowest in the through-thickness and highest in the longitudinal directions. The high magnitude of elongation can be representative of high toughness and ductility which is more important in structures. The low elongation of hot-rolled plates in the through-thickness direction and the greater anisotropy are so dangerous that can be detrimental where certain defects such as lamellar tearing occur.

Table. 2. Mechanical properties of the longitudinal, transverse, and through-thickness specimens.

	Yield Strength (MPa)	Mean Values	Tensile Strength (MPa)	Mean Values	True Fracture Strength (MPa)	Mean Values	Engineering Fracture Strength (MPa)	Mean Values	Upper Shelf Energy (J)	Mean Values
Longitudinal	379.8	385	525.5	530	1361	1388	365	365	106	117
	390.3		534.3		1415.4		365		128	
Transverse	428	424.2	568.6	567.5	975	980	510	511	36	36.5
	420.5		566.4		984.5		512		37	
Trough-thickness	419.6	415.5	523	540	911	913	445	460	119	115.5
	411.3		557.3		915		475		112	

Table. 3. Mechanical properties of the longitudinal, transverse, and through-thickness specimens.

	Fracture Elongation (ε_f)	Mean Values	Uniform Elongation (ε)	Mean Values	Reduction of Area (%)	Mean Values
Longitudinal	0.3	0.3	0.16	0.17	73.3	73.3
	0.3		0.18		73.3	
Transverse	0.23	0.21	0.15	0.14	45.6	45.6
	0.19		0.13		45.7	
Trough-thickness	0.16	0.16	0.09	0.087	54.7	54
	0.16		0.084		53	

Values of fracture strain (ε_f) in the longitudinal, transverse, and through-thickness directions were 0.3, 0.21, and 0.16, respectively, and the fracture strain anisotropy was 47%. Similar to fracture strength, fracture strain was maximum in the longitudinal and minimum in the through-thickness direction. This is in agreement with inclusion area percent. It is shown that all dimensional properties were considerably anisotropic and the lowest in the through-thickness direction. These observations are in agreement with those reported in the literatures on the readily apparent effect of test direction on tensile ductility (total elongation, fracture strain, or area reduction) [14, 15].

Figure 12 shows the relationship between total elongation and reduction in area for unalloyed hot rolled carbon steel (A36) [1]. It is shown that area reduction is approximately 1 to 2 times that of elongation. Except for the details, this range in the relationship is descriptive of all three plate directions. The ductility values of carbon steel plate in the longitudinal and transverse directions are conspicuously superior to those obtained in the through-thickness direction, where as low as 1% elongation and 2% area reduction were obtained in two incident cases. Most of the incident cases investigated were found to have total elongation values of less than 6% and area percents of less than 15% in the through-thickness direction.

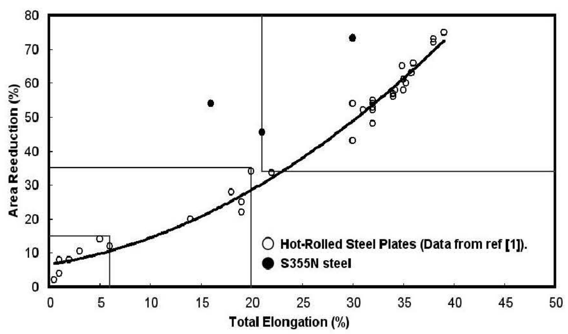


Fig. 12. The relationship between total elongation and reduction in area for unalloyed hot rolled carbon steel (A36).

These incident anisotropic steel plates were considerably susceptible to lamellar tearing and could not be used in welded structures. The values for S355N steel presented in Figure 12 indicate that the through-thickness ductility is as high as the transverse one. Therefore, the anisotropy in modern clean and rare earth treated steels is considerably low compared to steels of previous decades.

3-4- Notch toughness

The Charpy V-notch impact curves for specimens from different directions are shown in Figure 13. The values for the upper shelf energy of the specimens from the longitudinal, transverse, and through-thickness directions were 117, 36.5, and 115.5 J, respectively. A similar behavior was observed in area reduction; namely, it was maximum in the longitudinal and minimum in the transverse direction, with the anisotropy being 70%.

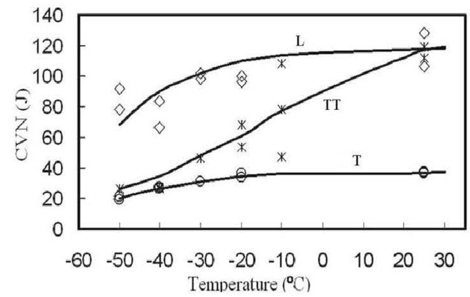


Fig. 13. The Charpy V-notch impact curves for specimens from different directions.

Neither in the longitudinal nor especially in the transverse Charpy V-notch specimens was the variation in absorbed energy with temperature absent; i.e., in all high and low temperatures, the absorbed energy exhibited close values. In the through-thickness specimens, however, the absorbed energy decreased linearly with decreasing temperature. At room temperature, the shelf energy of the through-thickness direction specimen was equal to that of the longitudinal one, while at low temperatures (-60°C), the absorbed energy of the through-thickness specimen was equal to that of the transverse direction specimen.

Figure 14 shows the variation in shelf-energy as a function of reduction in area for the hot-rolled C-Mn steels [15]. According to this Figure, the shelf energy changes much more rapidly for area reductions greater than 50 pct. At lower values of area reduction, there is an essentially direct relationship between shelf energy in joules and percent reduction of area. This is the range where stringered inclusions have resulted in a sharp decrease in the area reduction and shelf energy of the through-thickness specimens. Therefore, when stringered inclusions are pronounced, area reduction and shelf energy appears to be usable in evaluating the deleterious effects of these inclusions on through-thickness properties. However, shelf energy is much more sensitive than area reduction as a result of the stringered inclusions. A satisfactory agreement was found between the S355N test results and those obtained from the present study.

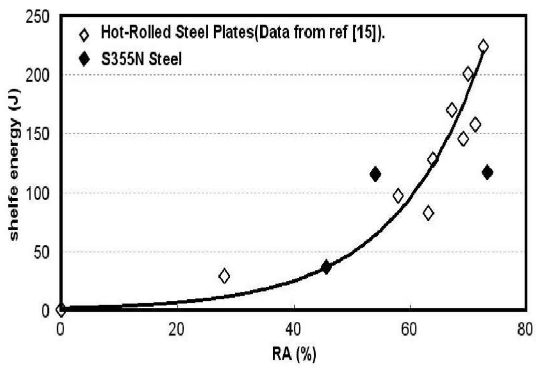


Fig. 14. The variation in shelf-energy for different values of area reduction in the hot-rolled C-Mn steels and S355N specimen.

Spitzig showed a linear relationship to exist between shelf energy (C_V in J) and area reduction (RA), which is shown in Figure 15. The line through the data is given by the equation $C_v = 15.5/(1\text{- RA})^2 = 15.5(d_o/d_f)^4$ where d_o and d_f are the original and final specimen diameters, respectively, (the constant being 11.4 if C_v is in ft-lb). Because $\varepsilon_f = \ln (d_o/d_f)^2$, the logarithm of shelf energy could have also been plotted against fracture strain (ε_f) [15]. We tried to modulate the S355N steel test results using this relation. It is clear that there is a clear relationship between S355N and Spitzig's test results, indicating that a linear relationship holds between area reduction and shelf energy in S355N steel.

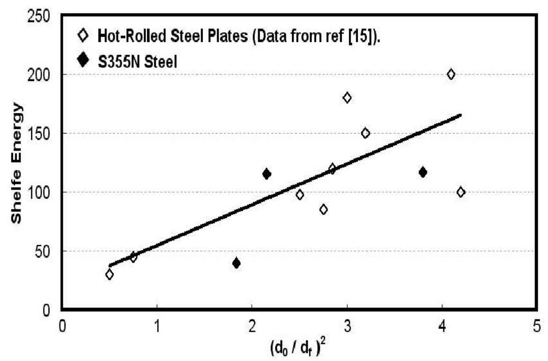


Fig. 15. Plot of variation in shelf energy (C_V in J) as a function of area reduction (RA).

4- Conclusions

- Metallurgical parameters such as distribution, area percent of inclusions, and test direction had no effects on the yield and tensile strengths; the highest value of the anisotropy of these strengths was 7%.
- Fracture strength can evidently show the anisotropy, as the anisotropy values of real and engineering fracture strengths were 34% and 30%, respectively.
- The anisotropy was readily apparent in tensile ductility (fracture strain and reduction of area). The anisotropy values in fracture strain and reduction of area were49% and 37% respectively.
- All fracture properties such as fracture strain and fracture strength had reverse linear relations with inclusion area percent on the plane parallel to the fracture surface.
- A notch toughness property has the highest anisotropy and is sensitively affected by inclusions; this is witnessed by the anisotropy of shelf energy being equal to 70%. The notch toughness and reduction of area exhibited similar behaviors. However, shelf energy was much more sensitive than reduction of area as a result of the stringered inclusions.

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