STRENGTH AND MICROSTRUCTURE OF COLD-ROLLED IF STEEL

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Abstract

With the emerge of vacuum technology, it is possible to produce ultra low carbon (ULC) steels with carbon content of less than 0.005 %mass which is called interstitial free (IF) steels. In this study, strength and microstructure of IF steel after cold-rolling have been determined. The initial steel plates were cold-rolled using two different cold reductions (CR) as 80 and 90% in total, thereafter the steel sheets were cut into specimens for tensile test and optical microscopy. Ultimate tensile strength (UTS) of the cold-rolled steel was high (650÷807 MPa), but the elongation (EL) was low (3.5÷5.3%). Meanwhile, UTS of the annealed steels was decreased to 290 MPa when soaking temperature was 800°C because of stress relief and recrystallization. It was concluded that higher CR (more severe deformation) increased the strength but decreased the ductility of the IF steels. In consistence with micrograph of the steels, X-ray diffraction (XRD) results showed that microstructure of the cold-rolled and annealed IF steels was only ferrite. Textures, one of the most important factors affecting the recrystallization, were found in cold-rolled steels.

Keywords: Cold reduction, Cold-rolling, IF steel, Residual stress, Texture

1 Introduction

The demands for the steel with excellence formability from automotive industry have accelerated the progress in the steelmaking process, leading to the development of the ultra low carbon (ULC) steels containing carbon less than 0.01 %mass [1, 2]. With the emerge of vacuum technology, it is possible to produce ULC steels with carbon content of less than 0.005 %mass which is called interstitial free (IF) steels [3-6]. It is well known that the interstitial elements such as carbon (C) and nitrogen (N) in the steel are lower owing to vacuum treatment, thereafter one of the most important properties of ULC steel (formability) is improved to apply for automotive body.

In general, two important objectives being pursued by the automobile industry are a decrease in car weight and improvements in safety [7]. To realize these requirements, several researches have been implemented to reduce thickness of the steel sheet, increase strength and improve press formability of the steel. For example, J. Galan *et al.* studied on improving strength and dent resistant capacities with bake hardenable ULC steels in order to fulfill the requirements of thinner sheet steel for automotive applications [2]. M. Wang *et al.* analyzed the source and disadvantages of macro-inclusions in titanium stabilized ULC steel and reported that the total

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oxygen in the steel strongly influences the surface quality of auto grade steel, particularly by generating sliver defects in ULC steel [8]. W. C. Doo *et al.* investigated inclusions in ULC steel melts consist mainly of Al oxides and multi-component oxide during an RH deoxidation treatment and confirmed that if these inclusions are not removed properly, they can deteriorate the properties of the final products [9]. In other application, R. Chukla *et al.* made an effort to develop a novel ULC steel with superior low temperature toughness, good weldability, high resistance to fatigue, *etc*., which are suitable for pipeline application by grain boundary engineering through thermo-mechanical controlled process (TMCP) [10].

As depicted in **Fig. 1**, thickness of conticaster semi-slab 50-60 mm is represented product from mini-mills applied compact strip production (CSP) technology. Thereafter, hot-rolling is conducted before cold-rolling is used to produce IF steel sheets for press forming. This brings some disadvantages for production, namely, low productivity, higher energy consumption, longer processing line, etc. Thus, it would be better if hot-rolling step could be eliminated but properties of IF steels still fulfill the requirement of application. Differing from other published literatures, this research has focused on strengths and microstructure of IF steel sheets which were directly cold-rolled from as-casted steel plates. The object of the investigation is to understand the effect of cold-rolling and annealing temperature on the microstructure and their influences on the mechanical properties of the steel sheets.

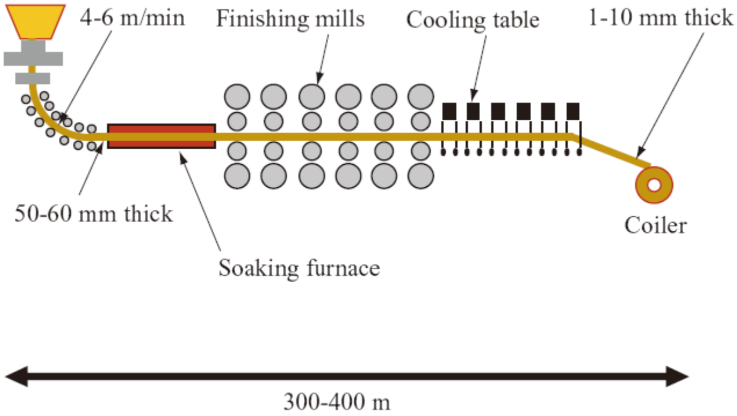

Fig. 1 Schematic diagram of thin slab caster [11]

2 Experimental

IF steels were melted from a mixture of high purity manganese (Mn), silicon (Si) and electrolyzed iron (Fe) in a vacuum arc furnace. Chemical compositions of the steels used in this study are given in **Table 1**, where oxygen and nitrogen were determined using O-N analyzer (Leco TC 300). Since both the steels were prepared in the same condition and the M1 was in focus, content of O and N in the M2 was not analysis and can be supposed that their content is approximately equal. Compositions of the IF steels were designed according to industrial steel grades (JIS G0555). Content of Si and Mn was varied to study effect of those elements on strength of the steels. The steels were casted in round plates (ϕ40×10 mm), then directly cold-rolled to sheets with several passes. Cold reduction is derived from equation (1). They were calculated as 80 and 90 % with correspondence with two different thicknesses of the final cold-rolled sheets.

$$CR = \frac{t_0 - t_f}{t_0} \times 100\% \tag{1.}$$

Here, t_0 and t_f are thickness of initial plates and final sheets, respectively.

Table 1 Chemical compositions of the IF steels (% mass)

IF steel	C	Si	Mn	P	S	O	N
M1	0.004	0.214	0.444	0.003	0.002	0.0168	0.0080
M2	0.005	0.130	0.292	0.004	0.002	–	–

Cold-rolled sheets were annealed at selected temperature, as illustrated in **Fig. 2**. Standard specimens (ASTM A370) of the cold-rolled and annealed steels were cut longitudinally the rolling direction and subjected to tensile testing using a MTS 809.10A machine. **Fig. 3** shows shape and dimensions of a specimen for tensile test. Some steels specimens were grinded, polished, 2% nital-etched and observed using an optical microscope (Axiovert 25A). Grain size was measured by the linear intercept approach, in which a line was superimposed over the optical microstructure. The true line length was divided by the number of grains intercepted by the line. This gave the average length of the line within the intercepted grains. Average grain size of the IF steel was obtained from three measuring times. Crystallized structure of the steels was examined using X-ray diffraction (XRD, Bruker).

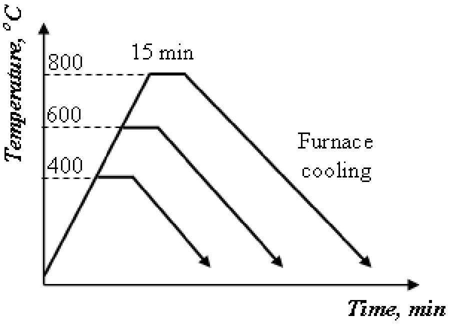

Fig. 2 Annealing scheme of the steel

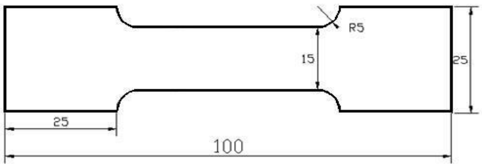

Fig. 3 Specimen for tensile test (in mm)

3 Results and Discussion

Fig. 4 shows stress – strain curves for the cold-rolled IF steels, of which the CRs were 80 and 90 %. It is acknowledged that cold-rolling saves energy and brings a good quality surface, high strength, but decreases ductility of the steel. Mechanical properties including ultimate tensile strength (UTS), yield strength (YS) and elongation (EL) of the present steels are given in **Table 2**. It is seen that the UTS and YS of the cold-rolled steels dramatically increased but attaching decrease in the ductility despite of that the steels contained a small amount of strengthening elements such as Si and Mn. These alloying elements, which are usually added to compensate for the softening effect of ultra low carbon content, contribute in the strengthening by solid solution hardening. Good strengths of the steels have been obtained, especially strengths of the cold-rolled steels were very high. Low content of [O] and [N] (less than 30 ppm each) is thought to have positive effect on mechanical properties of the steel because high nitrogen content may cause serious aging problem of the sheet [6, 12]. Since these IF steels were not deoxidized by aluminum or/and other elements, the oxygen content was rather high compared to industrial steel. High content of [N] (less than 80 ppm) as in conventional IF steel may high enough to contribute to the strength of the alloy, however, may harmful to the formability of the steels [5, 10]. To improve the formability, major attention has been focused on reducing the total amount of carbon and nitrogen during steel making and the removal of these interstitial elements from solid solution by the addition of stabilizing alloying additions [13].

Table 2 Mechanical properties of cold-rolled IF steels

IF steel	CR = 90 %			CR = 80 %		
	UTS (MPa)	YS (MPa)	EL (%)	UTS (MPa)	YS (MPa)	EL (%)
M1	750	500	4.0	700	500	4.3
M2	807	510	3.7	650	400	5.3

Influence of the CR on strengths of the steels is shown in **Fig. 5**, where the strength increased and ductility decreased as the CR was increased from 80 to 90%. Since the residual stress was not removed, the cold-rolled sheets were strengthened; and the UTS stayed in range of 650÷807 MPa, the EL was low as 3.7–5.3 %. At the same 80 % of the CR, strengths of the IF steel M1 were lower than those of the IF steel M2. In simplicity, this can be explained that lower content of Si and Mn in the IF steel M2 is the cause. As the CR was 90 %, however, the IF steel M2 shows higher strengths than the IF steel M1. Severe cold-rolling (CR = 90 %) was supposed to have a negative effect on strength of the steel M1 containing higher substitution elements (Mn and Si) compared to the steel M2. It is acknowledged that heavily deformation of the steel shows high UTS because two possible reasons are texture effect and intergranular stress [14, 15]. T. Suzuki remarked that a dimple fracture is common feature of metals and alloys subjected to severe deformation, resulting in a decrease of strength [14]. Therefore, this result can be roughly explained that more severe deformation of the harder grains in the steel M1 (comparison with the steel M2) may decrease the intergranular stress. It can be confirmed that mechanical properties of the IF steels is dependent on several factors as compositions, stress and deformed structure of the cold-rolled steels.

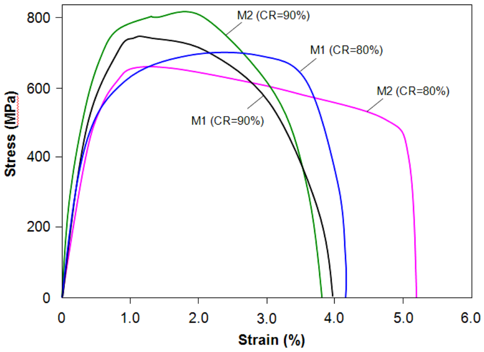

Fig. 4 Stress – strain curves of the IF rolled steels

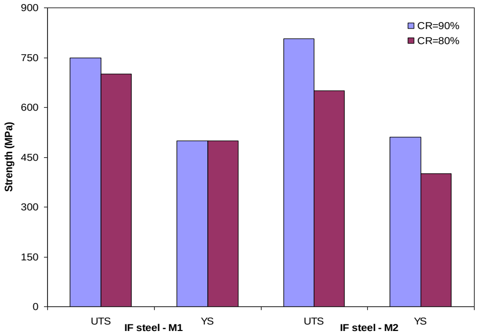

Fig. 5 Strengths of the cold-rolled steels

Although tensile ductility cannot be the criteria for the deep drawability of the steel, the total elongation should be the first evidence for evaluation. For example, the automotive application usually requires the IF steels to exhibit typically 200–280 MPa of YS and 30–47% of EL [4], K. Dehghani *et al*. concluded that the YS of the steels should be as low as possible to avoid the aforementioned defects in press forming [6]. However, some other IF grades of steel are being developed with UTS levels up 1000 MPa in combination with sufficient ductility for the high demands of structural automobile components [16]. As far as the IF steels are concerned, most research has been concerning on the formability improvement but keep high YS because this confers a high dent resistance for IF steel. Compromise between strength and ductility of the IF steel is essential to all producers. In this study, the cold-rolled sheets, which shown a high strength and low elongation, were annealed to investigate improvement of the ductility. The mechanical properties of the annealed IF steel (M1) at various temperatures (400, 600 and 800°C) are illustrated in **Fig. 6**. As the annealing temperature was 400°C, the EL slightly increased to 10% while the YS decreased to 480 MPa. When the temperature increased to 600 and 800°C, there was a drastically increase in the EL (48 and 50%, respectively) and a decrease in the YS (240 and 180 MPa, respectively).

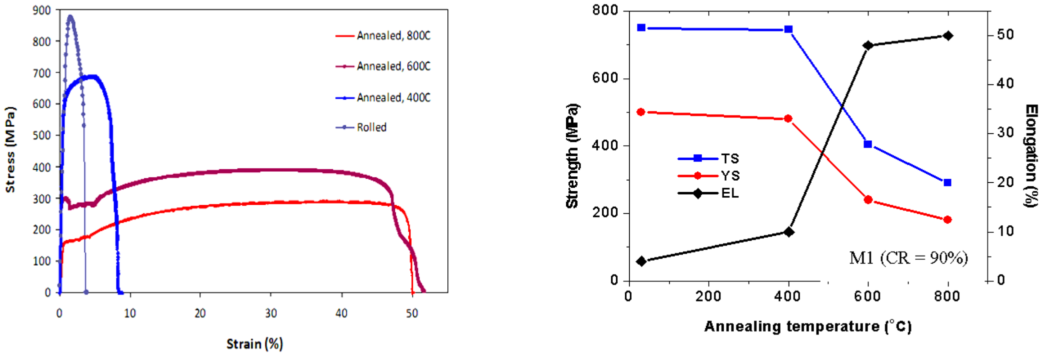

Fig. 6 Stress – strain curves (left) and mechanical properties of the annealed IF steels (right) – M1 and CR = 90 %

It is seen that an excellent combination of both the tensile properties and the ductility has been obtained after the steels annealed at 600°C. As similar to findings of Y. K. Lee *et al*., the ferrite grains were coarsened at higher annealing temperature, consequently decreasing the strength and increasing the ductility of the steel sheets [16]. The stress relief and recrystallization was considered to be occurred at these annealing temperatures. This can be asserted by observation of the steel microstructure during the annealing process. It is expected that the IF steels with excellent ductility could be applied for deep drawn parts while the IF steels with lower ductility could be apply for exposed panels with dent resistance. Although high ductility is usually associated with good quality during forming, the formability of the present steel sheets must be studied in the future.

Fig. 7 shows optical micrographs of the cold-rolled steels, in which microstructure is very homogeneous across the thickness and textures were found because the grains were deformed to lamina and elongated with the rolling direction. The effect of annealing temperature on the microstructure of the cold-rolled steels is shown in **Fig. 8**. During annealing treatment, various thermally activated processes may occur [17]. Naoki Yoshinaga *et al*. have carried out a study on effect of the deformed textures and microstructure on the subsequent recrystallization behavior of the IF steel, then remarks that the orientation distribution of the recrystallized grains forming at the early stages of the recrystallization dominated the final microstructure [18].

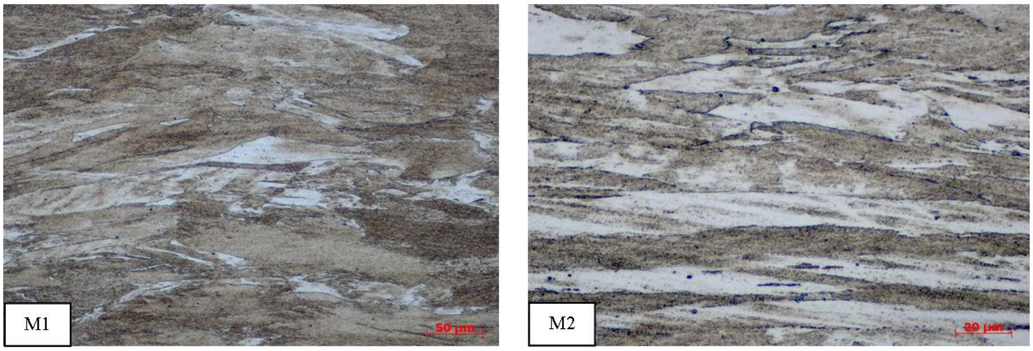

Fig. 7 Optical micrographs of the cold-rolled IF steels (CR = 90 %)

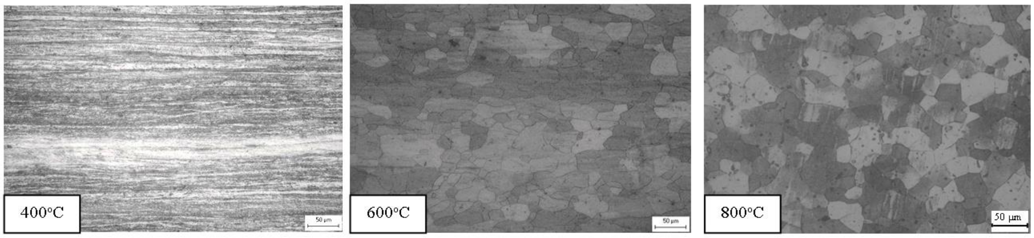

Fig. 8 Optical micrograph of the IF steel (M1, CR = 90 %)

It is noteworthy that one of the strengthening effects must be done by grain refinement controlled through annealing process, so the annealing parameters are considered as very important. This is completely consistent with the microstructure findings when the annealing temperature was 400, 600 and 800°C. It is clearly seen that the recrystallization did not occur at annealing temperature of 400°C, but did at 600 and 800°C. The morphology of recrystallized structures shows a significant difference at 600 and 800°C. At 600°C, it preserved the elongated shape of cold-rolled grains while the grains appear equiaxed in shape in the recrystallized structure at 800°C. In average, the ferrite grain size in the steels annealed at 600 and 800°C was approximately estimated as 30 and 50 µm, respectively. This is in agreement with that recrystallization not only releases much larger amounts of stored energy but new, larger grains are formed by the nucleation of stressed grains and the joining of several grains to form larger ones [17, 19]. Combination of mechanical properties and microstructure of the IF steels suggests that the textures or the recrystallized grains exist in the cold-rolled or the annealed IF steels, respectively. The steels with recrystallized microstructure had a high ductility and low strength, meanwhile the steels with textures had a low ductility and high strength. Concerning the dependence of yield stress on microstructural parameters, the Hall-Petch relationship is usually used [20]:

$$\sigma_y = \sigma_o + k_y d^{-0.5} \tag{2.}$$

Where σ_o is the internal stress, d the ferrite grain size and k_y a constant. On the other hand, the term σ_o includes the contribution from friction stress, solid solution effect, strengthening from precipitation and dislocation hardening. During annealing process, there are two occurred phenomena: removal of residual stress caused by cold deformation and recrystallization [19, 21]. Recrystallization did not occur when the cold-rolled IF steel annealed at 400°C, but the residual stress was removed; resulted in the strength was decreased. The strength variations after annealing at 600 and 800°C shown a good consistency with the microstructural evolution (i.e. grain size) and also indicated the effects of annealing temperature.

Several semi-empirical relationships have been published to quantify the strength of low carbon steels. The more generally accepted equations to quantify the lower yield stress are listed in **Table 3**, including the calculated values of both annealed steel M1. In these expressions, the contribution of substitutional solute elements (Mn, Si and P), interstitial solute element and grain size are included. The difference between calculated YS and real values shows that these equations can be used to estimate the yield strength which can be controlled through the following parameters as rolling condition, annealing temperature and chemical compositions of the steel.

Table 3 Real and calculated yield strength of the steel M1

Ann. Temp. (°C)	d (mm)	Equation	Ref.	YS_{Cal} (MPa)	YS_{Mean} (MPa)	YS_{Real} (MPa)
600	0.030	$YS = 88 + 37(\%Mn) + 83(\%Si) + 2918(\%N) + 15.1d^{-0.5}$	[22]	232	234	240
		$YS = 105 + 43.1(\%Mn) + 83(\%Si) + 1540(\%N) + 15.4d^{-0.5}$	[23]	243		
		$YS = 62.6 + 26.1(\%Mn) + 60.2(\%Si) + 759(\%P) + 212.9(\%Cu) + 3286(\%N) + 19.7d^{-0.5}$	[24]	229		
800	0.050	$YS = 88 + 37(\%Mn) + 83(\%Si) + 2918(\%N) + 15.1d^{-0.5}$	[22]	213	213	180
		$YS = 105 + 43.1(\%Mn) + 83(\%Si) + 1540(\%N) + 15.4d^{-0.5}$	[23]	223		
		$YS = 62.6 + 26.1(\%Mn) + 60.2(\%Si) + 759(\%P) + 212.9(\%Cu) + 3286(\%N) + 19.7d^{-0.5}$	[24]	204		

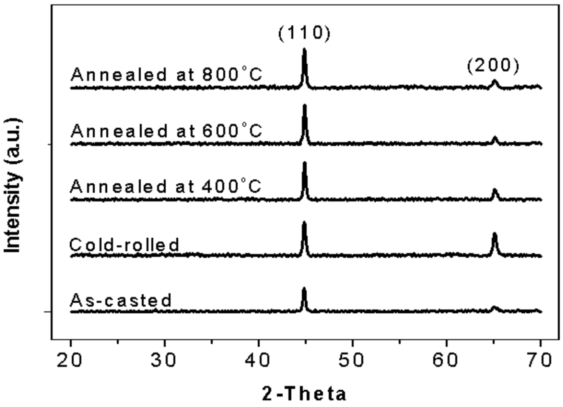

Fig. 9 XRD result of the IF steel (M1 and CR = 90 %)

As discussed above, phase structure of the IF steels must be only ferrite. **Fig. 9** shows the crystallized structure of the IF steel (M1) in the as-casted, cold-rolled and annealed conditions.

Only (110) and (200) ferrite structure were observed in microstructure of the steels. These results are in consistent with other findings on microstructure observation of steels, of which carbon content is lower than 0.005 %mass. However, mechanism of texture transformation and recrystallized orientation should be deeply studied for cold-rolled sheet steels.

4 Conclusions

Strength and microstructure of IF steel after cold-rolling with various cold reductions (80 and 90 %) have been studied by using tensile test and optical microscope. As-casted steel plates were directly cold-rolled to sheets, which were then annealed at selected temperature. The cold-rolled steels showed a high strength and low ductility although the carbon content was ultra low, meanwhile the annealed steels shown a low strength and high ductility. The UTS of the cold-rolled steel was in range of 650÷807 MPa, and the EL was about 3.7÷5.3 %. The cold-rolling step increased the strengths, but UTS of the annealed steels was decreased to 290 MPa at 800°C. After cold-rolling step, annealing treatment would be eliminated if the steels are not required high ductility but require high strength. Texture was found to be a along rolling direction in the cold-rolled steels. The results revealed that the ferrite phase, which is the most attractive phase for the application of these steels owing to excellent combination of strength and ductility, was the dominant in these steels despite of that they were in as-casted, cold-rolled or annealed conditions. Microstructure of the steels changed as the annealing temperature was increased up to 800°C. The textures changed to grains when the annealed temperature was above 600°C, which is thought to be higher than recrystallization temperature of these steels. Full recrystallization was observed in the steels which annealed at 800°C for 15 minutes. The effect of some factors on recrystallization and kinetics of this process for the fully-annealed steels will be presented in another paper. Annealing scheme can be selected based on the requirement of mechanical properties for a specific application of the IF steels.

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