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Technical Report

Development of Technologies for Lightening Crankshafts

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Abstract

Recently, for environmental protection, technology for reduction of fuel consumption of automobiles has become increasingly important and, thus, demand for weight reduction of the crankshaft, which is one of the most important parts in an internal combustion engine, has strengthened. For lightening the crankshaft weight, some methods to equip each pin shoulder of a crankshaft with a lightening hole by drilling or hot forging have been proposed and applied to real products. However, in those methods, there may be some constraints on such as production cost, obtained stiffness of the product, and so on. Therefore, a new crankshaft design has been developed to satisfy both weight reduction and sufficient stiffness of a crankshaft, instead of providing lightening holes. A new forging method to make such a new lightweight crankshaft has already been developed. By trial forging at a forging workshop in Nippon Steel Corporation, it has been confirmed that the new forging method is sufficiently applicable to mass production while successfully satisfying demand for both light weight and sufficient stiffness of the crankshaft.

1. Introduction

Recently, to protect the environment, exhaust gas emissions regulations for automobiles have been becoming severer and the need for higher fuel economy has been intensifying. Therefore, there is demand for crankshafts, which are important engine parts, to be lighter. In addition, automobiles have been rapidly motorized. For example, on series electric hybrid vehicles for which engines mainly for power generation are adopted, the total weight of the vehicles needs to be reduced from the perspective of energy efficiency and thereby the weight of crankshafts should be reduced.

Nippon Steel Corporation manufactures crankshafts by hot forging. Considering the situation mentioned above, reducing the weight of forged crankshafts to contribute to the automobile industry is a crucial task. Forged crankshafts are superior to cast ones from the perspectives of the strength and rigidity. However, as the shape is more complicated, the volume of flash, which are excess materials extruding from the die at the time of forging, increases, which reduces the forging yield, so it is not easy to form complicated shapes at low cost for the purpose of weight reduction.

Meanwhile, the hollow pin method has recently been put to practical use as a method to actively reduce the weight of crankshafts. In this method, the pin shoulder sections on the pin side of a crank arm are cored by machining or hot forging for weight reduction and thereby the weight of the counterweight sections that maintain the weight balance to the pin side is also reduced. However, this method has large restrictions from the perspectives of cost and rigidity.

To solve such a problem, Nippon Steel has developed a new shape that can achieve weight reduction and higher rigidity at the same time. For the shape, instead of boring a pin shoulder, the entire pin shoulder is made thinner and the outer edge of the pin shoulder of the arm is made thicker. This shape is expected to reduce the weight as compared with the design with a hole and thereby the performance of Nippon Steel's crankshafts will have an advantage. In addition, as a manufacturing method to realize the shape, Nippon Steel has developed a new method in which a pin shoulder is not dented in the later manufacturing process, but the outer edge of the pin shoulder of an arm section that has been formed to be thin in advance is bent to make it thick. The effectiveness was verified in a mass production trial. This paper describes the details.

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2. Crankshafts and Current Weight Reduction Methods

2.1 Performance required for crankshafts

Figure 1 illustrates a typical crankshaft for in-line-4 engines. A crankshaft is a rotary part that converts the reciprocating motions of the pistons by explosions occurring in the cylinders into rotary motions. The explosive power from the cylinders is transmitted to the pins off-center from the axis via the connecting rods. To reduce the rotary eccentric force produced at this time, counterweights are provided on the opposite sides between the pins and the journal shaft to maintain the weight balance.

Crankshafts need to have sufficient fatigue strength to bear the explosion loads described above. They should also be rigid enough for quietness and other purposes. Meanwhile, they should be lightweight for higher fuel economy, and so satisfying strength, rigidity, and light weight is key in the design. Of engine parts, crankshafts are heavier, so they significantly affect the fuel economy. Therefore, in conventional design, for example, dents called lightening pockets shown in Fig. 1 are formed on the axial center to reduce the thickness partly for weight reduction.

2.2 Nippon Steel's past design for reducing the weight of crankshafts

A crankshaft can be divided into the pin side and the counterweight side with the journals, which are the central axes of rotation, as the boundary. Nippon Steel's approach for weight reduction and optimization of the pin side is different from that for the counterweight side.

Specifically, first, the design of the pin side is optimized by the traction method. Then, the counterweight side that keeps the balance with the pin side is optimized by the three-moment method. This section describes the details.

(a) Optimization of the shape of the pin side by the traction method

The traction method[1, 2] is one means to optimize a shape using the surface shape as a design variable. Specifically, sensitivity coefficients for objective functions are calculated for each node in FEM analysis, the nodes are moved based on the sensitivity coefficients, and this operation is repeated to obtain an optimum shape by changing the shape step by step. In designing the pin side, the rigidity was used as a constraint, the mass and radius of center of gravity were determined as objective functions, and the traction method was used for optimization. Specifically, general-purpose software Optishape[3] was used to optimize the shapes of the pin shoulder section, lightening pocket section, and other sections considering restrictions in forging such as draft angle and minimum wall thickness. This approach can obtain an optimum (lightest) shape directly without assuming design parameters (e.g., thickness of each section and R). **Figure 2** shows an example.

(b) Optimization of the shape of the counterweight side by the three-moment method

The three-moment method is a means to estimate the bearing load during operation assuming a quasi-static state based on continuous beam theory. **Figure 3** illustrates weight reduction of a counterweight using this method. A crankshaft closely resembles a stepped continuous beam supported at multiple points. The bearing load is used as a constraint and the mass of each counterweight is determined as the design variable. By optimization under these conditions, the optimum weight distribution on the counterweight is determined and design for weight reduction is made.

2.3 Outline of the hollow pin method

As mentioned previously, recently, the hollow pin method in which the pin shoulder section is cored has been used. This section describes its effects and current problems.

2.3.1 Coring of pins and its advantages

Crankshafts are rotary parts. To rotate a crankshaft smoothly, the balance between the pin side and the counterweight side needs to be considered as mentioned previously. When the mass of the pin side is m, the radius of center of gravity is r, the mass of the counterweight side is M, and the radius of center of gravity is R with the journal shaft as the boundary as shown in **Fig. 4**, the crankshaft is designed such that the mass moment on the pin side (mr) and that

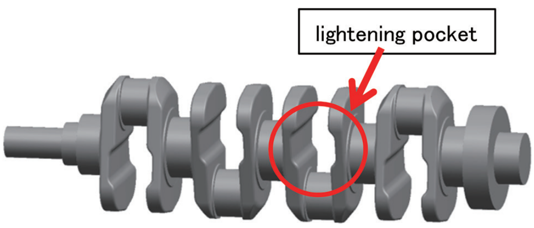


Fig. 1 Crankshaft for in-line-4 engines

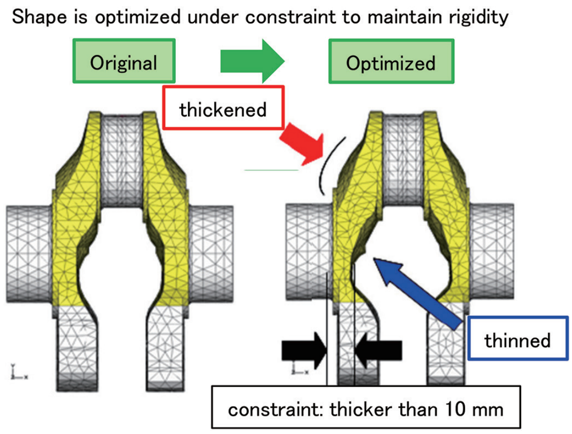
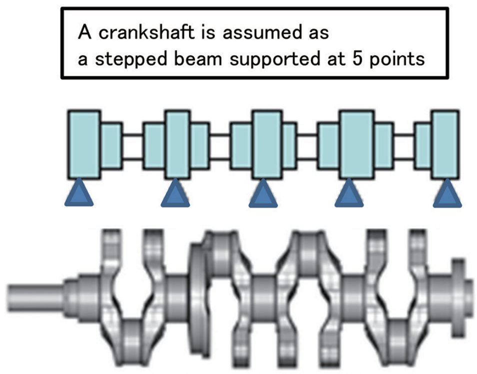


Fig. 2 Design optimization based on traction method



<Optimization conditions>

objective function	mass of C/W
constraint	maximum journal bearing load
design variable	mass of C/W radius of center of gravity of C/W

Fig. 3 Counterweight (C/W) optimization based on three-moment-method

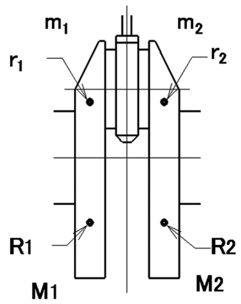


Fig. 4 Mass and radius of center of gravity of pin side and counter-weight side of each arm

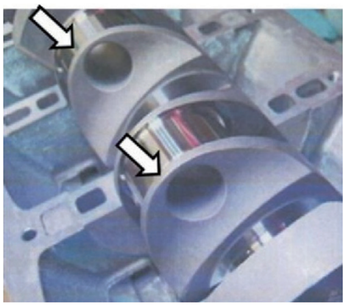


Fig. 5 Drilled holes in pins

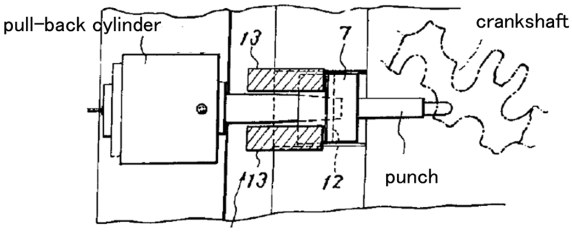


Fig. 6 Schematic drawing of punching system to make a hole in a pin

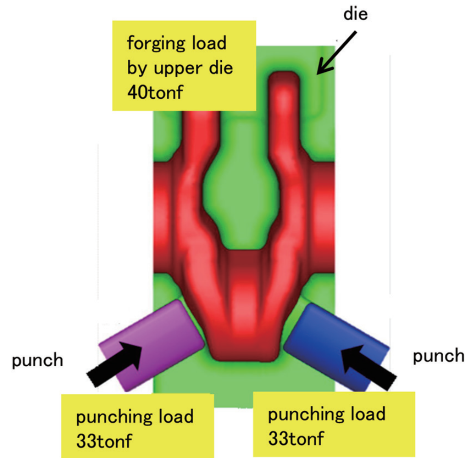


Fig. 7 FEM model of hole making analysis at pin shoulders with punch

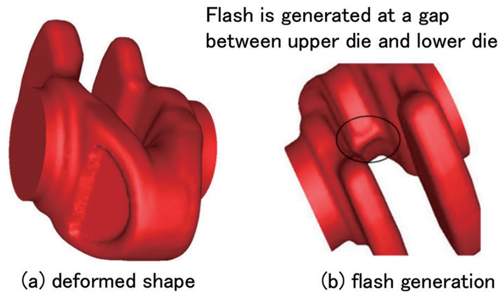


Fig. 8 Analytical result of hole making process

on counterweight side (MR) are in balance. Therefore, reducing the weight of the pin side can reduce its mass moment and thereby the weight of the counterweight side can also be reduced by the same mass moment.

In the hollow pin method, a hole is bored at a location away from the journal shaft, so the radius of center of gravity on the pin side can be reduced in addition to reduction of the mass. For this reason, it can greatly reduce the weight of the entire crankshaft. Thus, the hollow pin method can produce double weight reduction effects, so it can be said that the method is more effective than conventional weight reduction methods.

2.3.2 Example conventional coring of pins and problems

(a) Coring by machining

Figure 5 shows holes bored on pins by machining as an example. There are multiple ways to core pins; a pin is cored to midway in one method and a hole is pierced in another method. Both methods require a machining process that increases the manufacturing cost. In addition, the volume of the hole is removed by boring, which decreases the yield.

(b) Denting with a punch

As an example coring of pins by hot forging, equipment and manufacturing processes were studied based on the utility model that Nippon Steel filed.[4] **Figure 6** illustrates the equipment structure of the aforementioned utility model. Lowering the press pushes the boring tool (punching die) out via the cam as the mechanism. After boring, the cylinder pulls the punch back.

Figure 7 shows an analysis model in which a punching die is thrust into a pin shoulder as is the case with the utility model above. **Figure 8** shows that deformation occurred at the bottom of the pin. As shown in the figure, it has been found that, when the punching die is thrust into the pin shoulder section, the material is pushed out to the opposite side, which deforms part of the pin, causing flash.

In addition, force as high as 33 tonf is required to thrust a single punching die, so new equipment with high pressurization force needs to be installed to apply this method in practice.

Therefore, the authors started developing a new technology for coring pins that can realize the two items listed below:

- Coring is feasible by a series of forging without machining,
- No strain is generated around the target section by coring of a pin.

To establish such a weight reduction technology, the authors started working to design a new shape and develop a manufacturing method.

3. Development of a Weight Reduction Method Unique to Nippon Steel

3.1 Basic shape contributing to rigidity

To develop a shape that can reduce the weight of crankshafts while satisfying the rigidity, the authors first studied deformation working on a crankshaft under operation.

Explosive power is input to an off-center pin of a crankshaft as shown in **Fig. 9**(a) and thus the arms on both sides of the pin start opening in an inverted “v” shape, which causes bending deforma-

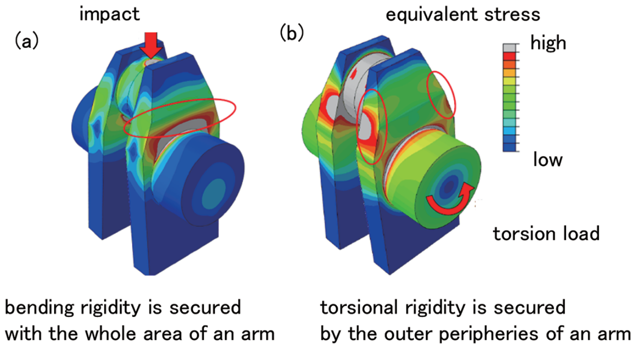
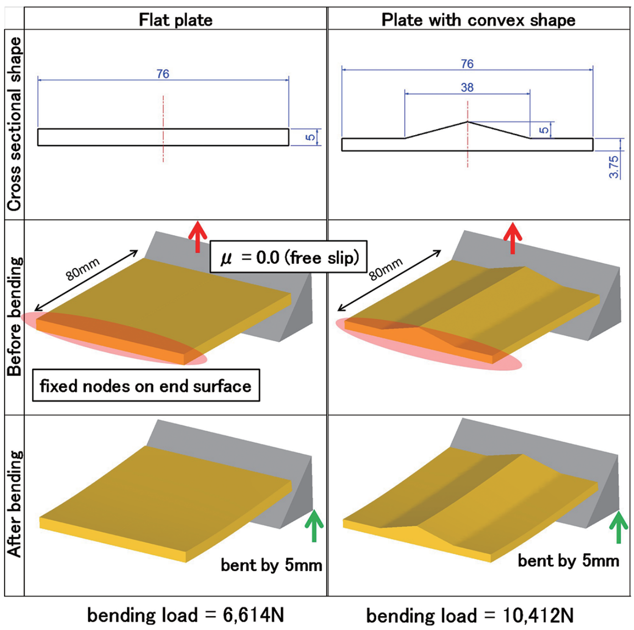


Fig. 9 Distribution of caused equivalent stress by (a) Bending and (b) Torsion

Table 1 Sheet bending analysis

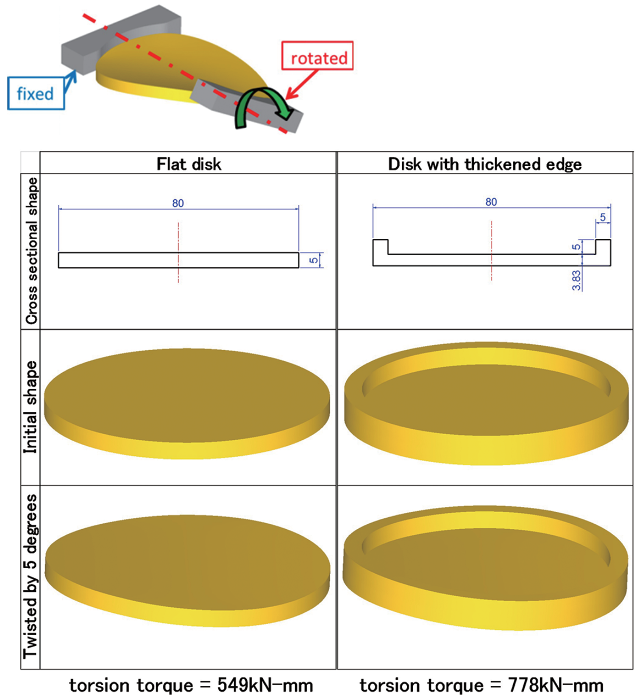


tion. Meanwhile, the pin rotates at the same time, which causes torsional deformation on the arms. Therefore, a crankshaft needs to have rigidity against bending deformation and torsional deformation.

Next, a shape that contributes to bending rigidity and torsional rigidity was studied using a simple model. Generally, regarding the bending deformation of sheet members, increasing the moment of inertia of area by increasing the thickness of the transverse section enhances the rigidity. **Table 1** shows the analysis results of bending deformation of sheets. The material was S45C at room temperature of 20°C. This also applies to the cases in **Table 2**. The commercial software DEFORM-3D was used for elastic analysis.

The left-hand column in Table 1 shows an example where a sheet with a width of 76 mm, length of 80 mm, and thickness of 5 mm was fixed at one end in the length direction and a tool having an inclined plane was used to apply force to the other end (upper direction in the figure) when the friction coefficient was determined as zero. The right-hand column shows the analysis results when a sheet having a convex cross section whose thickness at its center was 8.75 mm and whose thickness of the outer edge was 3.75 mm was bent.

Table 2 Disk twisting analysis



As specified in the table, although the cross-sectional areas of the two types are the same, the force required to give the same deformation volume is larger for the convex cross section than that for the sheet with even thickness. These results show that, for example, when the wall thickness around the center of the arm connecting a pin and journal is selectively maintained and secured and the outer edge is thinned, the weight can be reduced while the bending rigidity is maintained.

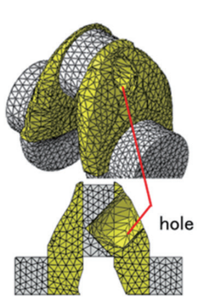
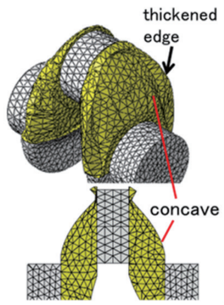
Meanwhile, the thickness at the outer edge of a sheet member significantly contributes to the torsional rigidity. Table 2 shows example torsional deformation elastic analysis of disks. The left-hand column in the table shows an example where a disk with a diameter of 80 mm and a thickness of 5 mm was fixed at one side and the other side was twisted and deformed until it tilted by 5°. The right-hand column shows the results for a disk having a 5-mm-wide and 5-mm-high outer rim with a bottom thickness of 3.83 mm whose volume and outer diameter were kept the same as those of the sheet on the left. The torque required to twist 5° is indicated in the table. Even though the volume and outer diameter were the same for the two types of disks, the disk having the outer rim required larger torque. This result shows that thickening of the outer rim is effective against twisting.

From the results above, this principle is used to reduce the weight of pin shoulder sections in our weight reduction design. The following sections describe the design, manufacturing method, and equipment development targeting standard crankshafts for in-line-4 engines.

3.2 Concept of weight reduction design

Table 3 shows the shape of a thinner pin shoulder optimized based on the basic concept described in the previous section along with an example shape that was simply bored. On the boring example, the narrow area at the center is dented by a hole. On the other hand, in the new design, a wide range of the pin shoulder is entirely

Table 3 Comparison of pin shoulder shape between models with a drilled hole and newly designed

	Pin shoulder with a hole	New design
Shape		
Bending rigidity	7.85x10^5 N/mm	7.85x10^5 N/mm
Torsional rigidity	4.44x 10^5 Nm/rad	4.44x 10^5 Nm/rad

formed to be thin and only the outer circumference of the arm is thickened, which reduces the weight while satisfying the rigidity. Specifically, the arm is thicker near its center to secure bending rigidity and the arm becomes thinner at the pin shoulder section toward the outer edge to reduce the weight. Meanwhile, the outermost edge is made thick to secure torsional rigidity in the design. A hole with a diameter of 25 mm and depth of 28 mm can reduce the weight of the pin shoulder by approximately 100 g. The newly designed shape reduces the weight by approximately another 100 g from that of the shape with a hole while the bending rigidity and torsional rigidity are maintained at levels similar to those of the bored pin shoulder.

3.3 Development of a manufacturing method

In the arm shape described in 3.2, the inner part is thinner than the outer edge of the pin shoulder. It cannot be formed in normal die forging because discharge of the workpiece is impossible. The authors considered and developed a new manufacturing method in which a fin (thin excess material) is formed at the outer edge of an arm's pin shoulder in advance and bent in the later process. Considering practicality, the number of manufacturing processes in this development was kept the same as those of conventional methods as a precondition of the study.

For example, on a line with a 5000-t press at Nippon Steel, a workpiece is subjected to preliminary forming, blocking, and finish forging. After these two types of die forging, it is processed by trimming and coining to obtain the product shape. To perform bending without increasing the number of manufacturing processes, in this development, a fin (excess material) projecting to the arm's outer edge is formed in the finish forging and it is then trimmed to obtain the shape in **Fig. 10**(a). Then, it is bent in the following coining process as shown in Fig. 10(b).

3.3.1 Design of the excess material and die

The workpiece after the coining process will be a product without further treatment. Therefore, an important task is to develop a technology to give necessary bending deformation when a workpiece is bent in the coining process while suppressing unnecessary deformation around the target section. **Figure 11** shows a workpiece and a typical example cross section of a die in bending. To allow only the excess material projecting upward to deform while preventing the other section from unnecessarily deforming, it is the most important to combine the inclined angle of the excess material fin (α) and the inclined angle of the die (θ) in an optimum way.

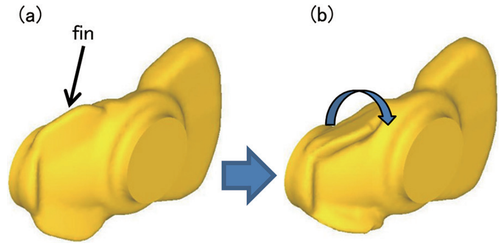


Fig. 10 Shape of newly designed arm when (a) Before bending and (b) After bending of fins

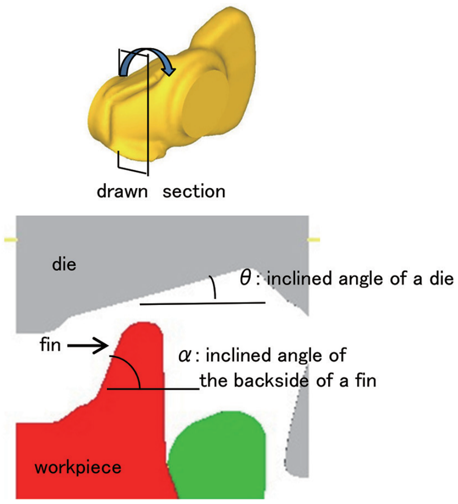


Fig. 11 Design of fin and bending die

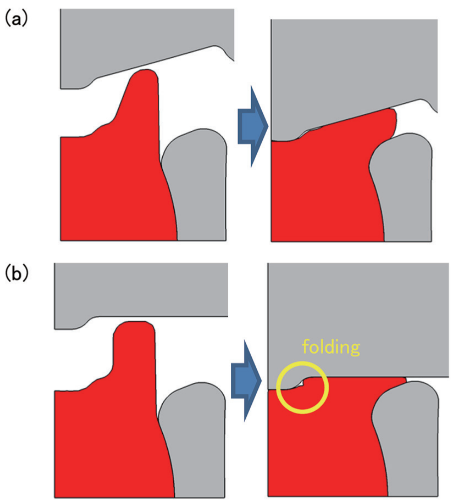


Fig. 12 Comparison of bending deformation between (a) Desirable design and (b) Undesirable design

Figure 12 compares the cross section of an example bent in a good shape with that in an improper shape in which both the excess-material fin and die are flat. If the shapes of the die and fin are not appropriate as shown in Fig. 12(b), the excess material bends (buckling deformation). **Figure 13** shows the equivalent strain distribution after the bending of the two examples above. For the example in the improper shape, the figure shows that strain is seen in a wide range and that strain is also generated on the outer circumference of the pin.

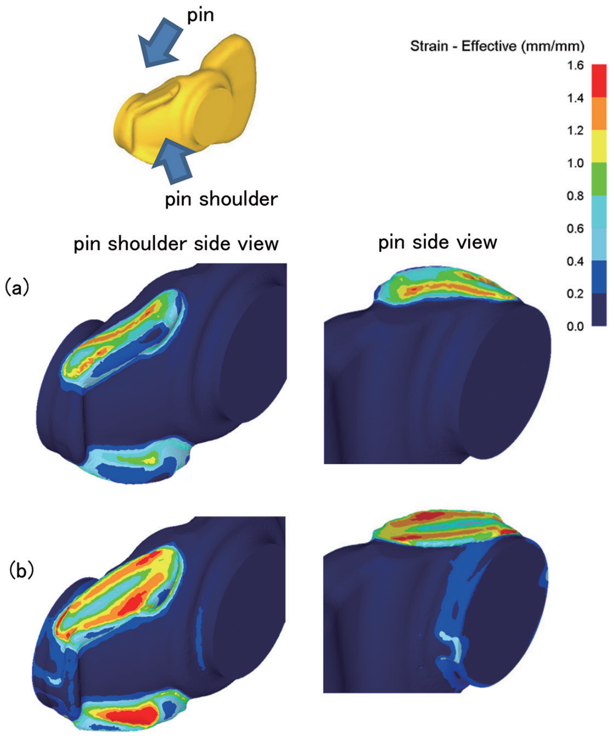


Fig. 13 Comparison of plastic strain distribution after bending between (a) Desirable design and (b) Undesirable design

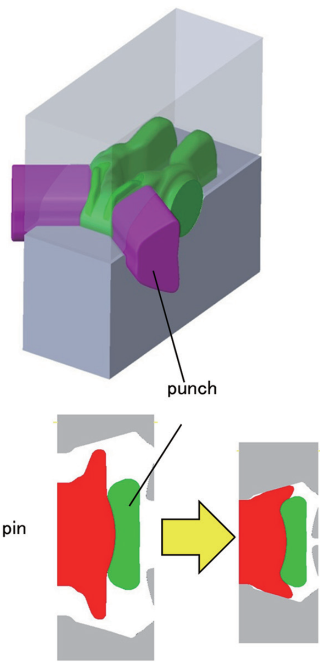


Fig. 14 Holding pin shoulder surface with punch

In bending forming, it is also effective to retain the surface of a pin shoulder with a punch to suppress its deformation as shown in **Fig. 14**. In this case, the punch is not used for boring, but only holds the surface, so the thrusting force can be very small.

3.3.2 Influence of varied temperatures

The largest advantage of the bending method is that deformation is given only to a limited area, so the influence of varied temperatures of a workpiece during forging is very small. Generally, it is unavoidable in hot forging that the temperature of a workpiece varies depending on heating, following transfer, and cooling conditions by several tens of degrees. **Figure 15** shows the analysis results when the end of an excess material is cooled to 1 000°C or 900°C from a uniform state of 1 100°C and then bent. The cross-sectional shapes after bending are not very different and no unnecessary strain is seen around the target sections for both cases as is the case with the example of the desirable shape in Fig. 13 (a). These results confirm the aforementioned advantage of this manufacturing method.

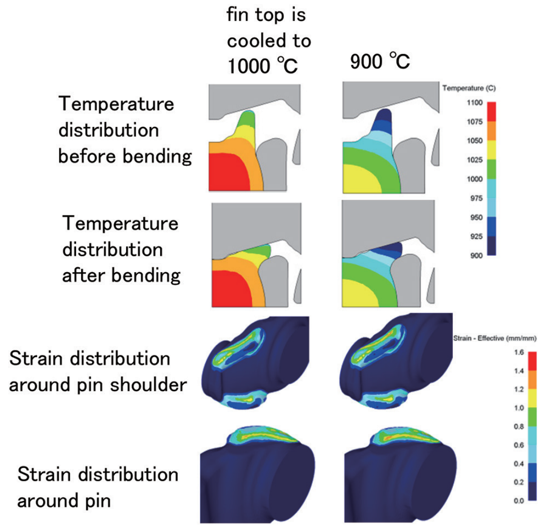


Fig. 15 Influence of temperature drop on bending deformation

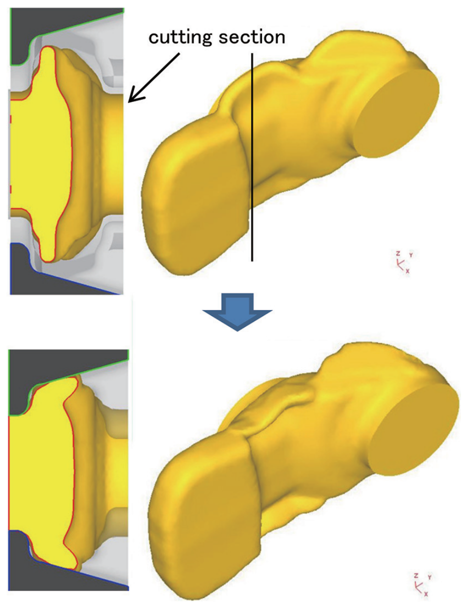


Fig. 16 Bending at lightening pocket portion

3.3.3 Bending forming of the lightening pocket section

This paper has so far described weight reduction of the pin shoulder section. Applying the same forging technique to the lightening pocket section can further reduce the weight. **Figure 16** shows example analysis of bending of the lightening pocket section. Also in this case, the thickness becomes thinner from the center of the arm outward (up-and-down direction in the figure) and the excess

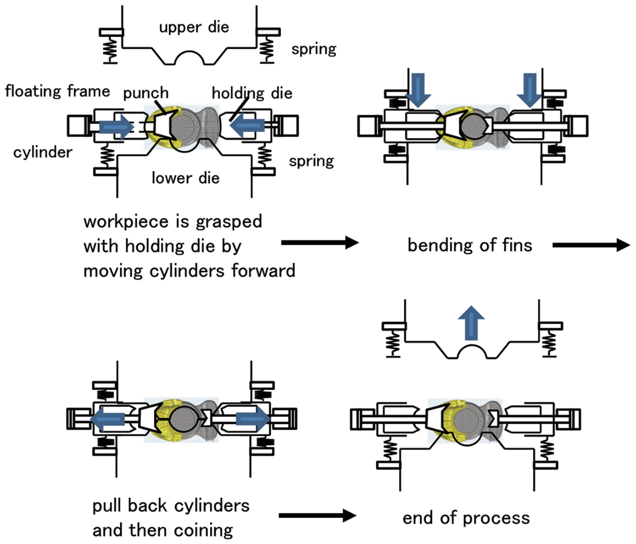


Fig. 17 Workpiece holding system with floating frame in fin bending and coining process

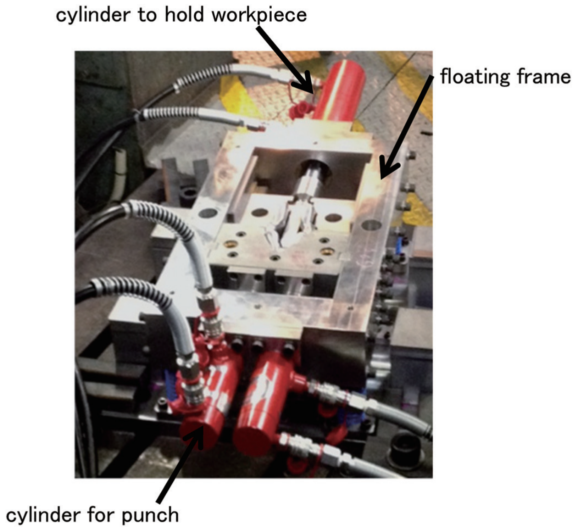


Fig. 18 Floating frame for experiment

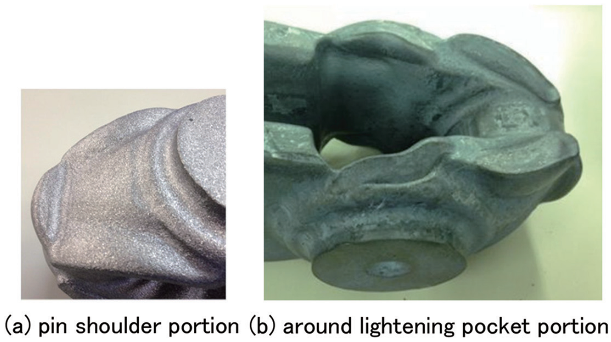


Fig. 19 Photographs of workpieces by laboratory experiment

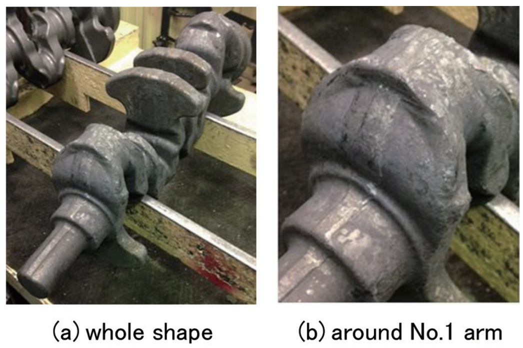


Fig. 20 Photographs of workpieces by test forging at Osaka Steel Works

material is bent to make the outer edge thick, achieving both light weight and high rigidity.

3.4 Development of production equipment

As shown in the figures above, on a crankshaft for in-line-4 engines, fins are arranged symmetrically to the plane including the centers of the pins and journals and bent. Therefore, to form the excess materials protruding upward and downward in the actual bending process symmetrically, it is important that the upper and lower dies come into contact with the workpiece at the same time to bend it. To that end, a mechanism to hold the workpiece at the center between the upper and lower dies all through the processing is required.

As a system that satisfies this requirement, the authors developed the workpiece holding system shown in **Fig. 17**. The figure shows the cross section that holds the journal section as an example. The holding mechanism section comes into contact with the springs installed onto the upper and lower dies, which maintains the mechanism at the center of the upper and lower dies (up-and-down direction in the figure) at all times. The upper and lower dies come into contact with the workpiece symmetrically. In this state, the upper and lower dies bend the workpiece. After completion of processing, the hydraulic cylinder holding the journal unloads and retreats. Then, the upper die is raised to discharge the workpiece.

As described above, the weight reduction method in which deformation is only local and the influence of temperature is very small has been established. The following chapter describes the results of verification of the effectiveness through prototyping of actual parts.

4. Verification of Formability and Effects of the New Method through Prototyping

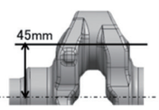
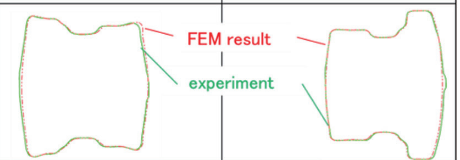
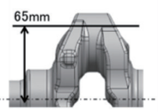
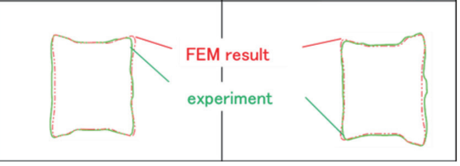
Firstly, to evaluate the effectiveness of the developed manufacturing method at a laboratory, a 500-t hydraulic press installed at the Amagasaki R&D Center of Nippon Steel Research & Development was used to prototype a partial model of the crankshaft for in-line-4 engines by hot bending. **Figure 18** shows the appearance of the holding mechanism explained in the previous chapter. Workpieces of S45C whose shape is equivalent to that after trimming shown in Fig. 10(a) were produced by machining. They were heated to 1250°C in a heating furnace and then bent to form shapes. **Figure 19** shows the formed test pieces. The obtained shapes are as studied in the analysis shown in Fig. 13(a), Fig. 16, etc. These results show that this manufacturing method can be sufficiently applied to actual production.

Secondly, actual crankshafts for in-line-4 engines in the full model were prototyped for mass production. These prototypes were made on a 5000-t press line at a Nippon Steel steelworks and only the pin shoulder sections were bent. **Figure 20** shows the appearance of the prototypes. The weight reduction effect by bending the pin shoulders on the prototype was 4% and the forging yield was same as that of current products. **Table 4** compares the cross-sectional shapes between the prototype and forging simulation. The figure shows that they match at high accuracy. In this prototyping, 100 workpieces were continuously forged without problems, demonstrating that mass production is possible.

The rigidity of this prototype was analyzed using 3D shape measurement results. As a result, it has been confirmed that both bending rigidity and torsional rigidity are at the same levels as those considered in advance through the analysis as shown in **Fig. 21**.

As shown above, Nippon Steel has established a new forging technology that can manufacture high-rigidity and lightweight crankshafts by developing a new bending design and manufacturing method.

Table 4 Comparison of obtained shape between FE analysis and experiment

Distance from central axis of journals	#1pin	#4pin
45mm 	 FEM result / experiment	
65mm 	 FEM result / experiment	

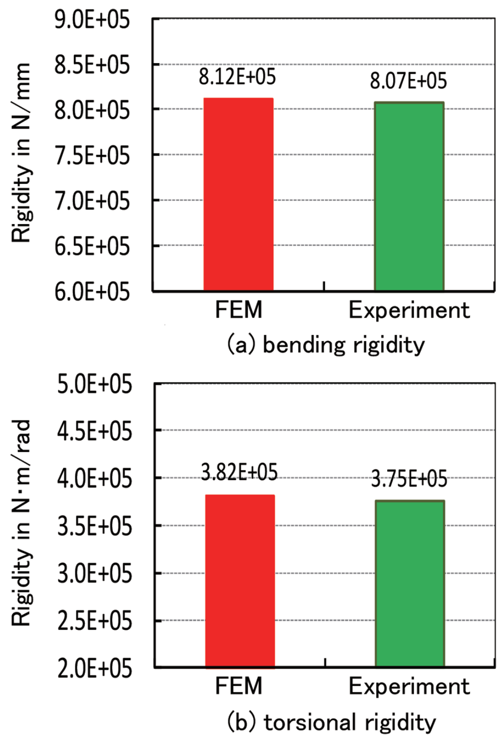


Fig. 21 Comparison of rigidity between FE analysis and experiment

5. Further Advancement—toward Better Design

The authors determined the target rigidity and have been pursuing weight reduction effects for crankshafts within the target until now. Our current design concept is to obtain a shape whose stress is evenly distributed on the entire member, and stress distribution has been checked through analysis, but the assumed state is “static.” However, when an engine is actually operated, in addition to the aforementioned static phenomena, various phenomena, such as vibration and change in the oil film pressure, occur at the shaft. Therefore, it is more important to design crankshafts while also studying dynamic phenomena in the early stage of designing.

Figure 22 shows an example of dynamic analysis by Nippon Steel. The figure shows the hydrodynamic pressure occurring on the bearings supporting the crankshaft when the engine is operated. How changes in the shape of the crankshaft change risks (e.g., seizure) can be examined and evaluated.

Regarding the influence of design change of crankshafts on the engine system and, on the other hand, the influence of design change of surrounding parts on the crankshafts, Nippon Steel will develop dynamic analysis evaluation techniques as described above to cope with model-based development, whose adoption has been rapidly spreading among various automobile manufacturers in recent years. In addition, to further reduce the weight and enhance the efficiency of engines, we expect that the diameter of a shaft will be smaller and that the stroke will be longer as shown in **Fig. 23** as an example. Nippon Steel will design lightweight crankshafts that contribute to optimizing entire engines through evaluation even for crankshafts in such new shapes including dynamic characteristics.

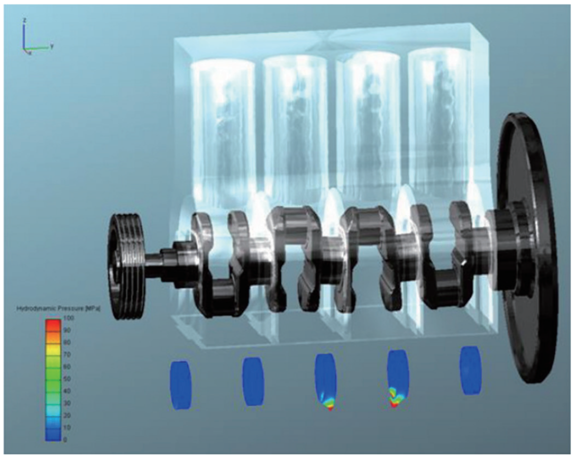


Fig. 22 Example of dynamic analysis of crankshaft in an operational state of an engine: Distribution of hydrodynamic pressure on each journal bearing

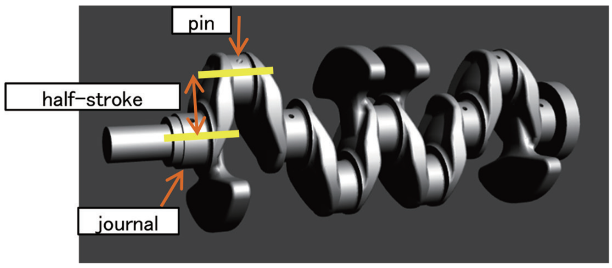


Fig. 23 Schematic drawing of a crankshaft expected in the near future

6. Conclusions

A new design and new manufacturing method that reduce the weight of forged crankshafts while satisfying rigidity have been developed. The conclusions obtained are listed below.

1) In place of the conventional hollow pin method in which a hole is bored in pin shoulders, a new shape, where the entire pin shoulder is made thinner and the outer edge of the pin shoulder of the arm is made thicker, has been developed. This shape can reduce the weight while securing rigidity.
2) As the manufacturing method to realize this shape, a new method has been developed in which the pin shoulder section is not dented in the later manufacturing process, but where the outer edge of the pin shoulder of the arm section, which has been formed to be thin, is bent to increase the thickness.
3) In this manufacturing method, only the bent section deforms (local deformation), so the influence of temperature variation during forging is very small.
4) The developed manufacturing method was used for a mass production trial in a 5000-t press line at Osaka Steel Works, Nippon Steel. The formability was checked and it has been confirmed that the prototypes satisfy the designated rigidity. The effectiveness of the new manufacturing method has been demonstrated.

Nippon Steel will improve the developed weight reduction method and the levels of its analysis techniques in the future. By making evaluations for all factors as early as in the design stage, Nippon Steel will propose crankshafts in view of engine optimization to automobile manufacturers, going beyond just being a crankshaft supplier.

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