Mechanical properties of 15%Mn steel with fine lamellar structure consisting of ferrite and austenite phases

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Abstract. New steel with fine lamellar structure consisting of austenite and ferrite was developed. 15mass%Mn-3%Al-3%Si steel sheet was used in this study. First of all, the effect of the cooling rate on the microstructure was examined. The cooling at the slower speed of 100 deg/hour created the dual phase structure consisting of both austenite and ferrite. The additional rolling developed the fine lamellar duplex structure. Improvement of both the tensile strength and elongation was achieved by rolling. The strength increases furthermore by the rolling up to larger reduction. The 90% rolled sheet shows high tensile strength around 1000MPa with large elongation (15%-20%). These results indicate that the multi-phased structure with controlled lamellar morphology is beneficial for the management of both high strength and large ductility.

1. Introduction
Austenitic steel is one of the advanced steels due to its extremely large ductility. For example, twinning induced plasticity (TWIP) steel with a large amount of manganese in addition to some aluminium and silicon (e.g. 25-30mass%Mn-3%Al-3%Si) was studied for the automotive application [1,2]. Previous study [1] has shown that TWIP steel exhibits high tensile strength with adequate elongation even at high strain rates, so that TWIP steel is desired to be applied for automotive use. However, the TWIP steel need expensive costs due to large amount of Mn. When the Mn content is reduced, the austenite becomes unstable and other phases such as ferrite and ε-martensite can appear. These phases are regarded as harder phases than austenite. Consequently, the combination of austenite and other phases is useful for the commercial production and even for strengthening. However, few studies have been conducted to clarify the process how the duplex structure in these steels can evolve. Consequently, the aim of this study is to clarify the basic concept for the process for the medium Mn duplex structured steel with good mechanical properties.

2. Experimental procedures
The hot rolled steel sheet with chemical composition of 15%Mn-3%Al-3%Si-balance Fe was used. The initial thickness is 12mm. Thermomechanical treatments examined in this study is illustrated in Fig.1. First of all, the effect of the cooling rate (a) was studied. The sample was reheated to 1200°C followed by cooling at various cooling media; water quench, air-cooling and furnace-cooling. Subsequently, the combination of the reheating and multi-pass rolling with various total reductions was also examined.
The rolling temperature was fixed at 600°C, at which the rolling can be conducted without any cracking/failure. The tensile test was conducted at a strain rate of $10^{-3}\text{s}^{-1}$ and the tensile axis was parallel to the rolling direction (RD). Microstructural observations were also conducted by transmission electron microscope (TEM) etc.

3. Results and discussion

3.1. Cooling-rate effects

Figure 2 shows the optical microstructures of the samples cooled from 1200°C by water-quench (a) or in the furnace (b). The cooling rate in the furnace (b) is 100 deg./hour. The water-quenched sample (a) shows the coarse grained ferrite structure (~ a few hundred μm) with several cracks introduced during the cooling. Similar ferrite structure can be found in the air-cooled sample. On the other hand, the furnace-cooled sample (b) shows duplex structure consisting of ferrite (white parts) and austenite (black parts). Both parts have elongated morphologies in several different directions. No crack exists in the furnace-cooled sample.

Nominal stress – nominal strain curves of the samples cooled at various cooling rates are shown in Fig.3. The water-quenched and the air-cooled samples fractured in brittle manner due to cracking during the cooling. When the cooling rate is slower, the elongation can be improved. The stress – strain curve of the furnace-cooled sample shows plastic deformation with work hardening, although fracture takes place immediately at the maximum of the nominal stress and no local elongation (necking) can be found. This feature suggests that the furnace-cooled sample still keeps brittle property.

3.2. Rolling effects

![Fig. 1. Thermomechanical procedures examined in this study](image1)

![Fig. 2. Optical microstructures of the 15Mn-3Al-3Si steels reheated to 1200°C followed by water-quenching (a) or furnace-cooling (b).](image2)

![Fig. 3. Nominal stress - nominal strain curves of the 15Mn-3Al-3Si steels cooled at various rates from 1200°C.](image3)
Figure 4 shows the optical microstructure of the samples rolled at 600°C up to the various reduction in thickness during the furnace cooling. In this figure, the horizontal and vertical directions are parallel to the RD and the nominal direction (ND), respectively. The 50% rolled sample has the microstructure similar to that observed in the just furnace-cooled sample (Fig. 2(b)) although both ferrite and austenite parts are elongate along the RD. This morphology changes to a lamellar structure when the rolling reduction reaches up to 75% (Fig. 4(b)). The layers of the lamellar structure become thinner with increase of the rolling reduction. The 90% rolled sample exhibits the uniform and fine lamellar structure consists of the ferrite and the austenite layers of mean thickness of a few μm. According to the point-counting measurements of the consisting phases, the area fraction of ferrite slightly increases. The fractions of ferrite in the 0%, 25%, 50%, 75% and 90% rolled samples are 39%, 39%, 42%, 45% and 53%, respectively. These results indicate that the phase transformation from ferrite to austenite proceeds mainly before the rolling and one of the significant effect introduced by the rolling can be regarded as the alternation of the morphology.

Figure 5 shows TEM microstructures of the 90% rolled sample. The analysis of selected area diffraction patterns clarified the existence of both austenite and ferrite layers as denoted in (a). The elongated dislocation structure (cell and/or subgrain) was also observed in both austenite (b) and ferrite (c) layers. Such dislocation...
microstructure cannot be found in the just furnace cooled samples, so that these evolved during 600°C rolling. Additionally, fine Fe₃Al (or Fe₃Si) particle can be found in ferrite layers (c).

Figure 6 shows the stress – strain curves of the samples rolled at 600°C to various reductions. Data of the furnace-cooled sample without rolling (0%) is also denoted. The yield stress becomes larger with larger reduction. Concerning of the elongation, although the simple tendency is difficult to be determined, it should be noted that rolling hardly brings worse effect to the elongation. It should be noted that some of the rolled sheets show large elongations as is in the 90% rolled sample. Additionally, all the rolled samples show gentle drops of the nominal stress corresponding to necking prior to the fracture. These features suggest that the rolling contributes both to the large strength and preferable ductility in the 15Mn-3Al-3Si steel.

In order to clarify the effect of the rolling, the fractography was conducted. The SEM images of fracture surfaces on the samples just furnace-cooled (a) or 90% rolled at 600°C (b) are shown in Fig.7. The furnace-cooled sample exhibits the mixture of the brittle river pattern and the dimple pattern in the ductile manner. On the other hand, the rolled surface exhibits the dimple pattern predominantly. This result indicates that the brittle fracture is prohibited by rolling. The reason of this inhibition can be considered as following: the origin of the brittle fracture of the furnace-cooled steel could be the ferrite with large amount of Al and Si since these elements can accelerate brittle fracture as it is well known in the Fe-Si ferrite alloy for a transformer in electronic power industry. This brittle fracture is partially due to mechanical twinning in ferrite [3]. Twinning has strong orientation dependence [2] and the microstructure (grain size, dislocation structure) also affect twinning. In case of the rolled 15Mn-3Al-3Si steel, the ferrite layers can contain strong <110>/RD texture. <110> is less preferable tensile orientation for twinning [3]. Additionally, the ferrite layer has many dislocation cells (or subgrains) which can also prohibit the twinning. One can finally conclude that the rolling can provide difficult structure for twinning.

4. Summary
This study demonstrated the efficiency of thermomechanical process on the microstructural control in 15Mn-3Al-3Si steel. The lamellar structure consisting of austenite and ferrite duplex phases can be evolved by the combination of slow-rate cooling and warm temperature rolling. This duplex steel has preferable mechanical properties.

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References
[1] Grässel O, Krüger L, Frommeyer G and Meyer L W 2000 Int. J. Plast. 16 1391
[2] Ueji R, Tsuchida N, Terada D, Tsuji N, Tanaka Y, Takemura A, Kunishige K 2008 Scripta Mater. 59 963
[3] Narita N and Takamura J 1992 Dislocations in Solids 9 135