The hot rolled duplex laminated steel presenting both high strength and high toughness

S L Chen\(^1\), Z X Cao\(^2\), M D Zhang\(^1\), H F Xu\(^1\), J Dzuan\(^3\), and W Q Cao\(^1\)

1. Central Iron and Steel Research Institute, Beijing, 100081, China, 2. Science Faculty, University of Sydney, NSW2006, Australia, 3.COMTES FHT a.s., Prumyslova 995, 33441 Dobrany, Czech Republic

E-mail: caowenquan@nercast.com

Abstract: In this study, a new steel with the chemical composition of Fe-0.15C-5Mn-3Al (wt-%) was designed. Its microstructure and mechanical properties were examined by optical microscopy, scanning electron microscopy and mechanical tests. It was found that hot rolling in the dual phase region of ferrite and austenite at high temperature resulted in micro-laminated dual phase microstructure. An excellent combination of high strength (~1200MPa) and ultrahigh impact toughness (~400J) of the micro-laminated dual phase steel was obtained. Based on the measurement of the phase volume fraction and the analysis of the fractography, it was shown that the high strength was mainly dependent on the high martensite volume fraction, while the ultrahigh impact toughness was attributed to the micro-laminated microstructure.

1 Introduction

Traditional dual phase (DP) steel is a typical composite material with a soft granular ferrite (F) matrix and hard granular martensite or austenite (MA) islands, which has good mechanical properties, such as low yield strength, continuous yielding, high ultimate tensile strength and high ductility, but relative low impact toughness\[^1,2\]. Another kind of composite material is the pack rolling (PR) steel with an obvious layered structure, which results in high impact toughness in the perpendicular direction of the rolling plane\[^3\]. It would be a promising material with both the excellent mechanical properties of the DP steel and the ultrahigh impact toughness of the PR steel. It is well known that the laminated materials were usually fabricated by stacking and repeated rolling different steels and/or other materials\[^3-6\]. The process is very complicated and difficult to be achieved in industry, which makes the metallurgical and material researchers spend a long time to find a simple and feasible way to fabricate the laminated materials in the steel industry.
In this research, a new kind of dual phase steel was designed with the chemical composition of 0.15C5Mn3Al. The microstructure and the mechanical properties of the steel were examined after hot rolling in the $\alpha+\gamma$ region. Our aim is to explore the possibility to fabricate the micro-laminated microstructure in our new designed steel and its effects on the strength and impact toughness.

2 Materials and methods
The steel with the chemical composition of Fe-0.15C-5Mn-3Al (wt-%) was designed in the present study. The steel was first smelt in a 50 kg vacuum induction furnace and casted into an ingot. Then the ingot was forged into a square slab with thickness of 30 mm. The slab was homogenized at 1200 °C for 2 h and subsequently hot rolled into a thin slab with 11 mm thickness at the temperature between 1200 °C and 1000 °C followed by air cooling to room temperature. 5Mn-C-Fe phase diagram and 5Mn-3Al-C-Fe phase diagram were calculated by using the Thermo-Calc software with TCFE 7 database provided by the CISRI-TCS Joint Open Laboratory.

Samples for microstructure studies were polished and etched with 4% nital solution. The microstructure was analyzed by optical microscopy (OM) and scanning electron microscopy (SEM). The volume fractions and the shape characteristics of the phases were measured and described according to the gray difference in metallograph. The micro-hardness of different phases was measured in the transverse plane. Two groups (L-S and L-T) of standard specimens for Charpy V-notch impact measurement were cut from the slab to examine the anisotropy of the impact toughness. L–T (resp. L–S) configuration is investigated in which L corresponds to the axial direction and T (resp. S) to the notch direction. More details of the sampling information are shown in Fig.1. The impact toughness was measured at both -40 °C and 25 °C. The dog-bone shaped tensile specimens with gauge length of 25 mm and diameter of 5 mm were cut with their axial directions paralleling to the longitudinal direction (rolling direction). Tensile tests were conducted in a universal testing machine with a strain rate of $10^{-3}$ s$^{-1}$ at room temperature.

![Figure 1 Charpy V-notch impact test specimens in both the L–S and the L–T directions](image)

3 Results and discussions
5Mn-C-Fe phase diagram and 5Mn-3Al-C-Fe phase diagram were calculated by using the Thermo-Calc software with TCFE 7 database as shown in Fig.2. The dual phase region of ferrite and austenite only exist below 750°C ($\alpha+\gamma$) or around 1450 °C ($\delta+\gamma$) in 5Mn-C-Fe phase diagram as shown in Fig.2 a. Aluminium has a great effect on promoting the formation of ferrite. It does not only increase the stabilization of $\alpha$-ferrite but also expands the $\delta$-ferrite phase region. The $\alpha+\gamma$ and $\delta+\gamma$ dual
phase regions are expanded and connected by adding 3 wt.% aluminium in medium manganese steel as shown in Fig.2 b.

![Figure 2](image1)

Figure 2 The calculated (a) 5Mn-Fe-C and (b) 5Mn-3Al-Fe-C phase diagrams

Fig.3 a and b show the hot rolled microstructure examined by OM. It can be seen that the steel is composed of two different phases arranged alternatively along the short transverse direction. The micro-hardness of the ferrite phase is about 191±13.8 HV(50g), while the micro-hardness of the martensite phase is about 413±14.4 HV(50g). The ferrite phase existed stably during the hot rolling due to the addition of aluminium[7], which is consistent with the calculated phase diagrams as shown in Fig.2. However, the martensite phase should be the phase transformed from the austenite during the air cooling process[8]. The ferrite is elongated seriously along the longitudinal direction and the transverse direction. Fig.3 c and d reveal the microstructure examined by SEM that shows the thin ferrite lamellae and the martensite matrix clearly.

![Figure 3](image2)

Figure 3 Laminated dual phase microstructures OM (a) L×S and (b) T×S, SEM (c) L×S and (d) T×S

Different from the traditional DP steel and the PR steel[3-6,9-10], the microstructure of the steel
exhibits a large number of thin ferrite lamellae with thickness 1-10 μm paralleling to the rolling plane which locate evenly in the matrix with martensite lamellae about 10-50μm. The ferrite volume fraction of the steel is 11±1.2%. The shapes of the ferrite and the martensite in this steel are completely different from the granular shape ferrite and MA islands in the traditional DP steel[9]. The thickness of the ferrite and the martensite lamellae is much thinner than that of the millimetre-laminated steels[3,5]. In addition, the process only includes hot rolling and air cooling, which is feasible in the steel industry comparing with the traditional DP steel and the PR steel.

The mechanical properties were given in Table 1 and Table 2. It can be seen that the new dual phase steel achieves a high yield strength and a high ultimate tensile strength but a low ratio of yield strength to ultimate tensile strength. The big increase from yield strength to tensile strength implies a high work hardening and good plasticity capacity. The uniform elongation of ~6% and total elongation of ~15% indicate a good ductility of the steel. In addition, ultrahigh impact toughness (~400 J) was obtained in the L-S direction samples. However, the impact toughness in the L-T direction (~80 J) is much lower than that in the L-S direction, indicating obvious anisotropy of the impact toughness.

| Yield strength /MPa | Ultimate tensile strength /MPa | Yield ratio | Uniform elongation /% | Total elongation /% |
|---------------------|--------------------------------|-------------|-----------------------|-------------------|
| This study          | 785                            | 1199        | 0.655                 | 6.0               | 14.8              |
| DP590               | 340                            | 590         | -                     | -                 | 21                |
| DP780               | 420                            | 780         | -                     | -                 | 14                |
| DP980               | 550                            | 980         | -                     | -                 | 8                 |

**Table 2 Impact toughness of the steel @ -40 °C and 25 °C**

| Impact toughness @-40 °C /J | Impact toughness @25 °C /J |
|----------------------------|-----------------------------|
| L-S                        | 372±43                      |
| L-T                        | 65±31                       |
| L-S                        | 405±59                      |
| L-T                        | 83±15                       |

As it was well known, the strength of the traditional DP steel could be related to the strength contribution and deformation interaction of the ferrite phase and the martensite phase[11]. Under the assumption that the plastic strains of two phases are equal, the flow stress of the laminated dual phase steel can be simplified to the following equation (eqn.(1)),

\[
\sigma = V_F \sigma_F + V_M \sigma_M
\]  

As it was measured, the micro-hardness is about 191 HV for the ferrite phase and 413 HV for the martensite phase. According to the relationship between hardness and tensile strength, \(\sigma_F\) and \(\sigma_M\) are equal to 623 MPa and 1344 MPa, thus the calculated ultimate tensile strength of the steel is about 623*0.11+1344*0.89=1265 MPa, which is very close to the measured ultimate tensile strength of 1199 MPa as given in Table 1. Another feature of this steel is its good ductility with the high volume fraction of martensite phase (~90%). The volume fraction of martensite phase should be limited from 10% to 30% in traditional DP steel to obtain high ductility[11]. However, the regular lamellar
microstructure with about 90% martensitic phase could reduce the stress concentration and retard the formation of micro voids, thus improve the non-uniform elongation.

The impact toughness in the L-S direction of the steel is about 400J, which is about 5-6 times of the traditional DP steels[12-13]. However, the impact toughness in the L-T direction is about 80 J, which is in the similar level with other steels[14-15]. In order to understand the ultrahigh impact toughness in the L-S direction and the anisotropy of the impact toughness in different directions, the macrographs of fractured Charpy V-notch impact samples were examined as shown in Fig.4. It can be seen that the extrahigh impact toughness could be related to the cracking along the rolling plane, which absorbed most of the impact energy when the V-notch is opened in the L-S direction as shown in Fig.4a and b. Only a slightly crack along the rolling plane when the notch is opened in L-T direction as shown in Fig.4c and d, which results in a much lower impact toughness.

![Fracture surfaces of specimens](image)

**Figure 4** Fracture surfaces of specimens. (a) 25°C and (b) -40°C in L-S, (c) 25°C and (d) -40°C in L-T

## 4 Conclusions

A micro-laminated dual phase steel was produced by simple hot rolling and air cooling processes. And this microstructure gives a very good combination of mechanical properties and ultrahigh impact toughness. The main conclusions can be drawn as follows,

1. A micro-laminated dual phase steel with ferrite lamellae and martensite lamellae arranged alternatively in the short transverse direction was successfully developed by the rational design of the alloy composition and the hot rolling process in the dual phase region.

2. An ultimate tensile strength of ~1200 MPa and a total elongation of ~15% of the steel indicate a good combination of strength and ductility.
(3) The ultrahigh impact toughness of ~400 J was obtained in the L-S direction of the micro-laminated high strength dual phase steel, due to the cracking along the interfaces of the micro-laminated steel.

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