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Determination of Condition of Recrystallised Grains After Annealing of Cold Rolled IF Grade Steel Sheets Based on Ultrasonic Measurements

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Abstract

The Interstitial Free (IF) grade steel sheets are used for auto body applications where these sheets require good formability/drawability property. To achieve this property the cold rolled sheets are annealed to obtain desirable texture in the recrystallised grains to avoid material failure during forming operation. The paper deals with an ultrasonic technique to determine the condition of the recrystallised grains after annealing operation. 79 % cold rolled IF grade steel sheets were annealed at 650 deg. C for different times. After annealing the scale was completely eliminated from the surface by pickling to make the surface conducive for transmission of ultrasonic surface waves. Ultrasonic transit time for a fixed distance in μs was measured in rolling as well as 45^0 to rolling direction using 4 MHz transmitting and receiving transducers. Unrecrystallised, partially recrystallised and fully recrystallised regions in this case were determined by measuring hardness in Rockwell B scale. In fully recrystallised grains the above transit time difference was found to be more than 2.20 μs in partially recrystallised grains it was within 1.52-2.20 whereas that for unrecrystallised grains, it was less than 1.52 μs.

Based on these experimental results, the condition of cold rolled and annealed sheets can be obtained which will help in optimising the annealing cycle for obtaining correct grain structure.

Keywords: *Cold rolling*, *Annealing, Ultrasonic surface waves, Formability*

1. Introduction

It is a great concern for the auto makers that the auto body made during the forming operation of the cold rolled and annealed auto grade steel sheets does not have defects like excess wrinkling, puckering, ear formation, local thinning or actual rupture. In extreme cases when the individual pieces are scrapped, a more serious consequence will be the down time required to correct the manufacturing process. To take care of these material problems it is necessary to obtain a desirable texture during annealing of the cold rolled steel sheets. The annealing cycle need to be optimized to develop maximum (111) and minimum (100) crystallographic planes in the rolling direction of the sheets. Ultrasonic parameters like attenuation and particularly velocity are affected by the density of such crystallographic planes in different directions in the cold rolled and annealed sheets. Mechanical properties like young's modulus of elasticity and elastic constants are depended on density of such crystallography planes, distributed in different directions and also on the ultrasonic velocity in the sheet material. When the cold rolled steel sheets are annealed, the stresses from the deformed grains are released and new grains with different crystallographic orientation are formed during recrystallisation, causing change in the ultrasonic parameters like attenuation and particularly velocity.

Moro et al [1] observed the variation in ultrasonic velocities in cold worked austenitic stainless steel tempered at different temperatures. A correlation could be found between the variation in ultrasonic velocity with tempering temperatures and degree of cold working. Pandey et al [2] reported the ultrasonic attenuation measurement results in high silicon steel sheets annealed at different temperatures. A sharp drop in the attenuation value was observed when the samples were annealed at the recrystallization temperature. Pandey et al [3] reported application of ultrasonic attenuation and velocity techniques for sorting abnormal microstructures in steel and cast iron. The authors [4] developed empirical equations between attenuation and mean grain size in hot rolled steel plates and quantified the behaviour of microalloyed precipitates containing Nb, Ti and V from the ultrasonic absorption term. Effect of heat treatment cycles in steel and aluminium alloys were studied by Murav'ev [5, 6]. Generazio [7] used attenuation measurement to study the microstructural changes during heat treatment in nickel and copper alloys and could determine the degree and completion of recrystallization. Palanichami et al [8] reported the use of longitudinal and shear wave velocity measurements for average grain size measurement in austenitic stainless steel. The use of ultrasonic longitudinal wave velocity measurements for studying the annealing behaviour of 20 % cold worked austenitic steel alloy D9 was reported by Vasudevan et al [9]. In order to study the annealing behaviour of 20 % cold worked samples of alloy D9 (Ti-modified austenitic stainless steel) Palanichami et al [10] used the ultrasonic longitudinal as well as polarized shear waves. The trend of transverse waves with annealing time during recrystallization was found opposite to that of longitudinal waves. The change in velocity of polarized shear waves in two right angle directions with change in annealing time could be well correlated using a polynomial equation with high accuracy.

2. Experiment

2.1 Details of the Digital Ultrasonic Equipment & Surface Wave Probe

Make & Model: Digital Ultrasonic Flaw detector EPOCH-4 with Wave Analysis Software, Panametrics, USA.

Probe: 4 MHz, 8 x 9 mm, 90° angle (Surface Wave)

Technique: Through transmission using two probes fixed in a perspex sheet at a fixed distance. Time of flight was measured from the RF signals using Wave Analysis Software

Couplant: Machine oil

2.2 Details of the experimental material

The hot rolled coils were given 79% thickness reduction during cold rolling to achieve the final thickness of 0.80 mm. The chemical composition of the IF grade steel has been shown in Table 1. The samples of size 200X200X0.8 mm were cut from the mid width of the coil for experimental study. The test samples were annealed at 650^0 C and soaked for different times in a salt bath furnace. After annealing these samples were pickled in acid to remove the oxide scales from the surface.

Table 1: Chemical compositions of IF grade steel sheet

%C	0.0028	**%Si**	0.008
%Mn	0.07	**%Al**	0.037
%P	0.008	**N ppm**	30
%S	0.009	**%Ti**	0.07

2.3 Experimental Measurements

Using Digital Ultrasonic Flaw Detector EPOCH-4, the transit times of the surface wave to travel between the transmitter and receiver T0 and T45 were measured within the accuracy of 1 ns along 0^0 and 45^0 from the rolling direction. The ultrasonic test results have been shown in Table 2.

Table 2: Details of the ultrasonic test results T0-T45, annealing time't' at 650^0 C, and hardness measured in Rockwell B

Sample No.	T0-T45,µs	t, sec	Hardness, HRB
1	1.44	15	87
2	1.36	30	86
3	1.52	60	84
4	2.2	180	36
5	2.32	300	33
6	2.24	420	30
7	2.36	540	29
8	1.96	660	28
9	2.04	780	28
10	2.24	900	28
11	2.36	1020	27

Table 3: Details of the plastic strain ratios r0, r45, r90 and r-Bar in cold rolled and annealed samples

Sample No.	r0	r45	r90	r-Bar
1	0.27	0.82	0.32	0.56
2	0.21	0.43	0.42	0.37
3	0.22	0.82	0.32	0.55
4	1.34	0.56	0.54	0.75
5	2.08	2.03	0.58	1.68
6	2.4	2.14	0.5	1.80
7	2.32	2.34	0.57	1.89
8	2.4	2.14	0.5	1.80
9	2.21	2.46	1.87	2.25
10	2.35	2.14	0.6	1.81
11	1.99	1.95	3.03	2.23

From the ultrasonically tested samples, test pieces along 0^0, 45^0 and 90^0 from the rolling direction were cut for tensile testing to measure formability/plastic strain ratio r0, r45, r90 and r-Bar as per ASTM test method E 517-00. The tensile test results have been shown in Table 2. Table 2 also shows the hardness values measured in scale HRB on these test samples. Different combination of the graph plots from these test results have been shown in Figures 1-7.

3. Results and Discussion

3.1 Observations

3.1.1 Hardness

The variation in hardness of the annealed samples with annealing time has been shown in Fig.1. The trend of the curve in the graph plot clearly indicates three different zones. In zone I, there is no much variation in the hardness and it appears, there is no significant change in the grain structure and orientation. This zone may be considered as stress releasing zone.

There is a sudden drop in hardness in zone II due to formation of new stress free grains with different grain orientations. In zone III, there is slow hardness drop indicating achievement of maximum recrystallised grains with different orientations.

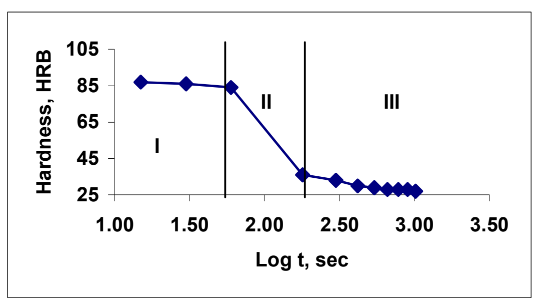

Fig. 1: Hardness plot of the test samples for different logarithmic soaking time scale at 650^0 C in a salt bath indicating (a) Zone-I Unrecrystallised (b) Zone-II Partially recrystallised and (c) Zone-III Fully recrystallised

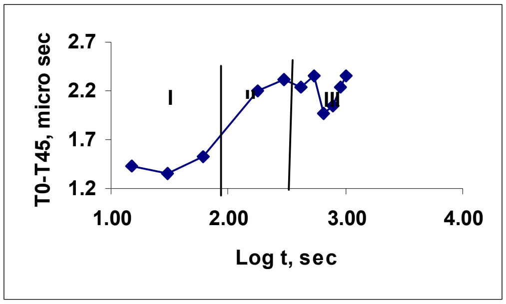

Fig. 2: T0-T45 plot of the test samples for different logarithmic soaking time scale at 650^0 C in a salt bath indicating (a) Zone-I Unrecrystallised (b) Zone-II Partially recrystallised and (c) Zone-II Fully recrystallised

3.1.2 Ultrasonic results

The difference in ultrasonic speed in rolling direction and at an angle 45^0 to rolling direction **is** indicated by T0-T45 and its variation with the annealing time has been plotted in Fig.2. The curve in the plot indicates three zones similar to those shown in Fig.1. In zone I, there is less variation in T0-T45 indicating less variation in the materials elastic properties due to less change in the grain structure and crystal orientations. This zone can be considered as stress releasing zone as shown in Fig.1. In zone II there is a sudden increase in the value of T0-T45 indicating rapid change in the grain structure (replacement of elongated deformed grains by new recrystallised grains with preferred orientations). In a BCC structure of steel like IF steel, during annealing, the density of (111) crystallographic planes in rolling direction is maximized and those of (110) and (100) planes minimized. The distribution densities of these crystallographic planes in different direction makes different values of T0-T45. The rapid change in zone II is a measure of rapid disappearance of cold deformed elongated grains and formation of more (111) and less (110) and (100) crystallographic planes in the rolling direction. In zone III, the variation in T0-T45 is a measure of change in the distribution of these crystallographic planes in rolling direction and in a direction 45^0 to the rolling direction.

3.1.3 Tensile test results

The variations of plastic strain ratios r0 in the rolling direction, r45, 45^0 to rolling direction and r90, 90^0 to rolling direction and r-Bar with the variation in annealing time have been plotted in Figs. 3-6. As shown in Fig.3, if we divide the plotted curve in three zones as mentioned earlier based on the annealing time, in the beginning of zone III, still increase in the value of r0 was observed, indicating continuation of formation of favourable crystallographic planes in the rolling direction. The graph plot between r45 and Log t as shown in Fig.4 indicates rapid formation of favourable crystallographic planes in the beginning of zone III and not in the zone II. However such events were observed at the end of zone III for plastic strain ratio r90 as shown in Fig.5, The average strain ratio, r-Bar also indicated sluggish change in zone II and rapid change in the beginning of zone III as shown in Fig.6. An attempt to correlate r-Bar with T0-T45 as shown in Fig.7 indicated many deviations of points in zone II.

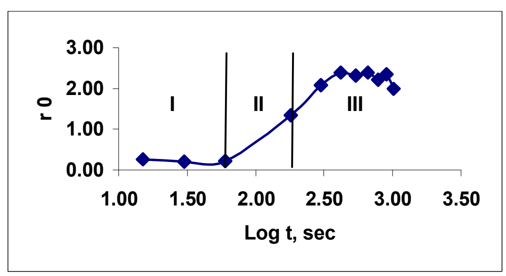

Fig. 3: r0 plot of the test samples for different logarithmic soaking time scale at 650^0 C in a salt bath indicating (a) Zone-I Unrecrystallised (b) Zone-II Partially recrystallised and (c) Zone-II Fully recrystallised

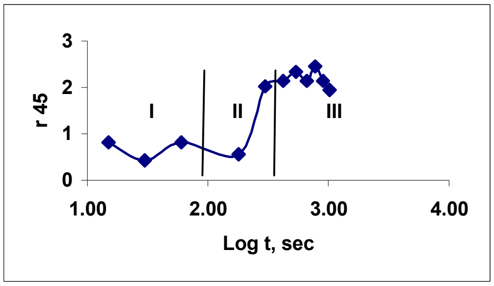

Fig. 4: r45 plot of the test samples for different logarithmic soaking time scale at 650^0 C in a salt bath indicating (a) Zone-I Unrecrystallised (b) Zone-II Partially recrystallised and (c) Zone-II Fully recrystallised

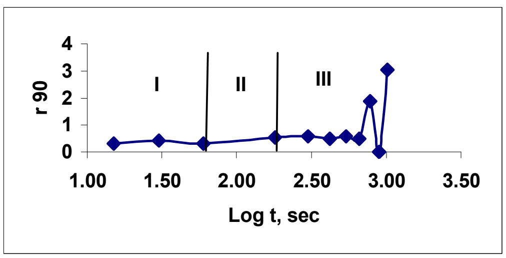

Fig. 5: r90 plot of the test samples for different logarithmic soaking time scale at 650^0 C in a salt bath indicating (a) Zone-I Unrecrystallised (b) Zone-II Partially recrystallised and (c) Zone-II Fully recrystallised

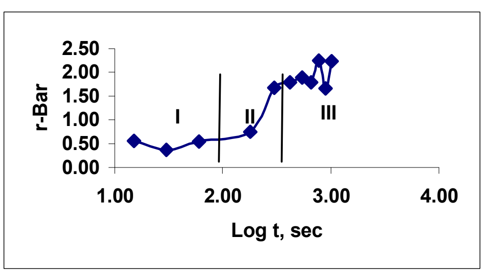

Fig. 6: r-Bar plot of the test samples for different logarithmic soaking time scale at 650^0 C in a salt bath indicating (a) Zone-I Unrecrystallised (b) Zone-II Partially recrystallised and (c) Zone-II fully recrystallised

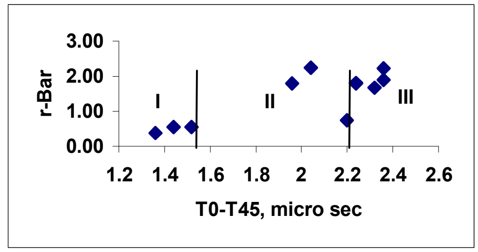

Fig. 7: r-Bar plot of the test samples for different values of T0-T45 indicating (a) Zone-I Unrecrystallised (b) Zone-II Partially recrystallised and (c) Zone-III Fully recrystallised

4. Conclusion

The main findings of the work can be concluded as given below:

1. The difference in travel times or speeds of ultrasonic surface waves in the rolling as well as 45^0 to rolling direction is quite sensitive to the annealing behaviour of IF grade cold rolled steel sheets.

2. The unrecrystallised, partially recrystallised and fully recrystallised zones during annealing as defined in conventional manner from the hardness measurements can also be defined in nondestructive manner from the ultrasonic transit measurements T0-T45. The experimental results revealed in fully recrystallised grains the above transit time difference more than 2.20 μs, in partially recrystallised grains it was within 1.52-2.20 whereas that for unrecrystallised grains, it was less than 1.52 μs.

3. The formability of the cold rolled and annealed steel sheets measured in terms of plastic strain ratios r0, r45, r90 and r-Bar were found to behave differently in these three zones. These properties were found to improve significantly in the latter parts of the annealing time.

4. An attempt to correlate r-Bar with T0-T45 revealed many deviations in points

in partially recrystallised zone II. This needs further work to look into the grain morphology and kind of grain orientations.

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6. References

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