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HIGH STRENGTH STEELS FOR AUTOMOBILE USE AND THE ROLE OF MICROALLOYING

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Abstract

There has been a steady increase in the amount of high strength steels used in automobile industries in order to meet the strong demands for the weight reduction and the improvement of the crashworthiness of auto-bodies. Various types of high or ultra-high strength steel sheets have been developed for this purpose. It is also well established that these high or ultra-high strength steel sheets should have good press formability, weldabilty and corrosion resistance etc. Phase transformations, precipitations and grain refinement hardenings are used together with solid solution hardening to strengthen the steel sheets with acceptable deteriorations of other properties than strength. Micro alloying is one of the key technologies in this field not only for the strengthening but also for the controlling of microstructures of steels.

Introduction

Safety and environment consciousness are the most important issues to deal with for automobile industries. Various types of high and ultra-high strength steel sheets have been developed and been applied to automobile components contributing to the weight reduction and the improvement of crashworthiness. Since required performances of steels vary from part to part, different concepts of hardening mechanisms, such as solid solution hardening, dislocation hardening, grain refinement hardening and dispersed particle hardening, are used to strengthen steels.

The controlling factors of the strength of various components other than the thickness of steels are listed in Table I [1]. When the requirements for a component are governed by the strength of steels, such as dent resistance, fatigue strength, buckling and bending resistance of the component, applications of higher strength steels are expected to contribute weight reductions of auto-bodies. When the required strength of a component is controlled by rigidity and corrosion of the steels used, however, applications of higher strength steels are, in general, considered not to be effective for a further weight reduction.

When higher strength steels are considered to be applied to auto-bodies, it is essential to improve the press formability of steels. The press formability of sheet steels is divided into four categories, deep drawability, stretchability, stretch flangeability and bendability, as shown in Figure 1 [2]. It is well recognized that the higher the strength the lower these characteristics of the press formability.

Table I. Required properties and main controlling factors of various vehicle parts.

Part		Required properties				
		Panel rigidity	Dent resistance	Member rigidity	Fatigue strength	Crash strength
Outer panels	Door outer etc.	◎	○			
Inner panels	Floor etc.	◎		○	○	○
Structural parts	Front rail Rear pillar etc.			◎	○	○
	Front side member Side sill etc.			◎	○	◎
	Door reinforcement etc.			○	○	◎
Under body parts	Suspension arm Disc wheel etc.			◎	◎	
Main controlling factors apart from thickness of steels		Young's Modulus	YS	Young's Modulus	TS	TS

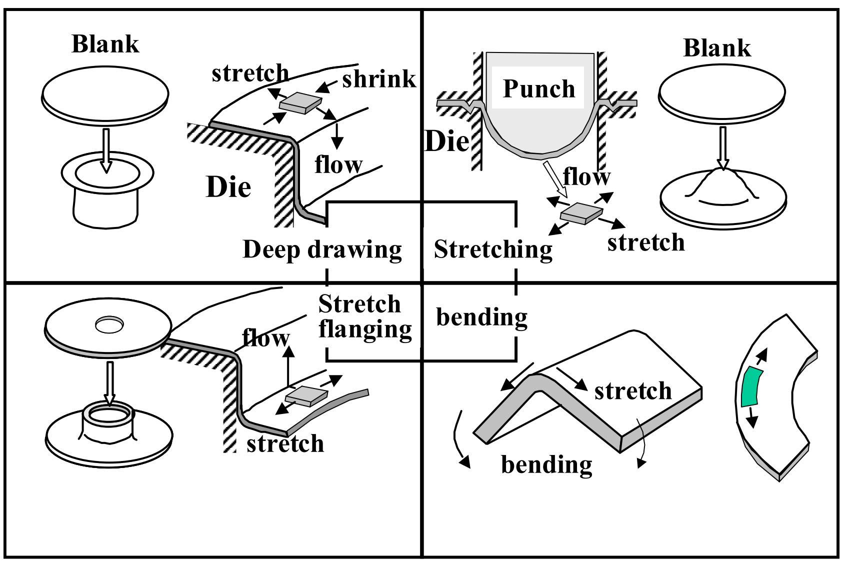


Figure 1. Categories of deformation mode in press forming of sheet steels.

High strength steels for different components of auto-bodies will be discussed here.

High Strength Steels for Chassis Parts

Corrosion and fatigue resistances as well as a sufficient rigidity are required to chassis parts, and as hot rolled steel sheets are, in general, applied. Press formability is also a key factor to adopt higher strength steels, and stretchability and stretch flangeability are considered to be the most appropriate mechanical properties to express the press formability of high strength hot rolled steel sheets. Mixed microstructures are selected to improve the ductility of steels. Dual phase and low alloy TRIP steels are typical examples of ductile high strength steels. Bainitic or ferrite and bainite mixed microstructures are, on the other hand, adopted to improve stretch flangeability of steel sheets [3].

Stretch flangeability is known to be improved by controlling the microstructure. As it can be seen in Figure 2 [4], the coiling temperature is one of the most important production conditions for this purpose. An Addition of Si is known to refine cementite particles and to improve the stretch flangeability [4]. Since the addition of carbide former elements, such as Nb, Ti, Mo and V, can reduce the amount of cementite precipitation, the stretch flangeability as well as the strength can be improved [5]. It is, however, worth to note that the stretch flangeability could be deteriorated at a certain coiling condition as reported by Kashima and Hashimoto [5]. Although the reason of this deterioration is not well understood, precipitated particles are thought to play an important role.

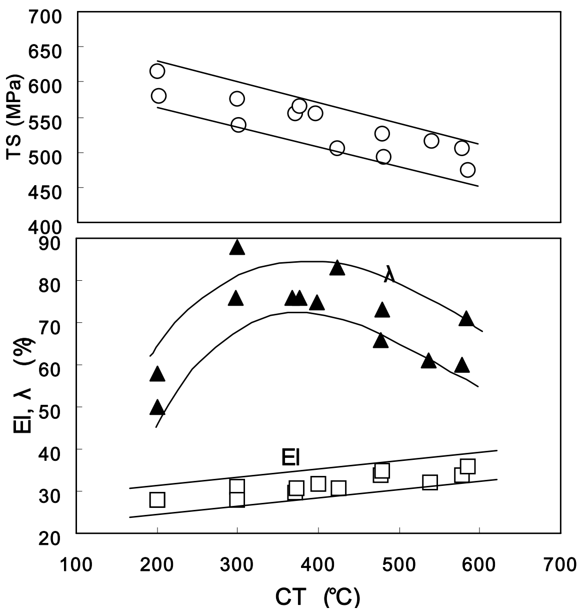


Figure 2. Effect of coiling temperature on mechanical properties of Fe-0.1 and 0.2C-0.3Si (mass%) steels. (reproduced)

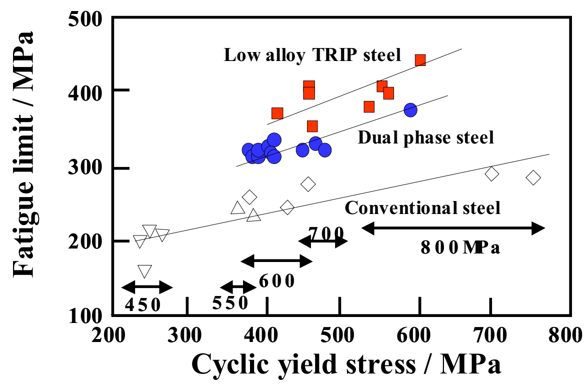


Figure 3. Relation between cyclic yield stress and fatigue strength in various types of high strength steels.

Fatigue strength is also one of the most important performances of steels used for chassis or under body parts. Dual phase and low alloy TRIP steels are reported to show higher fatigue strength than other conventional HSLA steels as shown in Figure 3 [6]. The mechanisms of this higher fatigue strength were studied in detail by Mizui et. al. [7] for dual phase steels and by Yokoi et. al. [8] for low alloy TRIP steels. Fatigue cracks are found, in general, to initiate in soft ferrite matrix. The ferrite matrix in dual phase steels is hardened by solute Si, the initiation of fatigue cracks is found to be retarded. This tendency is supported by the fact that the cyclic softening is strongly suppressed due to a steady cell structure under cyclic stresses (Figure 4) [8]. It is also reported that martensite particles can obstacle the propagation of fatigue cracks, which also contribute to improve the fatigue strength. In the case of low alloy TRIP steels, not only the effect of Si addition, but also the effect of transformation from retained austenite to martensite, which is considered to introduce compressive stresses retarding the crack initiation and propagation [8], contribute to improve the fatigue property.

Although Mizui and Yokoi reported the precipitation hardening is not as effective as the microstructure hardening to improve the fatigue strength, opposite findings have also been reported. Toyama et. al. examined the effect of strengthening mechanisms on the fatigue strength and found the precipitation hardenings by Ti, Nb and V give higher fatigue strength than any other hardening mechanisms as shown in Figure 5 [9]. Those two opposite results may due to the experimental methods and materials used. The specimens used for the fatigue test in Toyama's study, were mechanically machined the surface layer after the heat treatment, whereas as hot rolled steels were studied without removing the surface by Mizui et. al. When a HSLA steel is processed in a multi-pass hot working process such as a hot rolling process, a heat transfer form the materials to the tools of hot working causes a large decrease in the temperature at the surface layer of the materials. This cyclic temperature drop and recovery can accelerates the precipitations and coarsening of alloy carbides resulting in an insufficient hardening compared with the inside part of the steels. This can happen due to a big difference in the solubility of alloys between in austenite and in ferrite. Fatigue cracks may then initiate earlier at the soft surface area of steels. If the surface layer is removed, on the other hand, the precipitation hardened ferrite may have higher resistance to fatigue. This may be the reason why Toyama et. al. observed the better fatigue properties in precipitation hardened steels than others. It is also worth to note that the fatigue strength of steels strongly depend on the processing conditions as discussed by Mizui et. al. [7] Therefore, it should be carefully assessed if the microstructure is properly controlled when different hardening mechanisms are compared. It should, therefore, be emphasized that the precipitation hardening could play an important role to improve fatigue strength as well as steel strength if the strengthening effect can be maintained even at the surface. When the transformation start temperature from austenite to ferrite is effectively low, the precipitation hardening could be effective throughout the thickness of steels and could improve the fatigue strength.

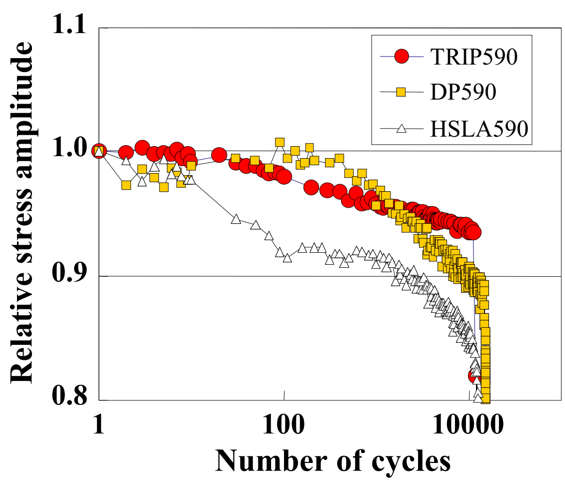


Figure 4. Comparison of cyclic stress response curves of low carbon TRIP, dual phase and precipitation hardened 590 MPa grade high strength steels.

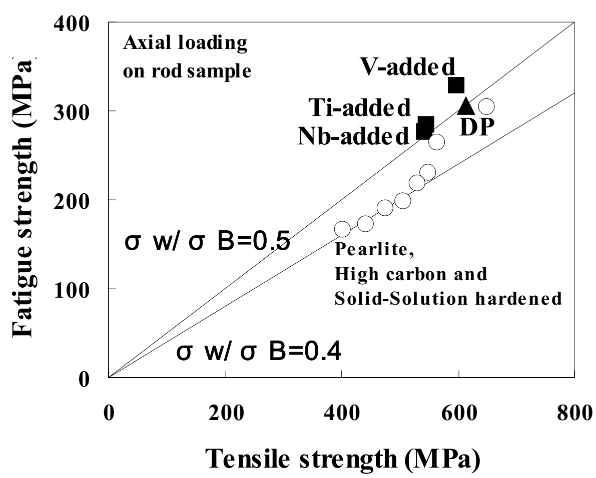
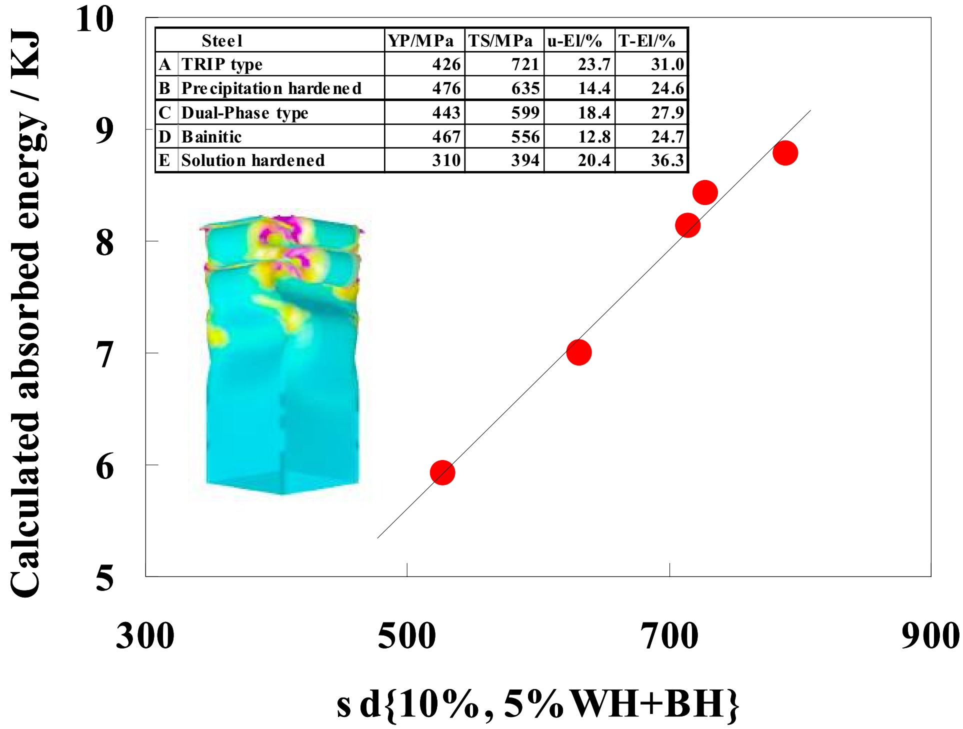


Figure 5. Effect of strengthening method on fatigue strength of medium carbon steels (reproduced).

High Strength Steels for Structural Parts

To protect the occupants in any crash events is considered to be one of the most important performances of automobiles today. Apart from structural studies for energy absorption, application of high strength steels is expected to improve crashworthiness of automobiles without or with the minimum increase in weight.

When a frontal collision is concerned, plastic deformations of structural components absorb crash energy and reduce the damage of the occupants caused by the collision. Thin wall tube structures such as front side members are expected to absorb crash energy by buckling deformations. The maximum strain rate during this axial crash of thin wall tube structures is expected to reach around 1000/s, which is a million times larger than the conventional mechanical testing [10]. Since the strain rate sensitivity varies from steel to steel, it is essential to clarify the strain rate sensitivity of the steel used for components to assess the crashworthiness. The most of the energy associated with the crash event is absorbed during the deformation of steels up to around 10% of strain (Figure 6) [11]. So the flow stresses at these relatively low strains control the crash energy absorbing property of steels. A lower strength is preferred during press forming and a higher strength is required at a collision event. Therefore a high strain rate sensitivity of the material is desired. It is well established that steels show larger strain rate sensitivities of the flow stress than other materials such as aluminum alloys.



	Steel	YP/MPa	TS/MPa	u-El/%	T-El/%
A	TRIP type	426	721	23.7	31.0
B	Precipitation hardened	476	635	14.4	24.6
C	Dual-Phase type	443	599	18.4	27.9
D	Bainitic	467	556	12.8	24.7
E	Solution hardened	310	394	20.4	36.3

Figure 6. Relationship between calculated absorbed energy and dynamic flow stress at 10% of strain.

Dual phase steels with mixed microstructures of ferrite and martensite, and low alloy TRIP steels with microstructures consist of ferrite, bainite and retained austenite, are reported to show higher energy absorbing properties than conventional high strength steels as shown in Figure 7 [10]. Since a good press formability is also an essential requirement to steels used for structural parts, these multi-phase steels are superior to conventional high strength steels. Although the strain rate sensitivity of flow stress is known to decrease as increasing the strength of steels, the existence of soft ferrite phase seems to be effective to show the higher strain rate sensitivity of flow stress. TRIP effect is also known to improve the strain rate sensitivity through an acceleration of the transformation from retained austenite to martensite at higher strain rate deformations (Figure 8) [11]. The more stable the retained austenite is, the higher the strain rate sensitivity of flow stress is observed. Another possible strengthening method to improve the strain rate sensitivity is the bake hardening. Bake hardenability has been used widely to improve the dent resistance of panels through increasing the yield strength after press forming and baking. Both solute carbon and solute nitrogen are used for this purpose. As it has been well established, the flow stress is also increased by the bake hardening especially when the amount of pre-deformation is larger.

Steels with different combinations of work and bake hardenabilities (WH and BH) were prepared to assess the effect of WH and BH on the strain sensitivity of flow stress [12]. Pre-deformation was applied along the transverse direction to the rolling direction, and the tensile test was conducted along the rolling direction either at around 10^{-3}/s of strain rate for static tensile test, or at around 1000/s for dynamic tensile test. All the specimens were kept at a low temperature except when they were tensile tested in order to keep the specimens away from aging at room temperature. It was found that the increases in static and dynamic flow stresses due to WH and BH strongly depend on BH instead of WH (Figure 9). The higher the bake hardenability, the larger the increase in flow stress after the pre-deformation and baking. It should be worth to note that the increases in static and dynamic flow stresses due to WH and BH are almost the same (Figure 10). This means the strain rate sensitivity dose not decrease with increasing the strength of steels by pre-deformation and baking. This is unlike to other strengthening method where clear decreases in the strain rate sensitivity are observed [12].

Dual phase and low alloy TRIP steels are known to show relatively high bake hardenabilities, increases in static and dynamic flow stresses of the multi-phase steels due to pre-deformation and baking are clearly higher than those for other high strength steels (Figure 11) [12].

Although a large plastic deformation occurs in the case of frontal collision events, the amount of deformation due to side collision is required to be small. It is, therefore, expected that higher strength steels than, for example, 590 MPa in tensile strength will be applied to components for

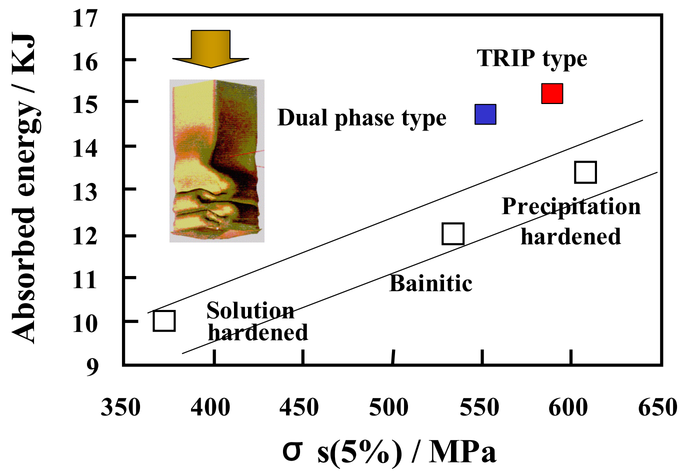


Figure 7. Calculated absorbed energy during an axial crash event of a 70×70mm square tube as a function of the flow stress at 5% of strain during quasi-static tensile test.

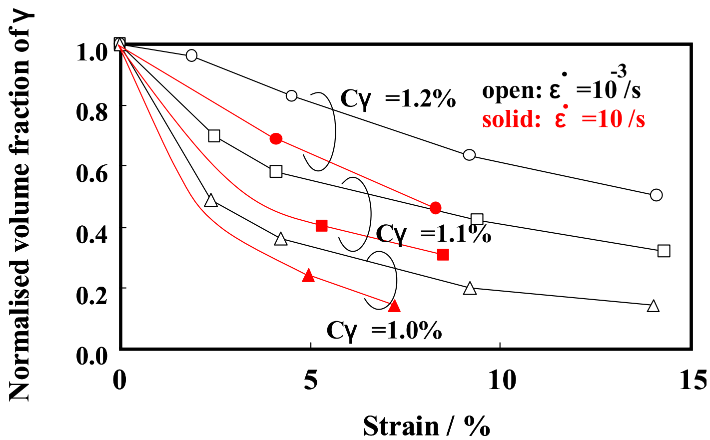


Figure 8. Effect of strain rate on martensite transformation during uni-axial tensile test on TRIP type-high strength steels. The carbon concentration in retained austenite was altered by heat treatment.

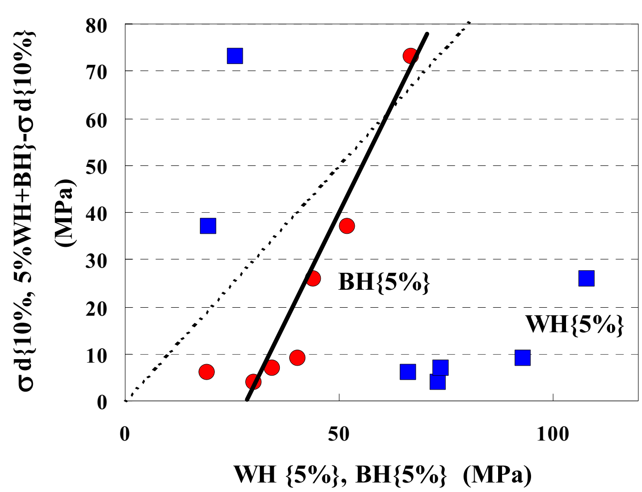


Figure 9. Relations between increases in flow stress by pre-deformation and baking (WH+BH) and WH{5%} or BH{5%}.

side collision conscious parts. Three different types of 980 MPa grade high strength steels have been reported (Figure 12) [13]. A better combination of ductility and stretch flangeability is essential to apply ultra-high strength steels to automobile components. As it is well recognized, the higher the steel strength, the worse the weldability due to a poor shape fixability of pressed parts and a larger carbon. In order to overcome this difficulty, relatively low carbon steels have been proposed for 980 MPa grade ultra-high strength steels as discussed by Yoshinaga et. al. [14].

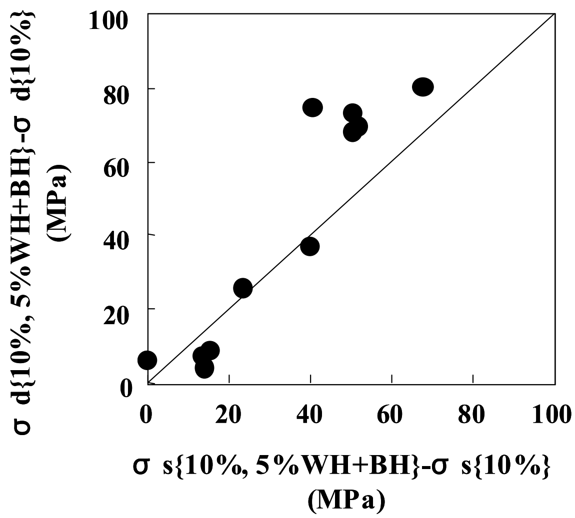


Figure 10. Relation between increases in dynamic and static flow stresses due to 5% pre-strain and baking treatment.

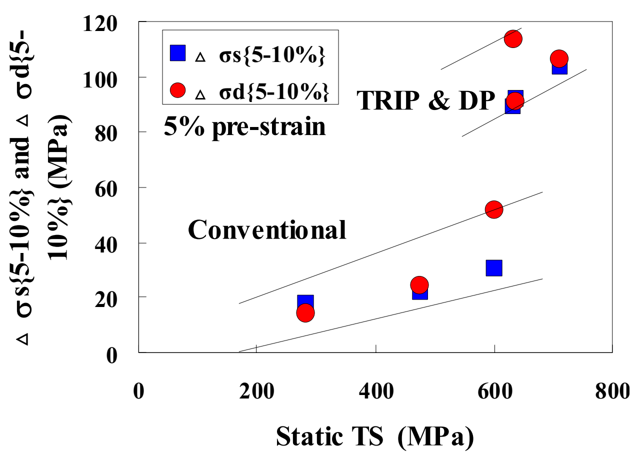


Figure 11. Increases in static and dynamic flow stresses due to 5% of pre-deformation and baking.

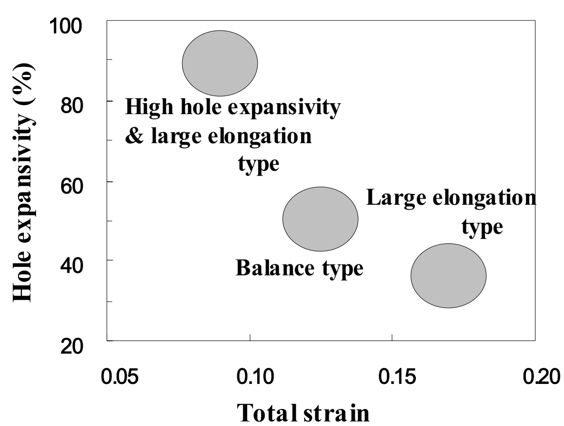


Figure12. Three types of 980 MPa grade cold rolled and annealed ultra-high strength steels.

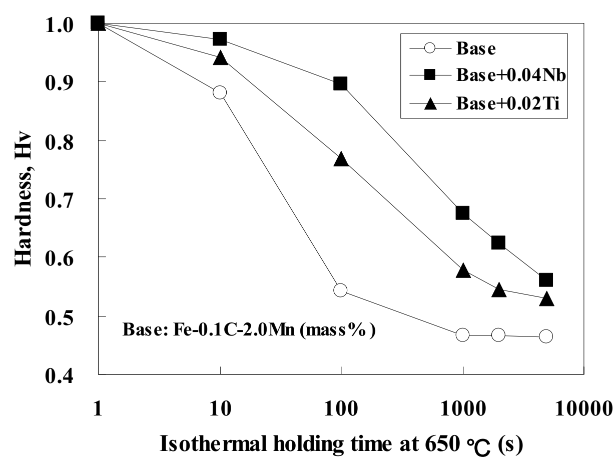


Figure 13. Effect of Nb and Ti addition on recrystallization of ferrite during isothermal holding at 650℃ after 67% of cold rolling.

Since the weldability is one of the most important performances of steels used in automobile industries, steels with increased carbon concentration are not usually accepted. It is, therefore, indispensable to adopt micro-alloying even in cold rolled and annealed high strength steels in order to obtain the required strength. It is, however, not well understood how micro-alloying elements affect the mechanical properties and microstructure evolution of cold rolled and annealed steels. An effect of niobium addition on recrystallization behavior was studied in Fe-0.1C-2.0Mn steels and compared with steels with titanium addition as shown in Figure 13. As it is expected, a niobium addition retards the recrystallization more than that of titanium. It can easily expected that the retardation of recrystallization could result in a grain refinement, which leads to an increase in strength of the steels. When ultra-high strength steels are concerned, the reverse transformation to austenite could occur before the completion of the recrystallization because. An example of this feature can be seen in Figure 14, where unrecrystallized ferrite remains untransformed. A reverse transformation behavior can be seen in Figure 15, where the transformations during heating and isothermal holding are observed. It is, therefore, important to understand the competition between recrystallization and transformation of ferrite quantitatively, since the unrecrystallized ferrite may contribute the final mechanical properties of the steels annealed at intercritical temperatures.

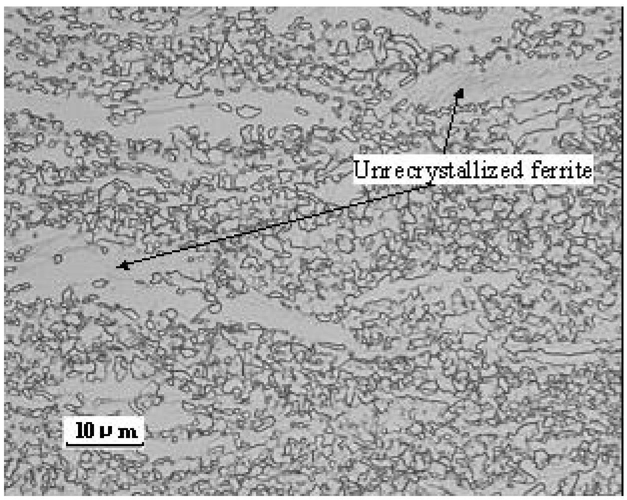


Figure 14. An optical micrograph of Fe-0.1C-2.0Mn-0.04Nb (mass%) annealed at 780 °C for 200 s after 67% of cold rolling.

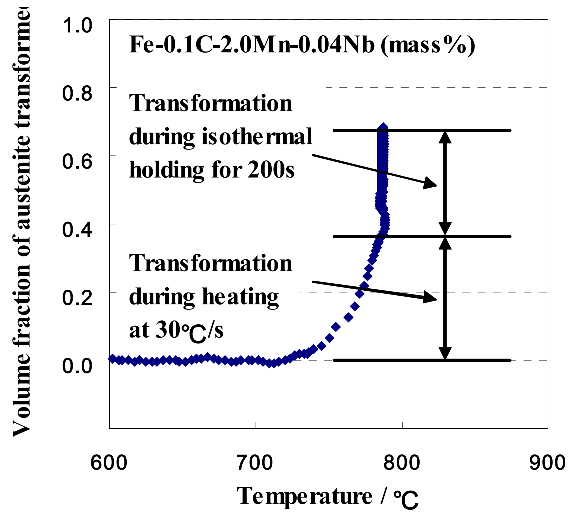


Figure 15. Reverse transformation behavior during heating and isothermal holding at 780 °C for 200 s in Fe-0.1C-2.0Mn-0.04Nb (mass%) alloy.

Conclusions

Various types of high and ultra-high strength steels have been developed to meet the requirements for the weight reduction and crashworthiness. Although different mechanisms are adopted to strengthen steels to maintain the required performances, microalloying is one of the key technologies to control the microstructure and mechanical properties of steels, especially at higher strength region. Detailed understandings of the role of microalloying during recrystallization, transformations and their competitions in steels are essential to control the microstructure and mechanical properties of high strength steels.

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