Excellent Total Mechanical-Properties-Balance of 5% Mn, 30000 MPa% Steel

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(Received on December 2, 2010; accepted on January 17, 2011)

1. Introduction

The demand for high strength-high ductility materials has increased with the demand for light-weight automobiles.1-4) The relationship between TS (Tensile Strength) and TE (Total Elongation) can be expressed by a so-called banana-curve. As steels having achieved high strength-high ductility balance, three types have been known; (1) DP steel, (2) TRIP steel, and (3) TWIP steel.5) Low carbon martensite or bainitic steels are inferior to those steels in terms of strength-ductility balance. The addition of Cr and Mo which enhances strength-ductility balance seems to be not preferable on account of cost issues and natural resource limit.

Furukawa et al. have showed the possibility that the addition of high Mn and high Si enhances strength and ductility balance.6) We have, therefore, decided to focus on steel containing high Mn and high Si, from the point of ubiquitous material design. In this paper, to clarify the possibility of the addition of high Mn and high Si, three kinds of structures; ultra-fine ferrite/cementite, martensite, and ferrite/retained austenite were prepared and investigated the relationships among structure, strength, ductility and toughness. In order to produce three kinds of structures, the thermo-mechanical treatments (a) warm-rolling, (b) hot-forging, and (c) so-called TRIP-treatment are used. The warm-rolling7-12) is aimed to obtain an ultra-fine ferrite + cementite microstructure. The hot-forging is aimed to obtain martensite structure, and the TRIP-treatment is aimed to obtain a dual phase structure consisting of ferrite and austenite.

In this study, we hope to obtain excellent properties of TSxTE larger than 30000 MPa%.

2. Experimental Procedures

A composition of steel used in this study is 0.10C–5.02Mn–1.96Si (mass %). The 20 kg ingot was prepared by vacuum melting and casting, using high purity electrically-purified Fe, Mn, and Si. For de-oxidation, both C de-oxidation and Al de-oxidation were used sequentially. Oxygen content was eventually controlled to be in the level of below 20 ppm. Total Al is 0.001 and N is 5 ppm.

From this ingot, a 38 mm square cross sectional rod was prepared by forging after soaking at 1200°C for 3600 s. The forging was conducted with 75% area reduction followed by air cooling with a cooling rate of about 0.5 K/s. This sample is (1) a forged sample itself, and from this sample, (2) hot-forged with tempering, (3) warm-rolled, and (4) TRIP-treated samples were prepared. This forged sample is denoted as F (Forged). Also, in order to see the effect of tempering, annealing at 550°C for 3600 s followed by air cooling was conducted on sample F. This tempered one is denoted as FT (Forged-Tempered). With sample F, warm caliber rolling was carried out. Rolling condition was a multi-pass rolling from 38 mm-square cross section to 17 mm-square cross section after soaking at 550°C for 3600 s, followed by air cooling. This sample is designated as WR (Warm-Rolled). From this sample, rods with a dimension of Ø3 mm×30 mm were machined and served for dilatometer testing to determine phase transformation temperatures at several different cooling speeds using Formaster-FII.

The objectives of dilatometer test are two kinds. One is to determine transformation temperature. The other is to perform a TRIP treatment precisely. In addition, small tensile specimens (1Φ×5 mm parallel region) were cut from a TRIP-treated sample and tensile tests were carried out. To determine transformation temperature, each specimen was heated to 1200°C and kept at that temperature for 120 s, followed by cooling. The cooling rates were seven kinds; from 0.5 K/s to 67 K/s. As for a TRIP treatment, two-step heat treatment was conducted. The specimen was heated to 675°C and kept for 120 s, followed by He gas quenching to room temperature, and then heated to 400°C and kept for 300 s, followed by He gas quenching to room temperature. This sample is denoted as TRIP. Here, the first heat treatment is aimed at forming a stable γ+α two-phase structure by keeping the specimen in the γ+α two phase region. For the next step, the specimen was aimed at enriching C in the γ phase and stabilizing the γ phase by keeping the specimen at relatively low-temperature α phase region.

For each specimen, microstructure observation by optical microscopy and SEM, crystallographic orientation analysis by EBSD, tensile test, and Charpy impact test were conducted. Identification and volume fraction of austenite (γ) and ferrite (α) phases was conducted by EBSD analysis. Tensile test was conducted on a round shape specimen with a parallel region of dimension of Ø3.5×24.5 mm at a strain rate of 0.5 mm/min. For tensile-testing of sample TRIP, special small test samples were machined from TRIP-treated samples. Charpy impact test was conducted on a full size specimen with a 2 mm V-notch at test temperatures at various temperatures from liquid nitrogen temperature to 100°C.

3. Results and Discussion

A CCT curve is shown in Fig. 1, which shows the change of dilatation occurring only around 340°C. Dilatation curves are almost same regardless of cooling rates from 0.5 K/s to 67 K/s, suggesting that transformation temperature are almost same. It is very interesting to note that transformation temperature little changes in the wide range of cooling rate, suggesting that all those specimens having a similar microstructure. This is believed to be good for hot stamping application, since the properties of the steel are not affected by cooling rate after hot stamping.

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Microstructures of samples F, FT, WR and TRIP are shown in Fig. 2. The microstructure of sample F consists of martensite and small amount of retained austenite which can be identified at lath boundaries in the martensite by EBSD analysis. The volume fraction of this retained austenite is determined to be 2 to 4 vol%. Sample WR has a microstructure of fine ferrite and fine cementite due to a large strain deformation in warm temperature range by multi-pass cali-ber rolling from 38-square mm cross section to 17-square mm cross section at 550°C. The microstructure of sample TRIP consists of two phases of ferrite and austenite of about 1 μm grain size.

Results of tensile test for samples F, FT, WR and TRIP are shown in Fig. 3. By comparing the TS–TE balance of those four different microstructures based on the same high Mn composition, it is found that sample F has more excel-lent balance properties. Sample TRIP has both strength and ductility increase simultaneously, in comparison to conventional low carbon ferrite/pearlite steel, due to the work hardening because of the retained austenite transforming to martensite during deformation. Samples WR and FT have relatively high strength-high ductility due to the strain hardening caused by the presence of fine cementite. The above samples show the stress-strain behavior that can be predicted from their microstructure except sample F. Among those behaviors, what is interesting in this study is the stress-strain behavior of sample F.

When the microstructure is martensite, it is normal that it is expected to have high strength, but not high ductility. In contrast to this concept, this data shows the martensite structure shows both high strength and high ductility, in other words, a good balance of mechanical properties. In particular, sample F has the highest TS among those four samples.

Results of Charpy test on samples F, FT, and WR are to be discussed. The USE (Upper Shelf Energy) is determined to be 311 J/cm² for WR, 177 J/cm² for F, and 31 J/cm² for sample FT. On the other hand, as for the ductile-brittle transition temperature (DBTT), there is no DBTT down to liq-uid nitrogen temperature for the WR, 20°C for the F, and >100°C for FT.

The parameter TS×TE is a good indicator for evaluating strength-ductility balance. Generally, TS×TE≥30000 MPa·% means an excellent strength-ductility balance. TRIP has TS×TE≥30000 MPa·%, while that of F has the same level of TS×TE. The comparison of these data is shown in Fig. 4 with other reference data of related steels. From Fig. 4, it can be said that the martensite structure with 5%Mn has an
excellent strength-ductility balance. For structural materials, it is important to have not only strength-ductility balance but also strength-toughness balance. The microstructure of F is martensite, and F shows TS of more than 1400 MPa and TE of more than 20%. In addition to this, F also shows USE of more than 177 J/cm². This level of total balance of TS and USE has only been shown for some alloy steels prepared by warm deformation in the ferrite region. Martensitic structure steels having this high level of TS and USE balance prepared by hot forging in the austenite region and without expensive alloying elements have not been so much reported before. This suggests the possibility of creating a material with high total balance just only by hot forging in the austenite region, suitable to hot stamping.\(^5\)

The addition of Si prevents cementite formation, thus preventing to decrease C content in austenite, leading to increasing γ phase stability, which contributes to enhancing work hardening rate and eventually ductility. Therefore, certain content of C and Si is considered to be important as well as Mn content. Thus the chemical composition has been determined to be 0.1C–5Mn–2Si, based on the references of TRIP steel so far reported.\(^5\)

Other high tensile steels such as high tensile steel reinforced by nanometer-sized carbides precipitates (nano-highten)\(^6\) as well as that reinforced by fine Cu precipitates (Cu-highten)\(^7\) are well known. The TS×EI for the nano-highten is about 16000 MPa%, while that of the Cu-highten is about 18000 MPa%. Thus, the higher ductility of samples FT and WR, whose TS×EI is more than 26000 MPa%, cannot be explained simply by work hardening due to fine precipitation. The addition of Mn may have some effect on their ductility, but this needs further investigation. Volume fraction of retained austenite is 0% for both samples FT and WR. Therefore, the effect of retained austenite on the ductility can be neglected for both samples WR and FT.

The reliability of tensile testing data has been confirmed by comparison between conventional bulk samples and small samples, and they have shown good agreement.

The strengthening mechanism of sample F seems to differ from that of TRIP structure. This is obvious when we look at the stress-strain curve of sample F, in which most of the elongation comes from the region after necking, i.e. after TS point. While sample TRIP secures ductility by increasing uniform elongation, sample F has higher elongation after necking. Even though there might existed some retained austenite at lath or block boundaries in sample F, and also some TRIP deformation occurred during plastic deformation, the contribution of TRIP deformation to the total elongation might be quite small. Thus further study is necessary in order to elucidate the mechanism of high total balance properties of sample F.

4. Conclusions

In this study, to aim developing 30000 MPa% steel, 0.1C–5Mn–2Si steel was examined for microstructure and mechanical properties.

(1) Transformation temperatures of this steel is almost 340°C, which changed little in the wide range of cooling rate from 0.5 to 67 K/s, and resultant microstructures are martensite. Three kind of microstructure, martensite, ultrafine ferrite + cementite and ferrite + austenite were successfully prepared by forging, warm rolling and TRIP-treatment.

(2) Excellent total mechanical-properties-balance of 30000 MPa% was obtained for martensite structure by hot forging and ferrite + austenite structure by TRIP-treatment. Martensite structure produced by hot forging had 140J of upper shelf energy in Charpy impact test, in addition to high strength of more than 1400 MPa and high ductility of more than 20%.

(3) 0.1C–5Mn–2Si steel has a good possibility for the application to hot stamping because of its excellent total balance of mechanical properties without depending on cooling rate.

Acknowledgement

The authors greatly acknowledge experimental support by Satoshi Iwasaki, Koji Nakazato, Takaaki Hibaru, Syuuii Kuroda, Yasushi Taniuchi, Sadao Hiraide, Noboru Sakurai, Elena Bulgarevich, and Aiko Takanabe.

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