Variation in Mechanical Properties of SAE 1006 Interstitial Free (IF) Steel Sheets During Cold Rolling

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Abstract

This research aims to study the variation in properties of hot-rolled SAE 1006 IF steel sheets during cold rolling to reveal the factors causing the decrease in formability of SPCG steel sheets during deep drawing. Results have shown that pickling does not affect the mechanical properties; however, cold rolling results in an increase in hardness, tensile strength and yield strength. Stress relieve annealing results in coarsening and homogenizing of grains which reduces brittleness and impart ductility. Temper rolling causes an increment in mechanical parameters again, improve surface hardness and flatness. By analyzing the microstructure and comparing it with the HESCO sample, it is revealed that there are still some elongated grains found along with coarse grains after annealing. Soaking time is not sufficient for the growth of homogenized structure, resulting in decreased ductility and formability during deep drawing.

Keywords: IF steel, Hall-Petch Equation, Formability, SPCG, JIS standards,

Introduction

Deep drawability, stretchability, stiffness dent resistance, and corrosion resistance are the main required properties for steel grades used in sheet form for automobile body exposed panels, such as door panels and fenders, and unexposed panels as floor and dashboard panels [1].

Cold-rolled and annealed interstitial-free (IF) steel sheets with good formability have been extensively used for automotive body panels [2]. These property requirements can be met by interstitial-free (IF) steel" IF steel was invented in the late 1960s in Japan. SAE 1006 interstitial free (IF) steel is an extra deep drawing high strength steel with an alloying element made up of a relatively low amount of carbon [1]. The use of hot-rolled steel sheets instead of cold-rolled steel sheets has been considered for cost reduction. However, it has been well recognized that hot rolled steel sheet does not have good drawability. The texture of the hot-rolled steel sheet substantially influences the cold-rolled and annealed steel sheets' textural evolution. Depending upon the finish temperature of hot rolling, microstructural changes occur. The microstructural change with the finishing temperature in hot rolling is partially responsible for the textural evolution difference during the subsequent cold rolling and annealing[2].

A significant part of hot-rolled sheets and strips is subjected to the process of cold rolling. During rolling, structural changes have to come into existence in which grains form the fundamental matrix of the material is gradually stretched in the direction of the principal deformation. At the same time, the directional arrangement of the crystallographic lattice is developed. So due to the deformation, the structural and crystallographic texture is formed. A typical feature of such a deformed structure is anisotropy of mechanical properties. The directional arrangement mentioned above is primarily undesirable regarding demands put on the cold-rolled strip or sheet. Therefore, heat treatment in the form of annealing is integrated to remove this phenomenon [3]. The sheet steels must be heat treated to obtain high strength and formability[4].

The chosen parameters of annealing, mainly temperature and time, have a decisive influence on the character of microstructure and hence mechanical properties after annealing. Strength properties of the material decrease with increasing annealing temperature, whereas, on the contrary, plastic properties increase. The higher the cold reduction of the material, the lower is the recrystallization temperature. However, the time needed for the accomplishment of recrystallization becomes very long at low temperatures. Properties of the material reflect in principle its microstructure. Low carbon steels have various microstructures according to the rolling and cooling conditions[3]. The recrystallized grains should have an optimum size after annealing, which ensures the material's favorable strength and plastic characteristics [5].

Since cold-rolled and annealed interstitial free (IF) sheet steels require good formability [2], Yield strength (YS) is one of the major factors influencing the press formability of steels. Usually, the yield ratio (YR = YS/TS) of the solution-hardened steels are 60-70 %. However, when steel sheets containing Mn, Cr, Mo, etc., are subjected to rapid cooling following continuous annealing, the YR decreases to approximately 50%, and the YS increases sharply with strain aging. This means that forming these steel sheets can be easily performed because of their low yield strength at the time of press forming [6].

The mechanical properties like yield strength, tensile strength, toughness, flexibility, hardness, fatigue strength, creep strength, and susceptibility to brittle fracture are strongly dependent on the material's grain size [7]. Refinement of grain size is the standard way to improve both strength and toughness [8]. Grain refinement is the only strengthening mechanism available that doesn't compromise on steels' ductility considerably, while the other strengthening mechanisms like quenching, cold working, precipitation hardening, and alloying decrease ductility significantly [7]. The grain refinement is directly linked with a strong increase in strength and a pronounced strain hardening. However, the uniform and total elongation

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is deteriorated. Nevertheless, ductility loss is not considered a severe problem as moderate formability is still achieved [5].

Experimental Work:

Material Used

SAE 1006 Interstitial Free (IF) steel samples were taken from International Steels Limited, Karachi. This steel grade is mainly used for a deep drawing purpose and in fuel tanks of motorbikes.

Setup for the Experiment

For the purpose of the experiment, nine different IF steel coils were selected and two samples, each of size 12" x 12" were cut from each coil after each work station of cold rolling, i.e., pickling, 4-HI cold rolled mill, annealing and temper rolling respectively.

Pickling

Coils were passed through three pickling tanks with a concentration of 2.96 to 5.3,10.69 g/lit to 11.49 g/lit and 14.66 to 14.73 g/lit, respectively.

Hi Cold Rolling

All coils were reduced from 3.2mm to 0.8mm in 5 passes, i.e., 75% reduction was performed.

Annealing

Coils were annealed at 720 ºC for 13.2 hrs and held at 720 ºC for 14 hrs, slowly cooled from 720 ºC to 613 ºC for 5.5 hrs followed by air cooling from 613 ºC to 380 ºC for 6.5 hrs and water-cooled from 380 ºC to 55 ºC. The total cycle time was 63.3 hrs.

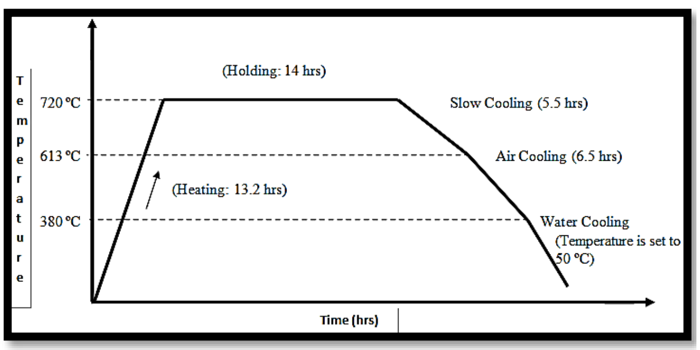

Figure 1: Heat treatment cycle for SAE 1006 IF steel sheet

Microscopy

Metkon Inverted Metallurgical Microscope IMM 901 was used for microstructural studies.

Tensile Testing Machine

Tensile testing was performed on Tinius Olsen Super "L" 60,000 lbf Tensile Testing machine. Specimens were prepared according to standard JIS Z 2202/ ASTM E-8.

Hardness Testing Machine

The hardness testing was performed on Rockwell hardness tester according to ASTM E-18.

Results and Discussion

Volume Fraction

Volume fractions of all the test specimens are measured through the point count method.

Slabs are hot-rolled at a temperature of 1000-1050 ºC. Complete reduction of the slab is made in a single pass. The finishing temperature for coils is about 850 ºC. The phase obtained mainly consists of two constituents, i.e., ferrite and pearlite. Since it contains extra low carbon, the main composition is ferrite and the remaining is pearlite. The cooling rate after hot rolling is not uniform; the composition of phases thus obtained is shown in table 1.

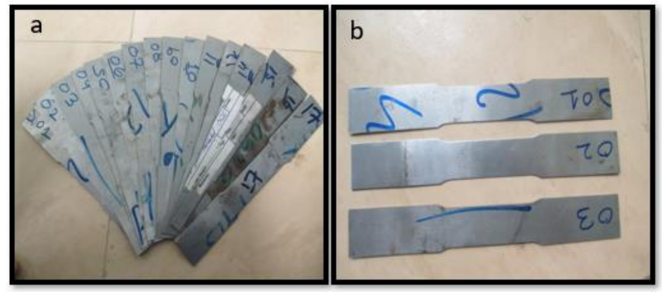

Figure 2: Tensile samples prepared according to standard JIS Z 2202/ ASTM E-8

Table 1. Volume fraction of Hot Rolled (As received) samples

Test specimen	Volume fraction of ferrite	Volume fraction of pearlite
1	0.846	0.154
2	0.833	0.167
3	0.858	0.142
4	0.878	0.122
5	0.885	0.115
6	0.849	0.151
7	0.867	0.133
8	0.852	0.148
9	0.871	0.129

Table 2. Volume fraction of Annealed samples (After Cold reduction of 75%)

Test specimen	Volume fraction of ferrite	Volume fraction of pearlite
1	0.901	0.099
2	0.900	0.100
3	0.927	0.073
4	0.939	0.061
5	0.927	0.073
6	0.908	0.092
7	0.910	0.090
8	0.918	0.082
9	0.928	0.072

The decomposition of austenite to a ferrite-cementite aggregate is essentially a diffusion-controlled process and proceeds by nucleation and growth mechanism.

Cold worked and annealed samples are also investigated. Table 2 shows an increasing percentage of ferrite as compared to table 1. This increase in the percentage of ferrite (about 7%) occurred because of stress relief annealing, which was performed after cold rolling along with a prolonged holding time of about 14 hours. The driving force for microstructural changes comes from the stored energy of deformation. The stored high energy of cold working in this orientation provides the driving force for these microstructural changes, i.e., dislocation annihilation that leads to nuclei formation and their growth into recrystallized grains. This allows ferrite to grow more at the expense of free energy. Therefore, the work hardening effect is reduced via recrystallization and strength decreased while ductility is restored.

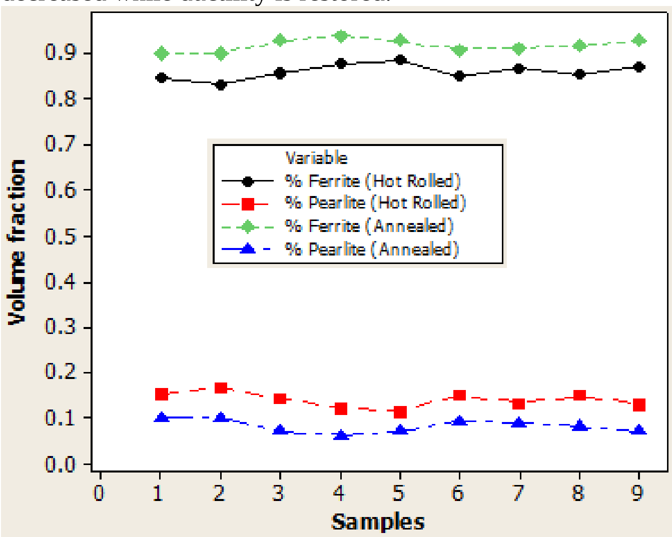

Figure 3: Scatter plot volume fraction of samples

The samples for evaluation of structure by optical microscopy were taken from central parts of rolled-out products (in the perpendicular section parallel with the direction of rolling). The structure was evaluated from selected samples after hot rolling, cold rolling, annealing and temper rolling. The microstructure of hot-rolled samples Figure 4(a) revealed a banded structure consisting of fine-grained ferrite of ASTM grain size no G = 5.70 with the occurrence of pearlite of about 11%. Nevertheless, not all ferritic grains were equiaxed. Figure 4(b) shows cold worked (€=75%) structure—such distorted structure results in bulk mechanical properties increment.

The microstructure of cold deformed samples after recrystallization annealing is shown in Figure 4(c). Most of the grains are equiaxed. The microstructure consists of ferrite with a low fraction of pearlite compared to hot rolled and pickled samples because of annealing. Grains should be homogenized after recrystallization annealing, but some of the samples' microstructures show some elongated grains and coarse grains after annealing Figure 4(e, f). This might be because of insufficient holding time. Proper holding tome allows grains to recover and grow at the expense of their free energy. Insufficient holding time causes a break or stoppage of grain growth. Figure 4(f, g) shows that most of the grains, after annealing, have been recrystallized compared to the rest of the grains. It is because recovery and recrystallization set in sooner in high energy orientations. High energy orientations are the first to recover and recrystallize well ahead of low energy orientations. Such structure causes a decrease in formability of steel sheet and cracks formation during deep drawing. Figure 4(d) shows the microstructure of temper rolled sample, much similar to annealed one. However, a slight increment in mechanical properties is because of dislocations that are induced during surface hardening after recrystallization annealing.

ISL temper rolled (SPCG) samples were compared with HESCO (an international supplier of sheet steels) temper rolled (SPCG) samples. Results have shown that the HESCO sample has a smaller grain size, better strength, stiffness and other mechanical properties than ISL samples.

Average Grain Size Measurement

The average grain size of the test specimens is measured by the Plainimetric Method. The grain sizes of the test's specimens are given in Table 3, 4, 5 and 6

Microstructures

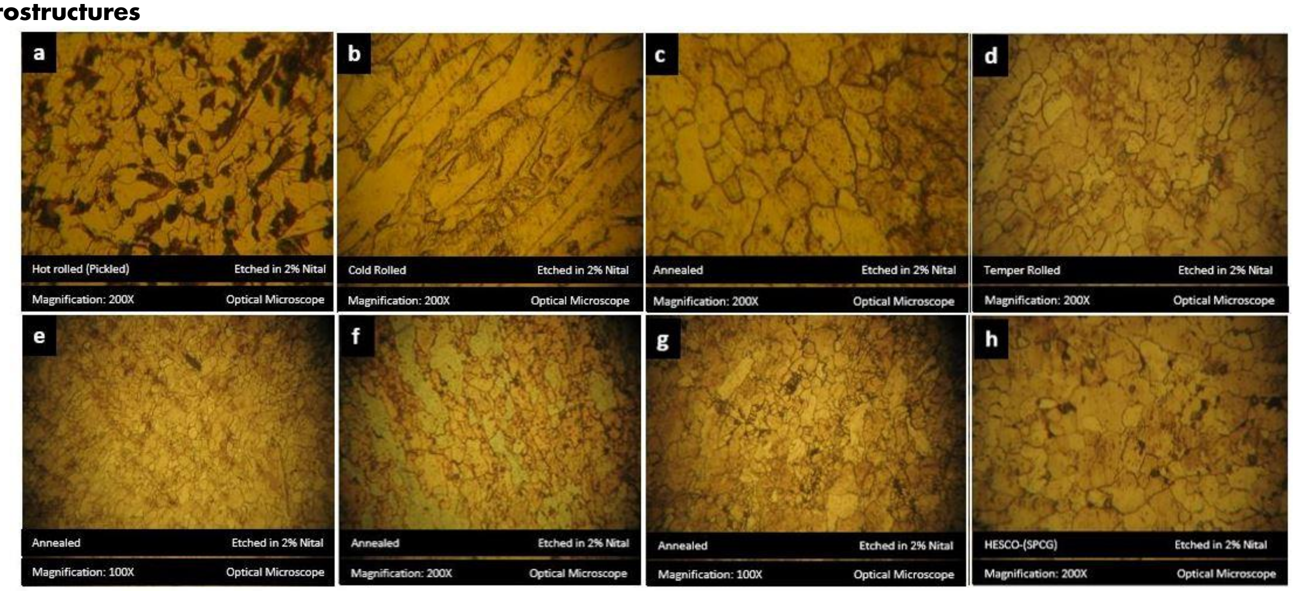

Figure 4: a) Hot rolled sample b) Annealed sample c) Cold rolled sample d) Temper rolled sample e) Annealed sample g) Annealed sample h) HESCO-(SPCG) sample

Table 3: Grain size of Hot Rolled (As received) samples

Test specimen	Lineal intercept (mm)	ASTM Grain Size No, G	Grain diameter (µm)
1	2.29×10^{-3}	5.55	47.89
2	1.31×10^{-3}	6.33	36.24
3	1.17×10^{-3}	6.49	34.23
4	1.90×10^{-3}	5.81	43.64
5	1.63×10^{-3}	6.02	40.49
6	2.59×10^{-3}	5.38	50.89
7	1.05×10^{-3}	6.64	32.44
8	1.106×10^{-3}	6.57	33.26
9	2.55×10^{-3}	5.40	50.53

Table 4: Grain size of Cold Rolled samples (€=75%)

Test specimen	Lineal intercept (mm)	ASTM Grain Size No, G	Grain diameter (µm)
1	1.06×10^{-3}	6.73	32.56
2	4.76×10^{-4}	7.75	21.82
3	2.76×10^{-4}	8.51	16.63
4	7.96×10^{-4}	7.03	28.22
5	5.81×10^{-4}	7.47	24.11
6	1.5×10^{-3}	6.14	38.79
7	1.8×10^{-4}	9.11	13.42
8	2.4×10^{-4}	8.68	15.65
9	1.29×10^{-3}	6.35	35.98

Table 5: Grain size of Annealed samples (After Cold reduction of 75%)

Test specimen	Lineal intercept (mm)	ASTM Grain Size No, G	Grain diameter (µm)
1	3.5×10^{-3}	4.927792	59.838154
2	2.9×10^{-3}	5.220299	53.898436
3	2.4×10^{-3}	5.450333	49.641996
4	3.2×10^{-3}	5.056137	57.158090
5	3.18×10^{-3}	5.115832	56.200127
6	5.81×10^{-3}	4.248302	76.267872
7	2.03×10^{-3}	5.716639	45.134225
8	2.39×10^{-3}	5.495923	48.895000
9	5.183×10^{-3}	4.409984	71.995000

Grain size analysis is carried out to analyze the changes occurring at the microscopic level in SAE 1006 IF steel during cold rolling. The hot rolled structure shows grains of uniform distribution approx. However, a bit fine because the cooling rate after hot rolling does not seems to be uniform. HR coil was cooled down in an open environment. Table 3 shows the average grain size of samples.

Cold rolling results in extensive plastic deformation at micro level. Grain structure is distorted, and grains are aligned in the direction of rolling. A high amount of energy is stored in grains by such a high amount of cold deformation (€=75%). The deformation/cold working/work hardening, the lesser will be the grain diameter (d), and the greater will be the ASTM grain size number (G). This is shown in table 4; the ASTM grain size number is decreased as compared to table 3. The brittle nature steel sheet produced during work hardening/cold rolling cannot be used in any practical application. Stress relief annealing allows restoring ductility and toughness in sheets. A proper heating rate and prolonged holding time of about 14 hours result in coarse grains. Grain diameter is the greatest among all as can be observed in table 5. Such grain structure is soft and had a better combination of strength and toughness.

Table 6: Grain size of temper Rolled samples

Test specimen	Lineal intercept (mm)	ASTM Grain Size No, G	Grain diameter (µm)
1	2.82×10^{-3}	5.2690	53.0085
2	1.87×10^{-3}	5.8523	43.0933
3	2.01×10^{-3}	5.7330	44.7664
4	2.60×10^{-3}	5.4025	50.7585
5	2.76×10^{-3}	5.2885	52.4707
6	5.58×10^{-3}	4.3035	74.6895
7	2.04×10^{-3}	5.7135	45.1529
8	2.23×10^{-3}	5.5902	47.1763
9	5.11×10^{-3}	4.3275	71.4964

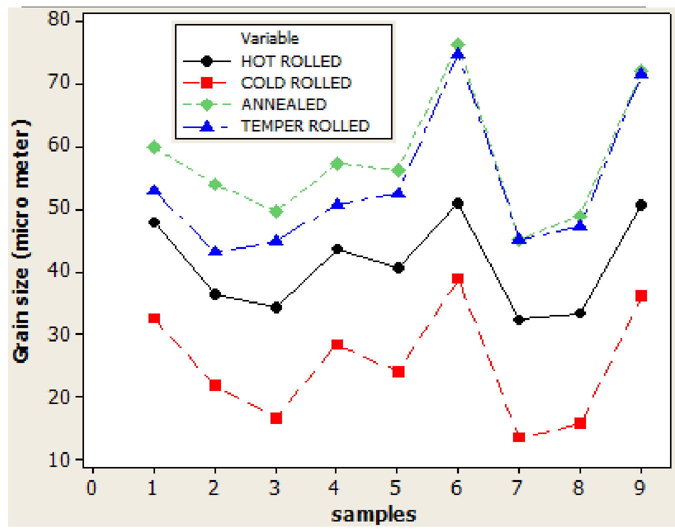

Figure 5: Scatter plot of grain sizes of samples

At temper rolling, surface hardness is just improved by 2-3 HRB. After annealing, the steel coil has so thoroughly been relieved of internal stresses that it tends not to bend during forming operation. Compared with the grain size of annealed ones, a minimal decrease in grain size is observed. This help in maintaining the final required roughness, mechanical and geometrical parameters like yield strength, tensile strength, toughness, flatness, etc. this slight increase in grain size (table 6) is necessary for obtaining the above mention mechanical properties

Hardness Test

Hardness results for hot-rolled samples showed that the average hardness for hot-rolled samples was about 50HRB. As discussed earlier, after hot rolling finished, the cooling rate was not uniform enough time was not available for grains growth; this results in hardness shown in table 7.

Table 7: Hardness of test specimens (HRB)

Test specimen	Hot Rolled	Cold Rolled	Annealed	Temper Rolled
1	42	89	36	42.3
2	44	92	39	39.7
3	41	91	40	41.7
4	42	93	34	43.3
5	42	91	39	40.0
6	45	89	37	42.0
7	43	91	37	42.3
8	40	91	36	39.7
9	41	92	32	40.7

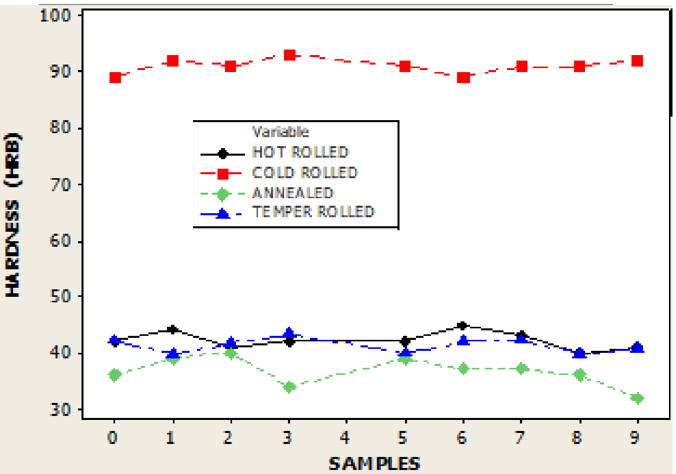

Figure 6: Scatter plot f hardness of samples

Extensive plastic deformation causes a very much increase (about 95%) in hardness. Grain structure is distorted, dislocations are pile up at grain boundary and this grain boundary causing hindrance for dislocation movement. These factors result in hardness after cold working, shown in table 7.

Annealing results in a release of stresses due to work hardening and restoration of ductility and decrease in hardness; grains recrystallize and grow at the expense of their free energy. The hardness of annealed samples is shown in table 7. However, because of hardening of the surface, i.e., skin pass rolling, a slight increment in hardness is observed as listed in table 7.

Tensile Test: Tensile strength

Table 8: Tensile strength of test specimens (MPa)

Test specimen	Hot Rolled	Cold Rolled	Annealed	Temper Rolled
1	317	598	270	265
2	323	603	267	253
3	325	603	283	253
4	351	665	280	254
5	343	650	264	253
6	337	621	270	260
7	325	610	257	255
8	361	603	257	267
9	320	609	262	262

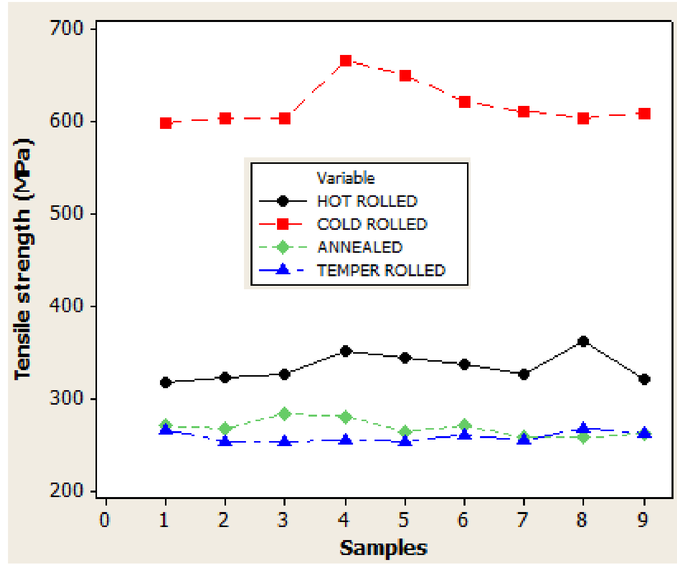

Figure 7: Scatter plot Tensile Strengths of samples

Yield strength

Table 9: Yield Strength of test specimens (MPa)

Test specimen	Hot Rolled	Cold Rolled	Annealed	Temper Rolled
1	226.0	436.5	89.6	149.1
2	232.0	425.2	95.3	131.1
3	231.5	491.5	105.4	143.5
4	249.0	388.5	103.4	156.4
5	253.0	430.0	94.4	151.1
6	241.0	432.8	107.5	156.1
7	233.0	411.1	102.3	156.6
8	259.0	384.5	91.5	157.5
9	239.5	454	103.5	160.4

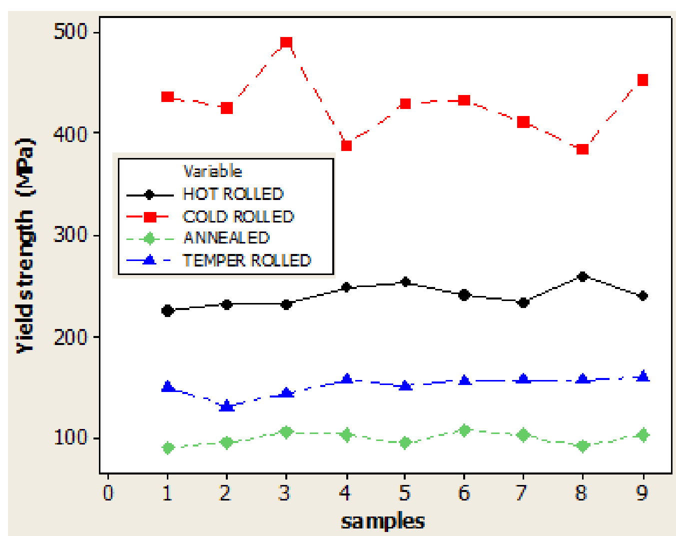

Figure 8: Scatter plot Yield Strengths of samples

Elongation

Table 10:.Elongation of test specimens (%)

Test specimen	Hot Rolled	Cold Rolled	Annealed	Temper Rolled
1	44	5	45.0	45.3
2	42	6	48.0	45.5
3	50	6	45.0	45.0
4	54	3	44.0	43.4
5	56	4	45.0	43.8
6	50	3	51.0	48.0
7	50	5	46.5	44.0
8	48	3	45.7	42.0
9	48	4	43.6	42.3

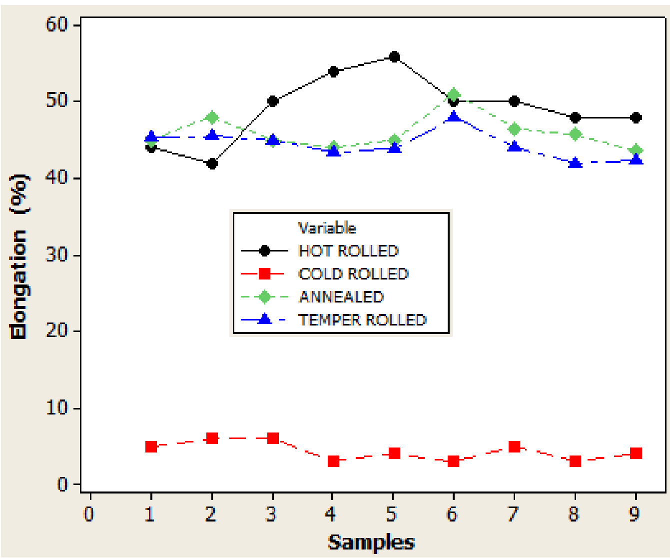

Figure 9: Scatter plot of elongation of samples

Hot rolled samples were found to have an average tensile strength of 350 MPa. The Minimum Practically acceptable strength is about 290 MPa; however, the thickness is about 3.2mm - 4mm, which is not desirable in practical applications because of the low strength to weight ratio and economy.

Deformation at room temperature (cold rolling) causes grains/lattice structures to distort. More and more dislocations are produced as the amount of cold reduction increases/continues. All such dislocation is that pile-up grain boundary and grain boundary act as barriers, i.e., it hinders the dislocation movement. This results in a significant increase in tensile and yield strength, as shown in Tables 8 and 9. Since so much interlocking of grains is created, elongation is significantly reduced, the material becomes brittle. This reduction in elongation/ductility can be observed in table 10.

Stress relieve annealing restores ductility, allowing the deformed grains to recover, recrystallize and grow. Prolong holding below A_{c1} causes stored energy to release and this energy acts as the driving force for the growth of ferritic grains. Grain structure becomes homogenized and interlocking of rains created during cold working is thus removed, resulting in lowering of strength (table 8 and 9) and increase in ductility/percent elongation as shown in table 10.

An increase in yield and tensile strength is observed at the fourth stage of cold rolling; temper rolling. A minimal reduction of about 0.5% – 2% of total thickness is performed to harden the surface. A small number of dislocations are created than in the second stage of cold working, i.e., 4-Hi cold rolling mill. This causes again an increment in mechanical parameters, which are applied to meet the final customer demands.

Hall-Petch Equation Working

The obtained results, as shown in the following table, do not any particular finds. Obtained values are varying and don not form any relation for conclusions of the performed working.

Table 11 (a). Hall-Petch equation values of Hot rolled and Cold rolled samples

<table>
<tr><th rowspan="2">S.NO</th><th colspan="4">Hot Rolled</th><th colspan="4">Cold Rolled</th></tr>
<tr><th>σ_o</th><th>K</th><th>σ_{calc}</th><th>σ_{exp}</th><th>σ_o</th><th>K</th><th>σ_{calc}</th><th>σ_{exp}</th></tr>
<tr><td>1</td><td rowspan="2">183.44</td><td rowspan="2">0.289</td><td rowspan="2">-</td><td rowspan="2">-</td><td rowspan="2">147.48</td><td rowspan="2">1.652</td><td rowspan="2">-</td><td rowspan="2">-</td></tr>
<tr><td>2</td></tr>
<tr><td>3</td><td>-</td><td>-</td><td>232.109</td><td>231.5</td><td>-</td><td>-</td><td>522.626</td><td>491.5</td></tr>
<tr><td>4</td><td rowspan="2">4191.5</td><td rowspan="2">-25.66</td><td rowspan="2">-</td><td rowspan="2">-</td><td rowspan="2">274.19</td><td rowspan="2">0.804</td><td rowspan="2">-</td><td rowspan="2">-</td></tr>
<tr><td>5</td></tr>
<tr><td>6</td><td>-</td><td>-</td><td>567.9</td><td>241</td><td>-</td><td>-</td><td>405</td><td>432.85</td></tr>
<tr><td>7</td><td rowspan="2">-3673.72</td><td rowspan="2">22.818</td><td rowspan="2">-</td><td rowspan="2">-</td><td rowspan="2">-94.346</td><td rowspan="2">1.956</td><td rowspan="2">-</td><td rowspan="2">-</td></tr>
<tr><td>8</td></tr>
<tr><td>9</td><td>-</td><td>-</td><td>-485.6</td><td>239.5</td><td>-</td><td>-</td><td>243.51</td><td>454</td></tr>
</table>

Table 11(b). Hall-Petch Values of Annealed and Temper Rolled Samples

S.NO	Annealed				T.Rolled			
	σ_o	K	σ_{calc}	σ_{exp}	σ_o	K	σ_{calc}	σ_{exp}
1	2.847	0.6741	-	-	305	-1.14	-	-
2								
3	-	-	98.145	105.45	-	-	134	143.5
4	1147	-7	-	-	151.06	0.038	-	-
5								
6	-	-	243	107.5	-	-	55.91	156.11
7	-167.69	1.813	-	-	149.579	0.047	-	-
8								
9	-	-	46	103.5	-	-	155.205	166.385

Conclusion

Cold rolling has a marked impact on mechanical properties. Variation in mechanical properties has been investigated for SAE 1006 interstitial free (IF) steel during the cold rolling process. The results have shown that pickling does not affect the mechanical properties. However, extensive plastic deformation, i.e., cold working, increases hardness, tensile stress, yield stress, and a decrease in ductility because the grain structure is distorted, dislocations are pile up at the grain boundary. This grain boundary causing hindrance for dislocation movement, a high amount of dislocation density is created and a significant amount of deformation energy is stored. Stress relief annealing results in coarsening and homogenizing of grains, reducing the high flow stresses of cold worked material and reducing high dislocation density created, thus impart ductility in the sheet. An increase in yield and tensile strength is observed at the fourth stage of cold rolling; temper rolling. A minimal reduction of about 0.5% – 2% of total thickness is performed to harden the surface; a minimal grain size reduction is observed. A small number of dislocations are created than in the second stage of cold working, i.e., 4-Hi cold rolling mill. This causes an increment in mechanical parameters again, improves surface hardness and flatness.

Also, ISL samples were compared with HESCO samples. Results have shown that HESCO has a smaller grain size, better strength, stiffness and other mechanical properties than ISL samples. It is revealed that there are still some elongated grains found along with coarse grains after annealing in ISL samples. Soaking time is not sufficient for the growth of homogenized structure, which results in a decrease in ductility and formability during deep drawing.

Regarding the fact that the client's demands on the resulting mechanical properties can vary a lot, it is impossible to establish a general heat treatment cycle that would be the best suitable to fulfill customer demands. ISL can also attain better quality and mechanical properties of its products by increasing soaking and cooling time during annealing.

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