An Approach to Increase Strength of Materials for Built-up Type Crankshafts

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Abstract

Recently, there is an increasing need for improving the efficiency of low-speed diesel engines for ships. In response, Kobe Steel has newly developed an inexpensive low-alloyed steel for semi-built-up type crankshafts. This steel has a high yield point and high fatigue strength while avoiding the risk of quench cracking, which often occurs in large, forged steel products. Crank throws were manufactured from multiple steel types, including the newly developed steel, and the material properties of samples of steel pieces taken from their major parts were evaluated. The results confirmed that the newly developed steel has mechanical properties and a fatigue strength superior to those of conventional steel. It is expected that this newly developed steel will be applied to next-generation engines and contribute to compliance with environmental regulations, which are expected to become increasingly stringent.

Introduction

In response to the more stringent exhaust gas regulations in recent years, the principal engines of large ships are mainly designed to have high internal pressure and long stroke to improve fuel efficiency. As a result, semi-built-up type crankshafts, which convert the reciprocating motion generated by the explosion force of engines into rotational motion, are exposed to large bending stress generated in the pin fillets of their crank throws. In addition, a large rotational torque is generated between each throw and journal that are shrink-fitted. Environmental regulations are planned to be gradually strengthened in the future,[1)] and it is expected that pin fillets and shrink fit parts will be subjected to an increasingly heavy load. Therefore, a high fatigue strength is required for the material of each crank throw to prevent fatigue fracture in the pin fillet. In addition, it is necessary to increase the gripping torque of each shrink-fitted journal to prevent micro-slippage. Hence, material properties with a high yield point are required near the shaft hole of an arm into which a journal is inserted during shrink fitting.

Semi-built-up type crankshafts are mainly made of carbon steel that has been heat-treated by air cooling after normalizing treatment. The tensile strength of the carbon steel is mainly specified to be about 600 MPa. A general method of improving the yield point and fatigue strength includes obtaining a martensitic and/or bainitic microstructure with high tensile strength by quenching during the heat treatment. In the case of large, forged steel products, however, the cooling rate becomes insufficient due to the large mass effect, disabling the transformation of carbon steel. Therefore, low-alloyed steel whose quenching property is enhanced by the addition of elements such as Ni, Cr, and Mo has been selected as a high strength material. The material for semi-built-up type crankshafts is low-alloyed steel strengthened to 800 MPa class.

Quenched low-alloyed steel with high strength, however, is not widely applied to medium or large-sized engines with a cylinder diameter of 500 mm or greater.[2)] The reason is that, as the size increases, the risk of cracking upon quenching during heat treatment increases in crank throws that have complicated shapes.[2)] Hence, Kobe Steel has developed a low-alloyed steel with a high strength of 800 MPa class in order to improve the yield point and fatigue strength required for the throws of semi-built-up type crankshafts. The newly developed steel requires no quenching and can avoid the risk of quench cracking peculiar to large crank throws.

On the other hand, the fatigue strength of material is known to be affected by the size of internal defects, such as non-metallic inclusions, decreasing as the defect size increases.[3)] Hence, Kobe Steel has developed a super-clean steel process technology for reducing non-metallic inclusions, which become the initiation points for fatigue cracks.[2)] This process has been confirmed to improve the fatigue strength of large, forged steel products.[4), 5)] However, no fatigue characteristics have been verified when it is applied to a semi-built-up type crankshaft.

This paper outlines the mechanical properties and fatigue strength of crank throws (hereinafter referred to as "throws"), applying the technology for the newly developed steel and super-clean steel process, while comparing them with the ones for conventional steel.

1. Manufacturing and material of semi-built-up type crankshafts

Fig. 1 shows the manufacturing process of semi-built-up type crankshafts. A steel ingot cast after melting and smelting is heated and formed into a throw shape by forging and gas cutting. The forming of throws involves four types of methods, each of which is shown in **Fig. 2**. After the forming, the material is heat-treated to obtain the required mechanical properties, and then machined. Next, each journal of the shaft and the throw of the respective eccentric part are connected by shrink-fitting and finished to the specified dimensions by a final machining.

Table 1 shows the chemical composition and method of heat treating the steels prepared in this new process. Also, **Table 2** shows the steel-type manufacturing method, as well as the standard strength in yield point (YP) and tensile strength (TS), of the crank throw. Table 1 includes 32CrNiMo6-3, which is the steel newly developed by Kobe Steel. This steel is air-cooled after normalizing during heat treatment (normalized & tempered). It should be noted that the composition of this steel is designed to make its metallographic structure similar to that of the conventional low-alloyed steel (34CrNiMo6), which is quenched and tempered. Therefore, the newly developed steel has the same strength as the conventional low-alloyed steel, but can avoid the quench cracking peculiar to large, forged steel. It should also be noted that the smelting of No. 1

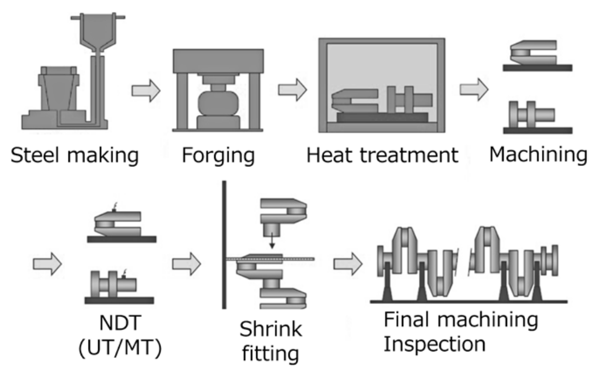


Fig. 1 Manufacturing process of semi-built-up type crankshaft

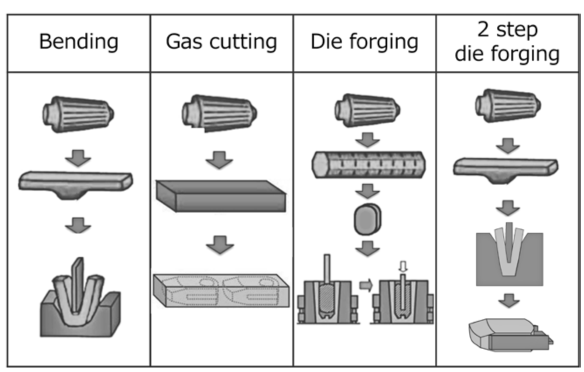


Fig. 2 Forging methods of crank throw

Table 1 Chemical composition and heat treatment methods of test steels

Steel type		Chemical composition (wt%)							Heat treatment
		C	Si	Mn	Ni	Cr	Mo	V	
32CrNiMo6-3 (developed alloy steel)	Max.	0.40	0.40	1.50	1.10	1.60	0.40	0.20	Normalized & tempered
	Min.	0.25	0.15	0.80	0.60	1.10	0.15	—	
34CrNiMo6 (conventional alloy steel)	Max.	0.38	0.40	0.70	1.70	1.70	0.30	—	Quenched & tempered
	Min.	0.30	—	0.40	1.40	1.40	0.15	—	
Carbon steel (conventional steel)	Max.	0.50	0.40	1.40	—	0.30	—	0.12	Normalized & tempered
	Min.	—	—	1.00	—	—	—	0.06	

Table 2 Forged crank throws manufactured from test steels

Throw No.	Steel type	Steel making process	Cylinder size (mm)	Forging method	Specified strength	
					YP (MPa)	TS (MPa)
1	32CrNiMo6-3	Super clean (Developed)	950	2 step die forging	≧590	≧780
2	34CrNiMo6	Tap degassing (conventional)	500	Gas cutting	≧590	≧780
3	Carbon steel	Tap degassing (conventional)	600	Die forging	≧350～370	≧590～610
4	Carbon steel	Tap degassing (conventional)	600	Gas cutting	≧350～370	≧590～610
5	Carbon steel	Tap degassing (conventional)	960	2 step die forging	≧350～370	≧590～610

throw shown in Table 2 has adopted the super-clean steel process technology, which reduces S and O in molten steel and promotes the floating separation of inclusions generated by dissolved oxygen, to reduce both sulfide-based and granular oxide-based inclusions. This has enabled the preparation of a steel ingot with high cleanliness.

In the present approach, the materials shown in Table 2 have been examined, as well as the yield point and fatigue strength in the vicinity of the arm-shaft holes and pin fillets of throws made by different methods. The following sections describe what has been done.

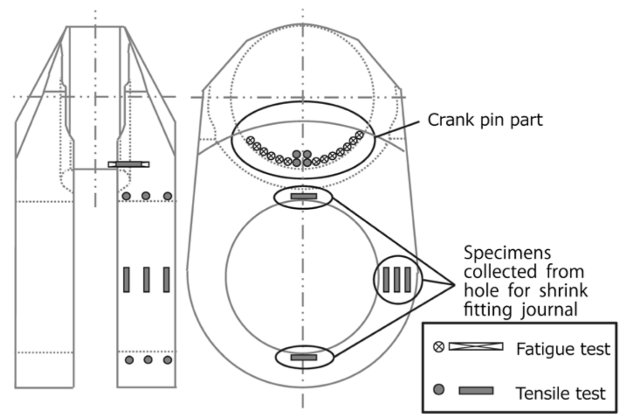


Fig. 3 Collection locations of tensile and fatigue test pieces

2. Investigation and test method for semi-built-up type crankshaft

2.1 Preparation of test pieces

The steel pieces for tensile testing and fatigue testing were collected from the vicinity of the shaft hole and the crank pin in the arm of a throw produced by the actual manufacturing process. **Fig. 3** shows the collection position of each test piece. From these steel pieces, tensile test pieces were prepared in accordance with JIS 14A (ϕ14 × 70 mm), and fatigue test pieces were prepared as smooth test pieces, each with a parallel part of ϕ10 × 30 mm.

2.2 Fatigue tests

An axial force fatigue test (push-pull) was performed on the fatigue test pieces prepared. The staircase method[6)] recommended by the International Association of Classification Societies (IACS) was used to evaluate the fatigue characteristics. The fatigue test procedure following the staircase method is as follows:

① For the first test piece, a fatigue test is performed at a stress level that is assumed to be close to the mean S_N of fatigue strength.

② For the second test piece:
②-(1) In the case where the first test piece runs out after predetermined cycles (N_0 = 2 × 10^6 cycles) are loaded during Test ①, the fatigue test is to be carried out at increment stress amplitude by d.
②-(2) In the case where the first test piece fails before predetermined cycles (N_0 = 2 × 10^6 cycles) are loaded during Test ①, the fatigue test is to be carried out at decrement stress amplitude by d.

③ On the basis of the results of the second test, the fatigue test is continued by changing the stress level acting on the third test piece by d.

④ The same test is repeated hereafter.

In this procedure, the differential stress d is selected so that it is as close to the standard deviation of fatigue strength as possible. The obtained results are evaluated in accordance with the following procedure.

$$F=\sum f_i,\ A=\sum if_i,\ B=\sum i^2 f_i \quad \cdots\cdots (1)$$

wherein, i: Numbering of the stress levels,
f_i: Number of test pieces at the stress level i.

It should be noted that i and f_i in Eq. (1) are to be counted only for the less frequent event, run-out or failure, that occurs in all of the test results.

Using the above F, A, and B, the mean value S_N and standard deviation s of the fatigue strength are calculated by the following equations:

$$S_N = S_{a0} + d\left(\frac{A}{F} \pm \frac{1}{2}\right) \quad \cdots\cdots (2)$$

$$s = 1.62d\left(\frac{BF - A^2}{F^2} + 0.029\right) \quad \cdots\cdots (3)$$

Here, S_{a0} is the minimum stress level. It should be noted that regarding the operator in Eq. (2), ±, the operator is to be negative if the number of failures is lower than that of run-outs, and vice versa.[6)]

This method allows the mean fatigue strength and standard deviation to be obtained, enabling statistical evaluation of the fatigue strength. In this paper, the differential stress d has been selected to be 25 MPa.

3. Test results and evaluation

3.1 Results of tensile test for shrink fit part

Fig. 4 shows the relationship between the yield point and the tensile strength of the test pieces collected from the vicinity of the journal shaft hole in each arm of No. 1 to 5 throws. It is shown that the yield point and tensile strength of the newly developed steel are greatly improved compared with those of the carbon steel. Also, they are equal to or higher than those of 34CrNiMo6, which is the target of the strength class, showing that they exceed the standard strength exhibited in Table 2.

3.2 Material properties of crank pins

3.2.1 Results of tensile test

Fig. 5 shows the relationship between the yield point and the tensile strength of the test pieces collected from the crank pins of throws No. 1 to 5. The yield point and strength of the newly developed steel are much higher than those of the benchmark, not to mention those of the carbon steel, showing a large margin with respect to the standard strength shown in Table 2.

3.2.2 Results of fatigue test

Fig. 6 shows the results of the fatigue test of the test piece collected from the crank pin of the crank throw made of the newly developed steel. Since there are 4 broken test pieces and 9 unbroken test pieces, the numbering is targeted at the broken test pieces, which have occurred less frequently. Since the minimum stress S_{a0} when the breakages have occurred is 460 MPa, the mean fatigue strength and standard deviation have been calculated by substituting the respective values into Eq. (1) to (3).

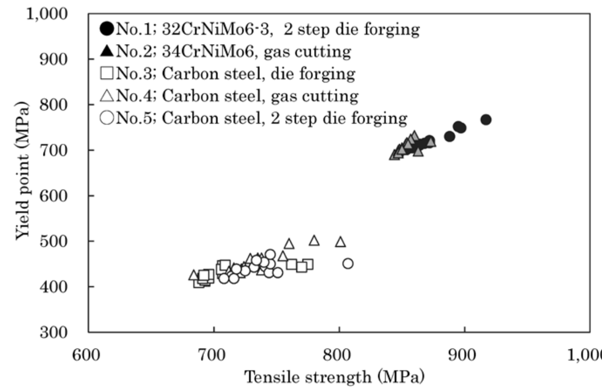


Fig. 4 Tensile test results of specimens collected from crank arm in the vicinity of hole for shrink fitting journal

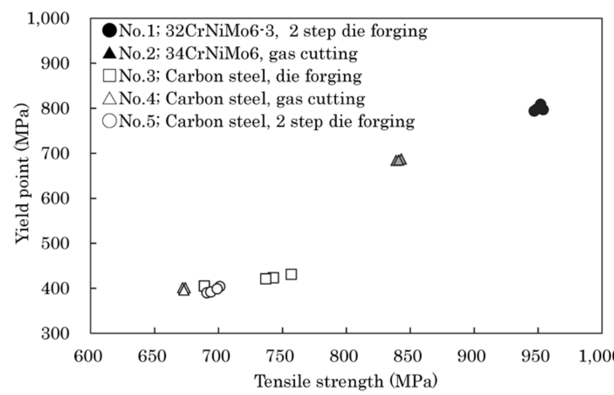
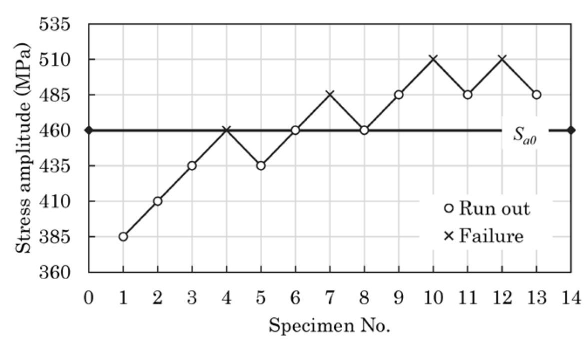


Fig. 5 Tensile test results of specimens collected from crank pin



S_a (MPa)	i	fi	ifi	i^2fi
510	2	2	4	8
485	1	1	1	1
460	0	1	0	0
	Σ	F = 4	A = 5	B = 9

Fig. 6 Result of fatigue test using staircase method on developed steel

$F=4,\ A=5,\ B=9,$

$$S_N=S_{a0}+d\left(\frac{A}{F}\pm\frac{1}{2}\right)=460+25\times\left(\frac{5}{4}-\frac{1}{2}\right)$$
$$=478.8\,(\mathrm{MPa})$$
$$s=1.62d\left(\frac{BF-A^2}{F^2}+0.029\right)$$
$$=1.62\times25\left(\frac{9\times4-5^2}{4^2}+0.029\right)$$
$$=29.0\,(\mathrm{MPa})$$

As with the newly developed steel, the mean fatigue strength and standard deviation have been calculated for the conventional steel by the staircase method. The results are summarized in **Table 3**.

3.3 Evaluation of fatigue characteristics

For the statistical evaluation of fatigue characteristics based on the staircase method, IACS recommends the evaluation be made using the lower limit strength of the confidence interval, assuming that the fatigue strength is normally distributed.[6)] When X = (1- α) × 100%, the lower limit of fatigue strength $S_{aX\%}$ at the X% confidence interval is calculated by Eq. (4).[6)]

$$S_{aX\%}=S_N-t_{\alpha,\,n-1}\cdot\frac{s}{\sqrt{n}}\quad\cdots\cdots\cdots\ (4)$$

Table 3 Mean fatigue strength and standard deviation of test steels for crank throws

No.	steel type	d (MPa)	n	S_N (MPa)	s (MPa)
1	32CrNiMo6-3	25	13	479	29.0
2	34CrNiMo6	25	13	438	17.4
3	Carbon steel	25	13	313	1.2
4	Carbon steel	25	13	263	1.2
5	Carbon steel	25	13	313	1.2

d: Stress increment or decrement
n: Total number of the fatigue test specimens
S_N: Mean fatigue strength
s: Standard deviation

wherein, $t_{\alpha,\,n\text{-}1}$: Inverse function of t-distribution with one-sided probability α and degrees of freedom n-1, and
n: Number of test pieces.

The IACS proposes to use 90% normally as the confidence interval.[6)] Accordingly, the calculation has been performed by substituting the lower limit of fatigue strength $S_{a90\%}$ of the 90% confidence interval when α = 0.1 into Eq. (4).

Meanwhile, crankshafts applied to marine engines must satisfy the designed fatigue strength specified by the classification society. In this paper, fatigue characteristics were evaluated by comparing them with the designed fatigue strength σ_{DW} specified by IACS.[6)] σ_{DW} is calculated by Eq. (5).[6)]

$$\sigma_{DW}=\pm\mathrm{K}\,(0.42\sigma_B+39.3)$$
$$\times\left(0.264+1.073D^{-0.2}+\frac{785-\sigma_B}{4900}+\frac{196}{\sigma_B}\sqrt{\frac{1}{R_H}}\right)\quad\cdots\cdots\ (5)$$

wherein, D: crank pin diameter (mm)
R_H: pin fillet radius (mm)
σ_B: tensile strength (MPa)
K: coefficient for manufacturing process.

For the coefficient K for the manufacturing process, 1.0 is given to the crankshaft manufactured by free forging, and 1.05 is given to the crankshaft manufactured by the continuous grain flow (CGF) forging.[6)] Kobe Steel has obtained special approval from all classification societies for applying K = 1.15 to the solid type crankshafts manufactured by the super-clean steel process. The manufacturing process with high coefficient K allows a crankshaft to be designed with high fatigue strength.

All of the these evaluated crankshafts are manufactured by free forging. Therefore, 1.0 is to be substituted into Eq. (5) to calculate $\sigma_{DW,\,K=1.0}$ and the fatigue strength of each throw is evaluated with normalized $S_{a90\%}$ of each one by $\sigma_{DW,\,K=1.0}$. The results are shown in **Table 4**. It should be noted that the

Table 4 Evaluation of fatigue characteristics at lower limit of fatigue strength with 90% confidence interval

No.	steel type	① σ_B (MPa)	② D (mm)	③ R_H (mm)	④ $\sigma_{DW,\,K=1.0}$ (MPa)	⑤ $t_{0.1,\,n\text{-}1}$ (MPa)	⑥ $S_{a90\%}$ (MPa)	⑥ / ④
1	32CrNiMo6-3	951	1,220	90	224	1.4	468	2.09
2	34CrNiMo6	841	645	40	229	1.4	431	1.88
3	Carbon steel	732	720	45	209	1.4	312	1.49
4	Carbon steel	673	730	55	197	1.4	262	1.33
5	Carbon steel	696	990	70	194	1.4	312	1.61

σ_B: Average tensile strength result of crank pin part
D: Diameter of crank pin
R_H: Radius of crank pin fillet
$\sigma_{DW,\,K=1.0}$: Designed fatigue strength (K=1.0)
$t_{0.1,\,n\text{-}1}$: Inverse function of t-distribution with one-sided probability α of 0.1 and degrees of freedom n-1
$S_{a90\%}$: Fatigue limit resulted from 90% confidence interval

tensile strength σ_B is the mean value of the tensile strength at the pin fillet of each crank throw plotted in Fig. 5. It is shown that the values of $S_{a90\%}/\sigma_{DW,\ K=1.0}$ for each throw are 1 or greater, which exceeds the designed fatigue strength. In particular, the crank throw manufactured by applying super-clean steel process technology and two-step die forging has excellent fatigue characteristics equivalent to $K = 2.09$ and has a large margin against the designed fatigue strength.

Conclusions

Test pieces have been collected from crank throws made of the newly developed steel and conventional steel, and their mechanical properties and fatigue characteristics have been evaluated. The following is an overview of the results:

- The vicinity of the journal shaft hole in the arm of a crank throw made of the newly developed steel has a higher yield point than the ones made of conventional steel. It also has a yield point higher than the strength standard for the conventional low-alloyed steel.
- The crank throw of the newly developed steel, the throw manufactured by super-clean steel process technology and die forging, has a high fatigue strength and its lower limit fatigue strength at 90% confidence interval is converted into the coefficient of designed fatigue strength specified by IACS UR M53 to be 2.09, indicating excellent fatigue characteristics.

On the basis of these results, Kobe Steel has obtained a special approval from many classification societies including Class NK that the newly developed steel, 32CrNiMo6-3, is the material for built up crank shafts, whose specified yield point is 650 MPa and tensile strength is 850 MPa, which are higher than conventional low-alloyed steels. In addition, the semi-built-up type crank throw made of newly developed steel through super-clean steel process technology and die forging has obtained a special approval for 1.15 as the value of the coefficient K for the manufacturing process, the coefficient in Eq. (5) for designed fatigue strength, as in the case of a solid crankshaft.[2)] As a result of obtaining these approvals, it has become possible to design the gripping torque and fatigue strength of semi-built-up type crankshafts to be higher than before by applying the above described original Kobe Steel technology.

It is expected that the newly developed steel and manufacturing technologies will be applied to the next generation engines and contribute to the response to environmental regulations, which are becoming increasingly stringent.

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