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Effect of Thermomechanical Treatment on the Microstructure and Mechanical Properties of an IF Steel

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This study focused on thermomechanical treatment of an interstitial-free (IF) steel. As-received IF steel underwent cold reduction of 80% followed by subcritical annealing at 680 °C for 10, 20, 30, and 40 min. These cold-worked and annealed samples were characterized using optical microscopy and scanning electron microscopy (SEM). Mechanical properties such as hardness and tensile strength were determined. Fracture surface was studied using SEM. On the basis of resulting mechanical properties and fractographic study, it was concluded that employing annealing time between 20 and 30 min at 680 °C imparts the desired combination of strength and ductility required for deep-drawing applications in automotive industry.

Keywords IF steel, SEM, tensile properties, thermomechanical treatment

1. Introduction

Interstitial-free (IF) steel was first introduced in Japan in the 70s. IF steel is widely known as affordable high-quality steel for deep-drawing applications, especially in automotive bodies. IF steels contain very small amount of interstitials such as carbon (20 to 50 ppm) and nitrogen (10 to 50 ppm) (Ref 1). This composition results in an extraordinary formability. Unlike low-carbon steels, IF steels do not show yield point phenomena during plastic deformation. This helps in avoiding stretcher strains (Luder bands) that can mar the surface finish of automobile body panels. IF steel has a high $\overline{R}$ (plastic strain ratio) value in excess of 2 and also has a good n value (work hardening exponent) essential for excellent formability (Ref 2, 3). These properties result because of a combination of low C and N contents and micro additions of titanium or niobium, which form various compounds like TiN, TiS, $Ti_4C_2S_2$, TiC, and NbC (Ref 4-6). The microstructure of IF steel consists of ductile ferrite grains along with precipitates of carbides and nitrides. These features further impart nonaging characteristics that help retain the ductility.

IF steels are usually manufactured in hot-rolled condition with thickness down to 3 to 4 mm. However, automobile industry needs sheets thinner than 1 mm, possessing excellent ductility (40 to 55%), good formability ($R > 2$), and smooth surface finish (absence of yield point phenomenon). These requirements necessitate subsequent cold-rolling operations. During cold rolling, the surface finish improves, strength and hardness increase but the ductility is drastically reduced to as low as 6% elongation (Ref 7). This affects the formability of IF steel sheets adversely. A combination of cold rolling followed by subcritical annealing helps in obtaining high ductility and formability together with good strength (Ref 2, 8). For automotive applications, typical range of desired values for yield strength, ultimate tensile strength (UTS), and % total elongation of IF steels are 140 to 180 MPa, 290 to 349 MPa, and 40 to 55%, respectively (Ref 1). Therefore, optimization of thermomechanical processing parameters is required to enhance the ductility at the same time maintaining adequate strength in the range suggested above. However, there is a lack of systematic study on cold working of IF steel followed by subcritical annealing to obtain above stated range of mechanical properties. In view of this, in this work, cold rolling of IF steel followed by subcritical annealing for varying duration has been performed. On the basis of resulting mechanical properties, optimum subcritical annealing parameters are recommended for a given amount of cold reduction.

2. Experimental Details

IF steel employed in this study has chemical composition as shown in Table 1. The as-received steel was in hot-rolled condition and its thickness was 4.28 mm. The as-received steel underwent cold reductions of 80% (CR) in steps in a laboratory 2-high rolling mill. After cold rolling, the steel samples were heated in a muffle furnace to 680 °C for 10, 20, 30, and 40 min. These samples were designated as CR10, CR20, CR30, and CR40, respectively. Following this, the furnace was switched off and allowed to cool naturally to room temperature. The approximate cooling rate was 7 °C/min. After subcritical annealing, the samples were cleaned using 200 and 400 grit size emery papers.

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Table 1 Chemical composition of the IF steel, wt.%

C	Mn	Al	N	Ti	Nb	S	P	Si	Fe
0.003	0.10	0.041	0.003	0.062	0.010	0.009	0.011	0.012	99.69

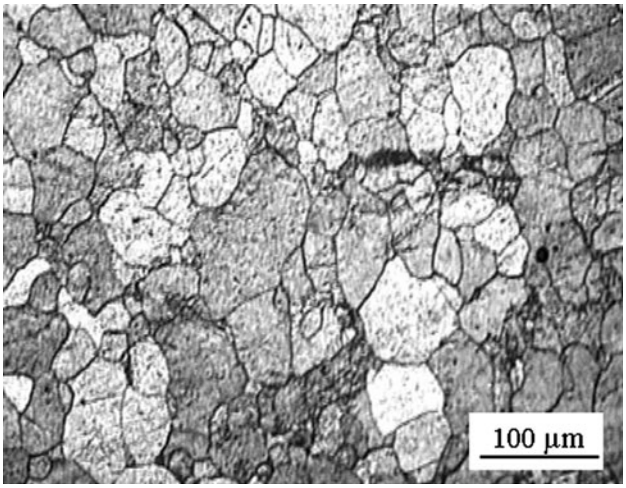

Fig. 1 Optical micrograph of as-received IF steel in hot-rolled condition (etchant 2% Nital)

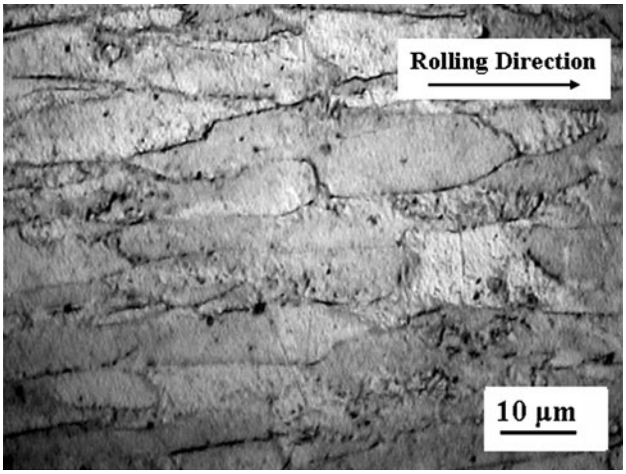

Fig. 2 Optical micrograph of CR IF steel (etchant 2% Nital)

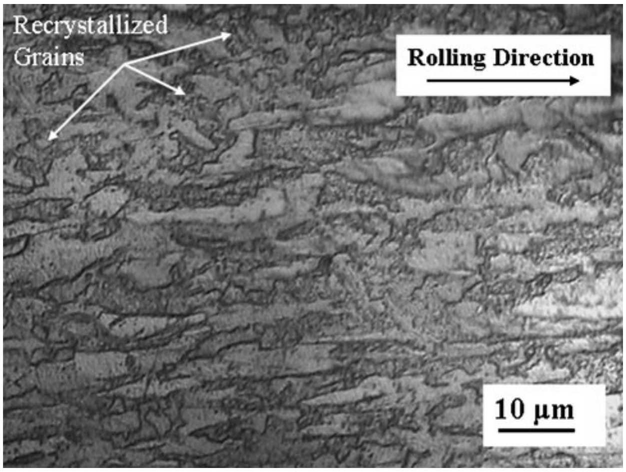

Fig. 3 The optical micrograph of CR20 IF steel (etchant 2% Nital)

Optical microscopy examination was conducted with a Carl Zeiss-Axiovert inverted microscope. The 10 mm × 10 mm samples for microscopy were cut from the sheets using a diamond saw. These were mounted in plastic and mechanically polished using 600 grit SiC papers followed by polishing on 1/0, 2/0, 3/0, and 4/0 grade emery papers. The samples were rotated through 90° after polishing on each paper. Final polishing was performed on velvet cloth using levigated alumina suspension in distilled water. The samples were etched using a 2% Nital solution. Scanning electron microscopy (FESEM, FEI QUANTA 220F) was also performed. The precipitates in the microstructures were identified using energy dispersive spectroscopy (EDS). After optical microscopy, the specimens were used for measuring hardness. Vickers hardness number (VHN) was determined by Vickers hardness tester (Model VM-50 PC) using 10 kg load. At least five readings were taken on each sample. For the tensile tests, the samples were prepared according to the ASTM standard (ASTM: E8M-04). The gage length used was 25 mm. Tensile tests were performed on a Hounsfield H25 tensometer using a crosshead speed of 1 mm/min. The fracture surfaces of the broken tensile samples were studied using SEM.

3. Results

3.1 Microstructure Evaluation

The optical micrograph of as-received hot-rolled strip of IF steel is shown in Fig. 1. The average grain size of hot-rolled strips is 33 μm. The microstructure consists of equiaxed ferrite grains along with precipitates. The optical micrograph of CR IF steel specimen is shown in Fig. 2. The deformed and elongated grains of average grain size 19 μm are oriented in the direction of rolling which is clearly visible. The optical micrograph of CR20 IF steel is shown in Fig. 3. The microstructure shows a mixture of elongated grains and finer recrystallized grains of ferrite. The elongated grains are still oriented in the rolling direction.

The properties of IF steel are also dependent on the types of precipitates that are present in these steels. It has been reported that there is an interrelationship between these precipitates and deep drawability of IF steels (Ref 5). Figure 4 and 5 shows the two types of precipitates observed in IF steel and their corresponding EDS spectrum. TiN precipitates are found to be most frequent in the IF steel irrespective of the processing parameters. TiN precipitates are quite bigger in size (1 to 2 μm) and these were easily identified in FESEM. Similar findings are reported in literature (Ref 5, 6). Very often, aluminum oxide particles are also observed in these steels (Ref 5) and they are also observed in this study.

3.2 Mechanical Properties

The stress-elongation curves for CR and CR plus annealed samples are shown in Fig. 6(a) to (e). No yield point phenomenon is observed in all the steel samples, which is a typical characteristic of IF steel (Ref 9). The tensile properties of CR and CR plus annealed samples are summarized in

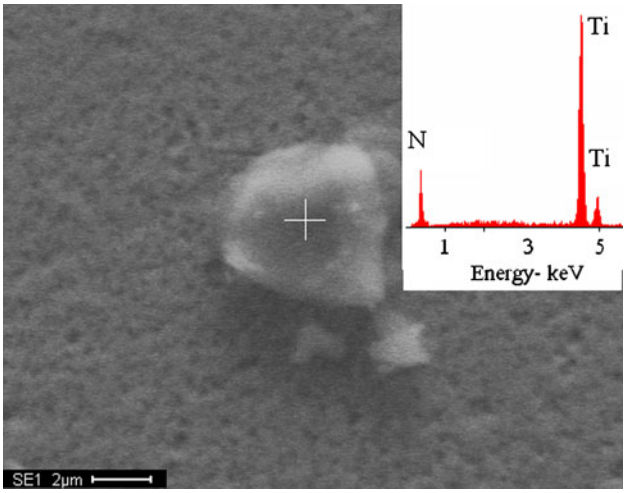

Fig. 4 SEM micrograph showing presence of TiN precipitate and its corresponding EDS spectrum in inset

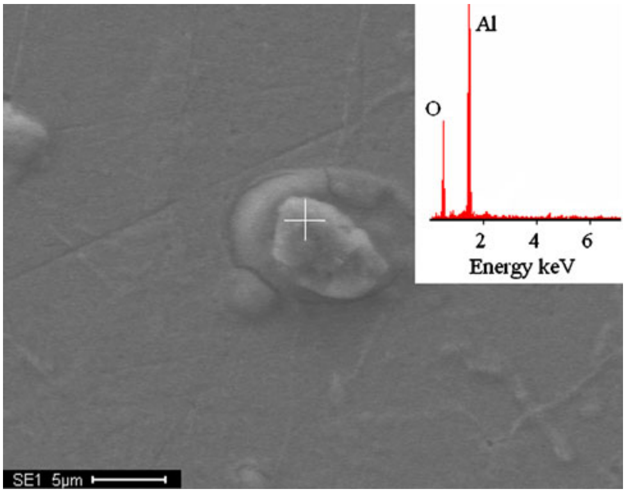

Fig. 5 SEM micrograph showing presence of Al oxide precipitate and its corresponding EDS spectrum in inset

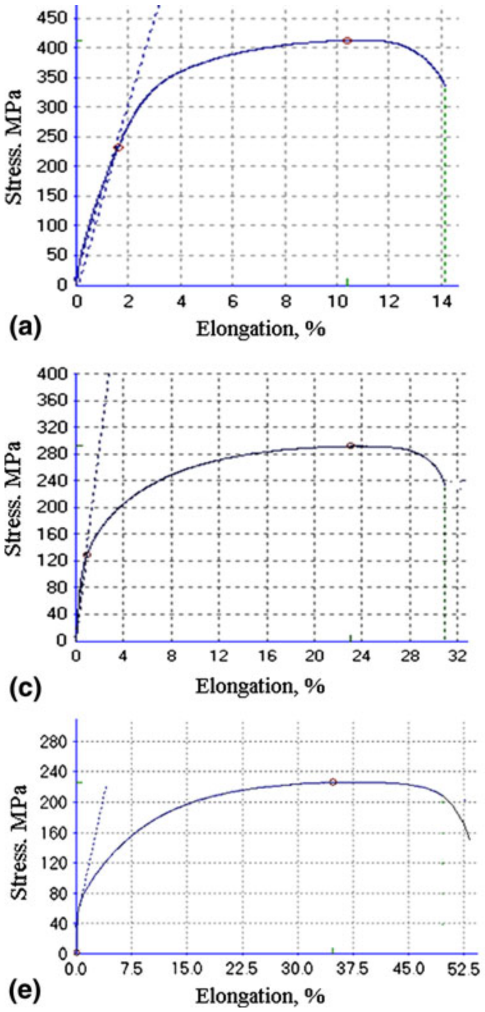

Fig. 6 Stress-strain curves for IF steel specimens: as-received hot-rolled CR (a), CR10 (b), CR20 (c), CR30 (d), and CR40 (e)

Table 2. It is observed that with increase in annealing time, strength and hardness decrease while the elongation increases. The decrease in UTS and hardness is rapid up to 20 min of annealing time, beyond which it decreases rather gradually. Elongation increases rapidly up to 20 min of annealing time and thereafter increases gradually.

3.3 Fractographic Study

Fracture surfaces of broken tensile test specimens were investigated using SEM. The fractographs are shown in Fig. 7(a) to (d). The fracture surface of CR specimen shows cleavage appearance with river markings typical of a brittle fracture (Fig. 7a). The fractograph of CR10 specimen exhibits mixed mode fracture features (Fig. 7b). It shows both dimples and cleavages. Brittle fracture features disappeared from the fractographs of CR20 and CR30 specimens (Fig. 7c, d). Complete dimpled appearance typical of ductile fracture is observed in CR30 specimen.

Table 2 Mechanical properties of cold-rolled and annealed IF steel

Sample designation	UTS, MPa	Elongation, %	Hardness, VHN
CR	590	7.10	186
CR10	415	15	145
CR20	302	31	95
CR30	278	46	86
CR40	226	54	81

4. Discussion

For deep-drawn automobile body panels, typical range of values required for UTS and % total elongation in IF steels are 290 to 349 MPa and 40 to 55%, respectively (Ref 1). In this work, 80% cold reduction of hot-rolled IF steel (CR) resulted in elongated grains in the direction of rolling (Fig. 2) and total elongation fell to 7.1%. Such cold-rolled sheets possessing lower ductility make deep drawing difficult. Therefore, optimization of thermomechanical processing parameters is required to obtain the desired combination of strength and ductility in sheets for such application. To improve the ductility, these CR sheets underwent subcritical annealing treatment (680 °C) for various durations. Annealing of cold-worked metal is expected to result in recovery, recrystallization, and grain growth phenomena (Ref 10). This should result in improvement of ductility by eliminating the effects of work hardening caused by cold rolling.

Tensile tests performed on all different cold-worked and annealed samples did not exhibit yield point phenomena. A yield point phenomenon is undesirable as it causes formation of Luders bands which mars the surface finish of sheets (Ref 10). Yield point phenomenon is seen only when ferrite contains dissolved interstitial C and N atoms. In the subcritical annealing

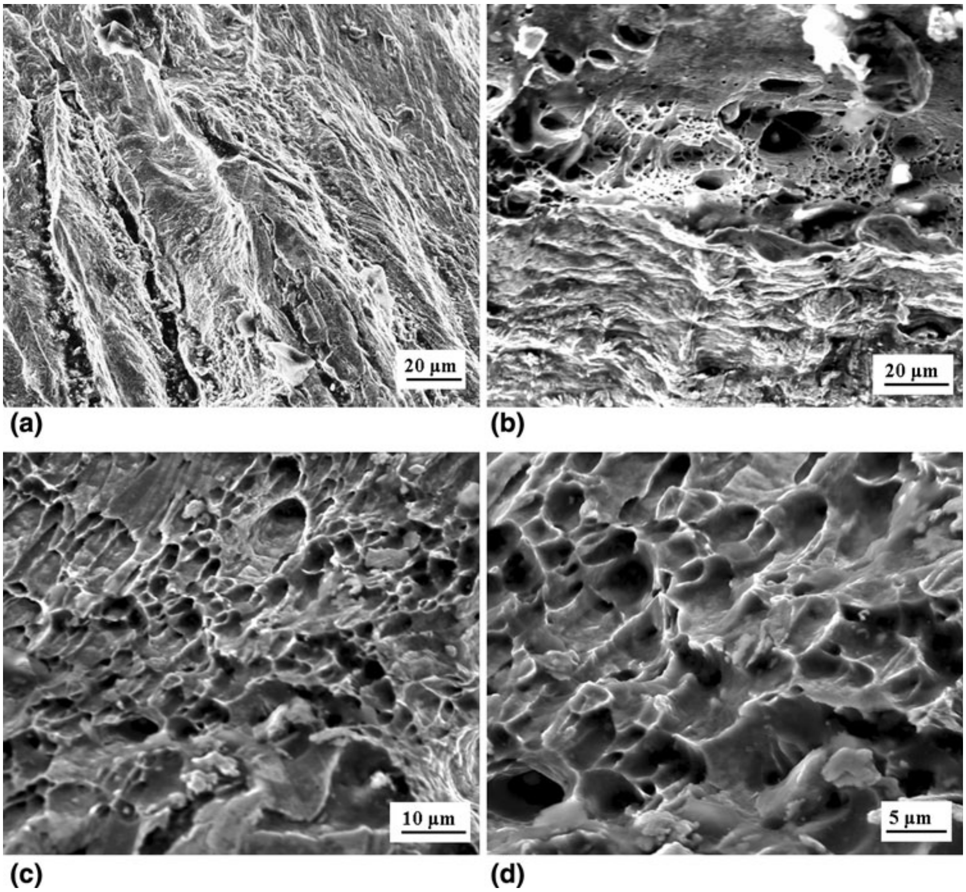

Fig. 7 SEM fractographs of fracture surfaces of tensile specimens: (a) CR, (b) CR10, (c) CR20, and (d) CR30

approach, the dissolution of precipitates is not expected as the heating is done below A_1 (723 °C) temperature. Precipitates such as TiN and Al_2O_3 were inferred from the EDS analysis as shown by the peaks corresponding to Ti, N, Al, and O (Fig. 4, 5). The carbides, if any, were not traceable probably due to low x-ray energy values for C (0.284 keV). The presence of precipitates ensured the removal of interstitial C and N atoms that are responsible for the yield point phenomena observed in steels during plastic deformation.

Table 2 summarizes the tensile properties of differently processed IF steel samples. With increase in subcritical annealing time, the strength initially drops rapidly up to 20 min by about 50% and then slowly between 20 and 30 min by 8%. The hardness values follow a similar trend with VHN values dropping by about 50 and 10%, respectively. With the increase in annealing time, it is observed that the fraction of elongated deformed grains decreased with concomitant increase in fraction of relatively finer grains of ferrite (Fig. 3). Therefore, the drop in strength and hardness values may be attributed to the partial replacement of cold-worked grains by recrystallized grains. This is typical of a cold-worked metal that is annealed.

The total % elongation values increased rapidly from 7.1 to 31% in 20 min of annealing. Thereafter, it rose up to 46 and 54% in 30 and 40 min, respectively. The deep drawing of IF steel requires elongation values in excess of 40%. This study shows that the desired strength and elongation can be obtained if the specimen is annealed for duration between 20 and 30 min at 680 °C (Table 2).

Fracture surfaces of broken tensile test specimens (Fig. 7a-d) were observed to investigate the mode of fracture. It is observed that with increase in the annealing time, the mode of fracture changed. In CR specimen, the fracture surface has predominantly brittle features. The fracture surface of CR10 sample shows dimples as well as cleavage features. However, CR20 and CR30 specimens exhibit disappearance of brittle fracture features. Complete dimpled appearance typical of ductile fracture is observed in CR30 sample. This is consistent with high value of total % elongation obtained in CR20 and CR30 samples (31 to 46%). Thus, based on fractographic study too, it can be concluded that employing annealing time between 20 and 30 min at 680 °C imparts the desired combination of strength and ductility to the IF steel.

5. Conclusions

In this study, thermomechanical processing of IF steel has been performed using various process parameters. No yield point phenomenon has been observed in the stress-strain curve of thermomechanically processed IF steel samples, which is desired in manufacture of automobile body panel. The presence of TiN and Al_2O_3 precipitates identified through SEM/EDS suggests effective removal of dissolved interstitials responsible for the yield point phenomenon.

CR samples exhibited predominantly brittle fracture features. CR10 and CR20 IF steels exhibited mixed mode of fracture. However, fully ductile fracture is observed in CR30 and CR40 samples. Beyond 30 min of annealing time, although the % elongation increased to 54%, the strength decreased to 226 MPa, unacceptable for automotive applications. It can be concluded that the CR30 showed a combination of strength (278 MPa) and high ductility (46%) that is close to the typical range of values required for UTS (290 to 349 MPa) and % elongation (40 to 55%) in IF steels, respectively. Thus, based on the present investigation, the optimum thermomechanical processing parameters for automobile body panels are 80% cold reduction followed by subcritical annealing at 680 °C for duration between 20 and 30 min.

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