Development of 900MPa category high strength non-heat treatment steels for connecting rod

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One of the recent demands is to reduce CO2 emissions and consequent environmental loads, and it eventually aims at CN (carbon neutral) in the future. When it comes to automobile, improving efficiencies of its engine is one of the effective methods to reduce CO2 emission. It is considered that the weight reduction of connecting rod (hereinafter referred to as “con-rod”), which is one of movement parts of engine, contributes to greater efficiencies of engine, because of reducing weight of not only the con-rod itself, but also peripheral parts. On this standpoint, we have developed the higher strength steels for con-rod to meet increasing demands for lighter con-rod.

The non-heat treatment steels are often applied to con-rod. Controlling the cooling rate after hot forging is important to get high strength of non-heat treatment steels. The non-heat treatment steel is strengthened with faster cooling rate, however, the strength would be then degraded once bainite is generated by the over-speeded cooling rate. Based on above, we have examined to improve the strength of non-heat treatment steels for con-rod.

The amount of carbon and vanadium are increased to obtain more precipitation strengthening of vanadium carbide. However, increasing the amount of carbon and vanadium may result in the generation of bainite, which would lead to the degradation of the strength, because faster colling rate doesn’t get obtained. Therefore, we have focused on the differences of the bainite generation level depending on alloy elements and optimized the addition balance of manganese and chromium. These approaches have led to suppression of bainite generation caused by large amount of alloy elements added, then acquired the higher strength of non-heat treatment steel for con-rod.

In this conference, we will report the development of the high strength non-heat treatment steels for con-rod, furthermore, the study of strengthening mechanism.

Keywords: *non-heat treatment, connecting rod, precipitation strengthening, carbon neutral*

1. Introduction

One the recent demands is to reduce CO_2 emissions and consequent environmental loads, and it eventually aims at CN (carbon neutral) in the future. When it comes to automobile, motivity electrification is one of the effective methods to reduce CO2 emission. The motivity is electrified rapidly, whereas persisting the car with engine over the next few years is predicted. Therefore, improving efficiencies of its engine is one of the effective methods to reduce CO_2 emissions as well. It is considered that the weight reduction of connecting rod (hereinafter referred to as “con-rod”), which is one of the movement parts of engine, contributes to greater efficiencies of engine, because of reducing weight of not only the con-rod itself, but also peripheral parts. Furthermore, applying non-heat treatment steel, which is strengthened without quenching and tempering, to con-rod contributes to reduce CO_2 emissions (Fig.1). On this standpoint, we have developed the higher strength steels for con-rod to meet demands and the other necessary properties, which are machinability and Fracture splitability (Fig.2).

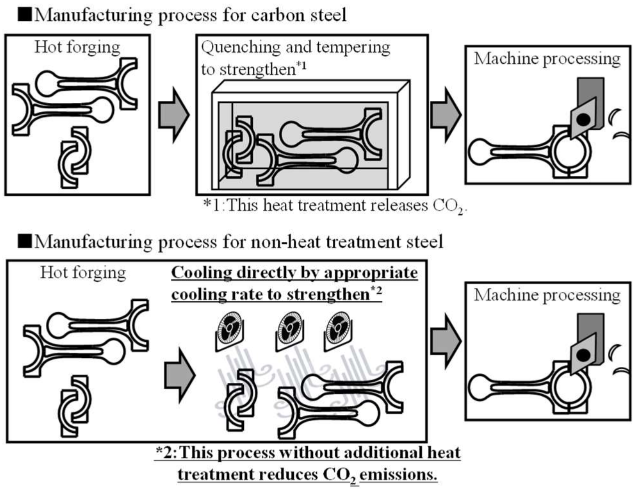

Fig.1 Manufacturing process of con-rod for carbon steel and non-heat treatment steel.

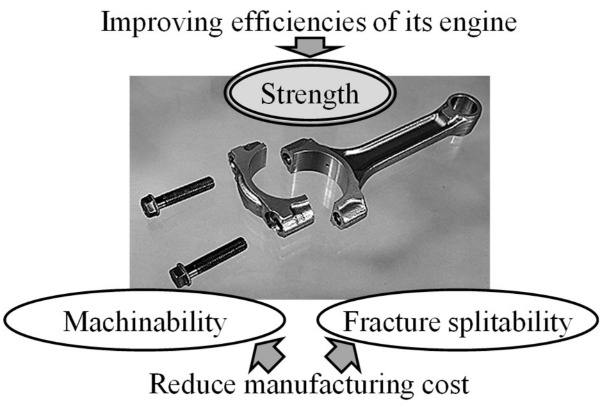

Fig.2 Necessary properties of the steels for con-rod.

2. Development of high strength non-heat treatment steels for connecting rod

2.1 Designing the chemical compositions of new steel

To strengthen the con-rod, increasing buckling strength, which is elastic limit, is required and the buckling strength is closely related to 0.2% proof stress. As shown in Fig.4 (b), the non-heat treatment steel consists of soft ferrite and hard pearlite. The general strengthening method is to increase the hardness by increasing the amount of C and then fraction of pearlite accordingly. Although, increasing hardness deteriorates machinability. Therefore, in the non-heat treatment steels, which requires both strength and machinability, 0.2% proof stress is increased without increasing hardness excessively, which means increasing yield ratio (0.2%proof stress/ tensile stress) is the effective strengthening method.

We have steel grades of up to 700MPa category as a product heretofore. Based on 700MPa category, we have designed new steel grade. First, the amount of C is increased to increase the fraction of pearlite without excessive hardening. Next, the amount of V is increased to strengthen soft ferrite by precipitating V-carbo-nitride (hereinafter referred to as “V(C,N)”).

Controlling the cooling rate after hot forging is important to get high strength of non-heat treatment steels (Fig.2). The faster cooling rate precipitates finer and more numerous V(C,N) and then strengthen the non-heat treatment steel. However, the strength would be then degraded once bainite is generated by the over-speeded cooling rate. Furthermore, increasing amount of C and V may result in the generation of bainite, as shown in (Fig.3), which would lead to the degradation of the strength, because faster cooling rate does not get obtained (Fig.4(a)). Therefore, we have focused on the differences of the bainite generation level depending on alloy elements[1]. In details, decreasing amount of Mn and increasing amount of Cr approaches have led to suppression of bainite generation caused by large amount of alloy elements (kind of C and V) added, then acquired the higher strength of non-heat treatment steel (Fig.3(b)).

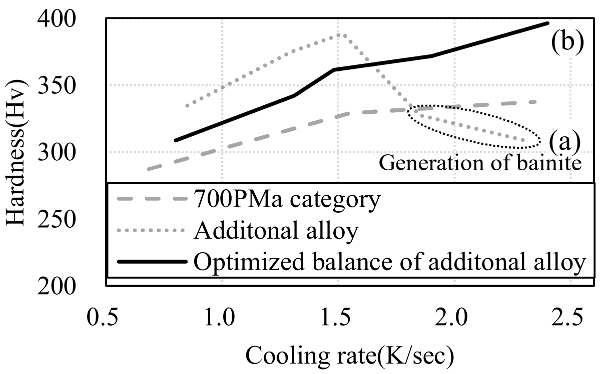

Fig.3 Relation between cooling rate and hardness on 3 steel grades.

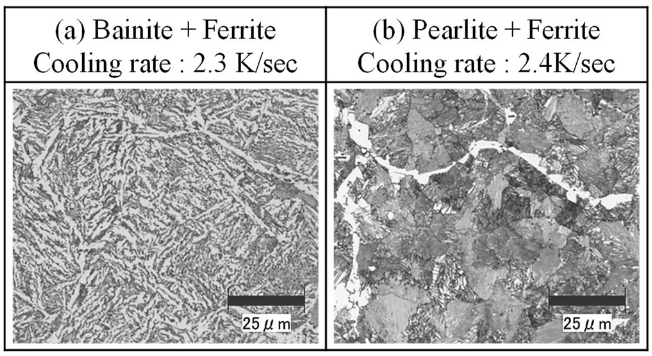

Fig.4 Microstructures of Steel (a) and (b) in Fig.3

2.2 The chemical compositions and the mechanical properties of the high strength steels for con-rod

Table 1 shows the chemical compositions of existing steel grades, which is 700 MPa category, and newly developed steel grades, which are 900MPa category. Fig.5 shows the mechanical properties of prototype con-rod created based on 900MPa category.

Table1 Chemical composition of 700 and 900MPa category.

(wt%)

Category	C	Si	Mn	P	S	Cr	V
700MPa	0.33	0.25	1.25	0.05	0.11	0.17	0.26
900MPa	0.51	0.25	0.53	tr.	0.04	0.51	0.34

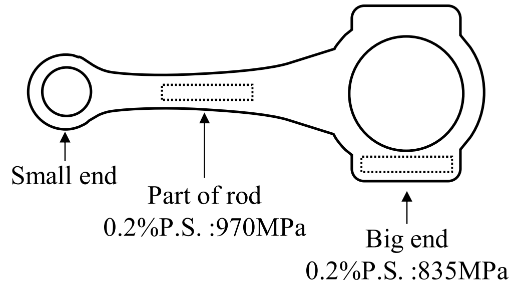

Fig.5 Strength of prototype con-rod created based on 900MPa category.

3. The study of strengthening mechanism

3.1 Verification of strengthening mechanism by increasing amount of V

Fig.6 shows the TEM images of the part of rod of con-rod in 900MPa and 700MPa category. Fig.7 shows the analytical result by EDX of (a) precipitation and (b) matrix in Fig.6.

The larger amount of V is detected at (a) precipitation than (b) matrix. Furthermore, C is also detected at (a)precipitation slightly, showing the precipitations are V carbides (hereinafter referred to as “VC”). Incidentally, N has not been detected although we assumed the precipitations are V(C,N).

The area fraction of precipitation of 900MPa category is larger than that of 700MPa. It is considered that the increasing area fraction of precipitation by additional V is one of the strengthening mechanisms.

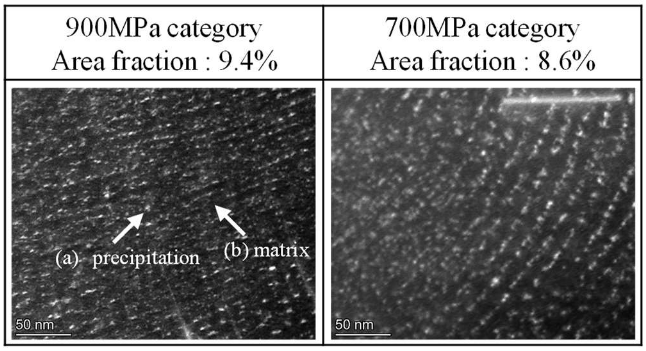

Fig.6 TEM images of part of rod

Fig. 6 (a) precipitation	Fig.6 (b) matrix

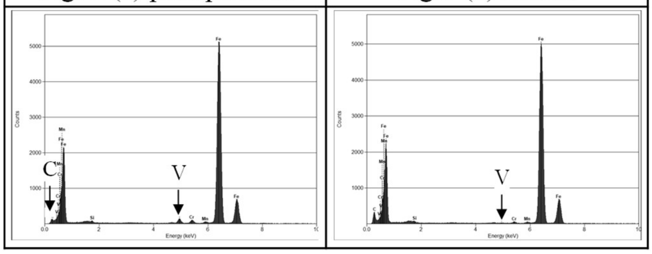

Fig.7 Composition of the precipitation and matrix which is analyzed by EDX.

3.2 Verification of strengthening mechanism by controlling cooling rate

As shown in Fig.5, the 0.2% proof stress of the part of rod is higher than that of big end. It is assumed that the cooling rate of the part of rod is faster than that of big end due to con-rod shape. Therefore, we have observed the part of rod and big end by TEM to confirm the effect of cooling rate.

Fig.8 shows the result of observations. We have confirmed that the precipitations are VC. VC of the part of rod are finer and more numerous than that of big end. Therefore, it is considered that the precipitating finer and more numerous VC by faster cooling rate after hot forging is another strengthening mechanisms.

Part of rod Average diameter : 2.89nm	Big end average diameter : 3.48nm

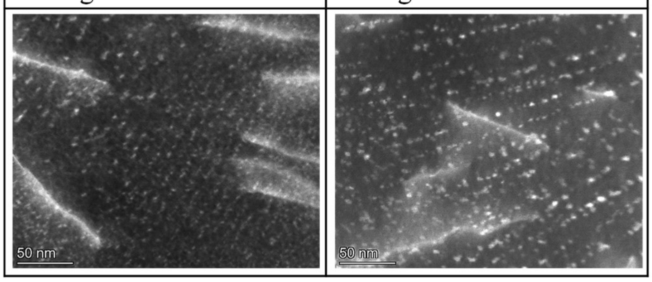

Fig.8 TEM images of part of rod and big end in Fig. 5.

We have calculated the approximate amount of precipitation strengthening by VC dispersion. We assumed that the strengthening mechanism is the precipitation strengthening by Orowan mechanism. We have used the formula of Ashby-Orowan type to calculate the amount of precipitation strengthening Δσ (MPa)[2].

$$\Delta\sigma = 0.84m\left(\frac{1.2Gb}{2\pi L}\right)\cdot ln\left(k\frac{x}{2b}\right) \cdots\cdots\cdots(1)$$

m: Taylor factor, *G*: modulus of rigidity, *b*: Burgers vector, *L*:interparticle distance on slip plane (= $r(2\pi/3f)^{1/2}-r$), *x*: average cross-section diameter on slip plane (= $2r/\pi$), *k*: coefficient of modification (2.7 in ferrite), *r*: radius of VC, and *f*: volume fraction of particles. We have used 2.89nm at the part of rod, 3.48nm at big end as *r* (the radius of VC), and 0.59vol%, which is calculated assuming that all amount of additional V(= 0.35 wt%) precipitates as VC, as *f* (volume fraction of particles). Table 2 shows the result of calculations. The difference of 0.2% proof stress experimentally between the part of rod and big end is 135MPa. On the other hand, the difference of precipitation strengthening is 93MPa, similar to the difference of 0.2% proof stress. Therefore, it is considered that strengthening by faster cooling rate is caused by finer and more numerous VC.

Table2 Comparison between experimental proof stress and calculated value of precipitation strengthening.

		0.2% proof stress _Experimental (MPa)	Precipitation strengthening _calculated (MPa)
(a)	Rod	970	790
(b)	Big end	835	697
	(a) – (b)	135	93

4. Summary

We have developed the high strength non-heat treatment steels for con-rod to meet increasing demands for lighter con-rod and less CO_2 emission by abbreviating quenching and tempering. In order to strengthen, amount of C and V are increased, and the balance of Mn and Cr are optimized which resulted in suppression of bainite generation, then we have acquired the higher strength non-heat treatment steels.

Furthermore, we have studied about the strengthening mechanism and verified below two points.

(1) Additional V increases the area fraction of precipitation (VC), then the amount of precipitation strengthening was increased.

(2) The faster cooling rate resulted in the finer and more numerous precipitations, then the amount of precipitation strengthening was increased.

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