Technical Paper

Application of Partial Diameter Enlargement Technology (JIKUHIDAI) to Gear Shaft

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The partial diameter enlargement technology (JIKUHIDAI) that can thicken part of a shaft hardly requiring the assistance of a die is a recent plastic processing technology.   Using this technology, shafts with a gear that have been manufactured by shaving large-diameter rods due to the requirement of limited quantities can now be formed using rods of a thin diameter equal to the diameters of shafts and by thickening the gear parts of the thick rods.   This reduces the shaving allowances and shortens the machining time.   Partly because this technology has been developed only recently, forming conditions to obtain a desired shape (width and diameter) of thickened parts and forming limit conditions such as cracking due to plastic deformation during thickening have not been determined.   Unless these forming conditions are determined, the technology cannot be used to produce in a large variety.   To solve this problem, research has been conducted and a method has been developed to determine forming limits for cracking and other phenomena.   The development has enabled application of the technology to the manufacture of gear pump parts that are produced in a large variety.   The partial diameter enlargement technology is overviewed and research work is described.

Key Words: *Partial diameter enlargement of shaft (JIKUHIDAI), plastic processing, forming, enhanced yield, buckling, S-N curve*

1.   Introduction

Some parts are now produced in a large variety but in small quantities due to the large variation required to meet user needs. These parts include shafts whose axial parts are a gear. Because these shafts are produced only in small quantities even though their variations are large, they have been machined by shaving round rods.   The diameter of the rod as the material is large matching the largest diameter of the gear part.   Thus, the remaining axial part of the rod other than the gear part has to be shaved, resulting in wasting of the material for the shaved portion.   It also lengthens the processing time.   One way to avoid material wasting is to thicken part of the shaft by forging or by other method to improve the material yield.   However, a dedicated die is required for this process.   When a large variety of shafts are required, a die has to be fabricated for each type and the initial cost for all the dies becomes high.   The die depreciation cost will be high if only small quantities of shafts are manufactured.

Compared with this, using the partial diameter enlargement technology for shafts developed by Iura Corp., the diameter of only the gear part of a shaft is enlarged matching the outer diameter of the gear while retaining the original, thin diameter of the axial part.   This improves the material yield and shortens the processing time.

Partly because this technology was developed only recently, factors and methods to set forming conditions to control a desired enlargement shape have not been determined yet. Forming limit conditions such as cracking especially are unclear, requiring a processing test for each different material and shape, thereby making it difficult for this technology to be applied to parts that are produced in small quantities and in a large variety.   To solve this problem, this research has found a method to determine forming limits based on the shape after shaft enlargement.   The research has enabled condition setting for products with several hundred different items each using the same material, paving the way for use in gear pump parts. The partial diameter enlargement technology is reported hereunder.

2. Shaft Partial Diameter Enlargement Technology

2.1 Shaft Partial Diameter Enlarging Machine

A full view of the shaft partial diameter enlarging machine is shown in **Fig. 1**.

Parts for construction machinery are large compared with vehicle parts and their loads increase as they have to be enlarged correspondingly. A machine capable of applying a load of maximum 1500kN in an axial direction of a rod was purchased from Iura Corp. in June 2006 to handle the increase in load.

(a) Full view of processing machine

System Specification

Pressure	max.1500kN
Motor output	18.5kW (For driving)
Spindle rotating speed	5 to 100rpm
Bending angle	max.8°
Moving speed of pressurized part	About 30mm/sec.

(b) Drive side

(c) Pressurizing side

Fig. 1 1500kN shaft partial diameter enlarging machine

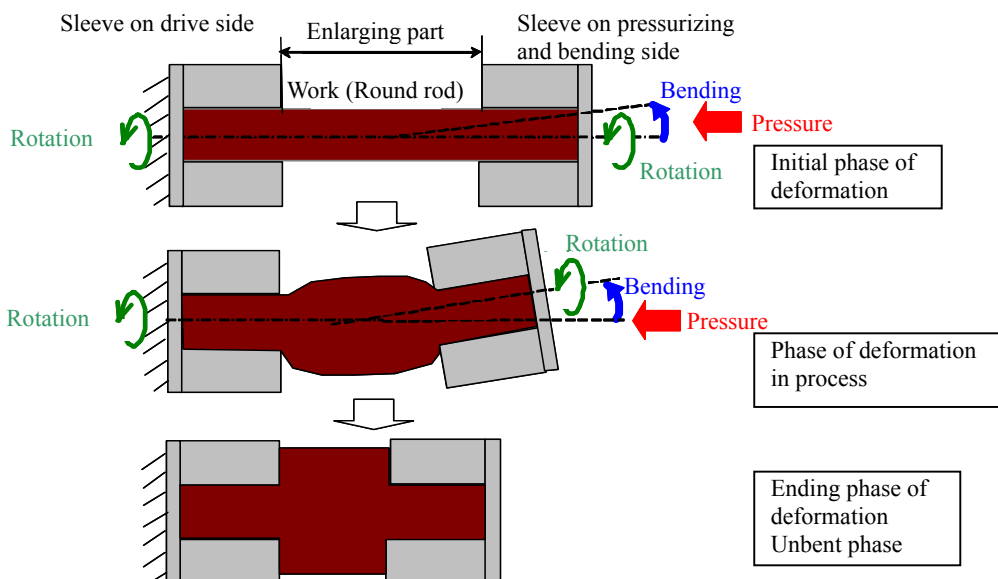### 2.2 Mechanism of Shaft Enlargement

Fig. 2 Mechanism of deformation for shaft enlargement

The mechanism of shaft enlargement in detail is described by dividing the deformation mechanism of shaft enlargement into four phases, namely, initial phase of deformation, phase of deformation in process, ending phase of deformation and unbent phase (**Fig. 2**).

1) Initial phase of deformation
   Enlargement phase by increases in pressure and bending angle

   The load sequence of shaft enlargement is as follows:

   Start of revolutions → Pressure loading → Bending moment load

   (1) Pressure loading

   First, pressure in a compression direction is applied to the round rod. In this condition, a compressive stress σc that is uniformly distributed in the axial direction is generated (**Fig. 3**).
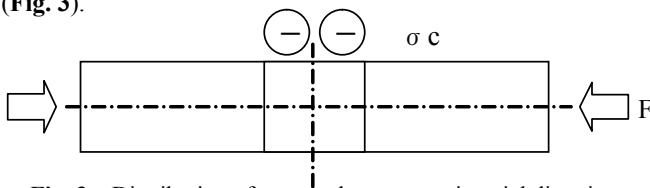

   Fig. 3　Distribution of stresses by pressure in axial direction

   (2) Bending moment load

   When bending moment alone works, a compressive stress σ cm is generated above the center line and a tensile stress σ tm is generated below the center line, in the axial direction (**Fig. 4**).
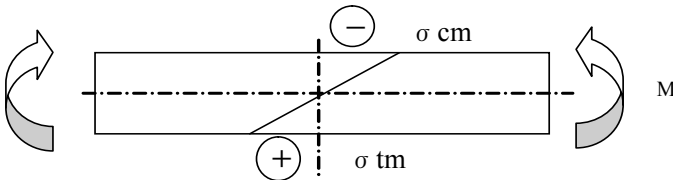

   Fig. 4　Distribution of stresses in axial direction by bending moment

(3) Simultaneous load of pressure and bending moment

   In the initial phase of shaft enlargement, pressure (1) and bending moment (2) work simultaneously. The stress distribution then becomes an axial stress state as illustrated in **Fig. 5** by the principle of superposition.

   Above neutral axis: σ c + σ cm
   Below neutral axis: σ c + σ tm (σ tm < 0)

   At σ c + σ cm > σy (yield stress), the area becomes plastic. Once a plastic state is set, plastic deformation progresses in the direction of a force (energy) when even a slight force (energy) is supplied. At this time, plastic deformation takes place in the enlarged diameter direction also based on the condition of a constant volume and the diameter enlarges.
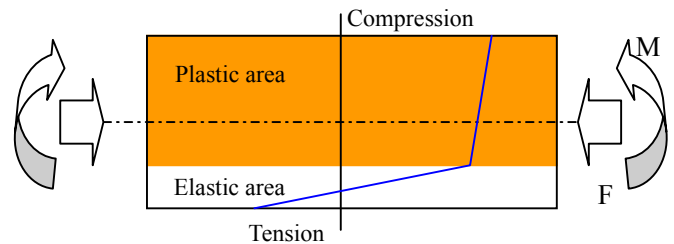

Fig. 5　Distribution of stresses in axial direction by superposition of pressure and bending

   As a rod is turned, the foregoing phenomena are repeated over the entire surfaces, thereby enlarging the entire diameter.

2) Phase of deformation in process
   Phase of enlargement due to an increase in curvature

   When a work undergoes plastic deformation after pressure and bending angle reach their target values, the yield point rises due to work hardening. However, the hydraulic cylinder for angle that maintains the bending angle constant supplies energy in the form of reaction, enabling continuation of plastic deformation and achieving diameter enlargement.
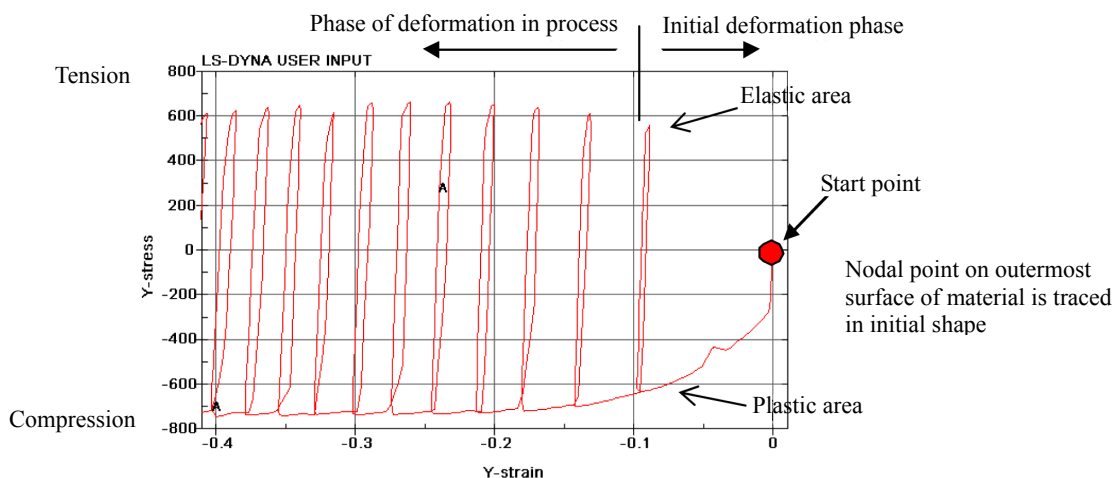

Fig. 6　History of stress and strain in axial direction

The relation between the stress and strain in the initial phase of deformation and phase of deformation in process described above is plotted by simulation (**Fig. 6**).

The first load shows the initial phase of deformation. The loading and unloading in and subsequent to the second loading showed the process of phase of deformation in process. The observation point was set at the nodal point in the outermost surface on the compression side. In this example, the yield stress increased from 370MPa to 600MPa by the load in the initial phase of deformation.

For this reason, a plastic state is not set when the work is reversed and is set to the bending and tensile side, and there is no permanent deformation. This also shows that enlargement is achieved most on the bending and compression side.

3) Ending phase of deformation

An enlarged width is set based on the dimensions in the drawing. The enlarged width is sensed and enlargement forming is finished when this set enlarged width is reached.

4) Unbent phase

The inclination angle on the pressure side is returned to "0" to reset the enlarged round rod to almost straight.

This explains that the enlargement phenomenon progresses by a compressive stress in an axial direction by pressure and bending force. In the enlargement phenomenon, therefore, pressure and bending force are the principal control parameters.

Parameter	Large	Small
Pressure	Deformation speed high	Deformation speed low
Bending angle	Deformation speed high	Deformation speed low
Rotation speed to forming	Fillet easily cracked	Fillet cracked less easily
Initial gap between sleeves Lo	Eccentricity and buckling easily caused	Eccentricity and buckling caused less easily

3. Forming Limits in Shaft Diameter Enlargement Processing

Fine cracking develops in the material when a shaft diameter is enlarged under, for example, an excessively large load. Because a die is not used, the enlargement diameter direction is set free and a long rod buckles if an inappropriate load is applied. Formation limit conditions for cracking, buckling and other elements therefore have to be determined. The following three formation limit elements were selected after studying the mechanism of shaft diameter enlargement and results of tests conducted so far.

(1) Cracking (Cracks in fillet)
(2) Buckling
(3) Enlargement ratio

Methods to estimate evaluation of these elements based on the shape after diameter enlargement were determined, as described in the following. First, the shapes before and after enlargement are defined schematically as shown in **Fig. 7**.

The enlargement ratio k and enlarged width ratio m are defined as follows.
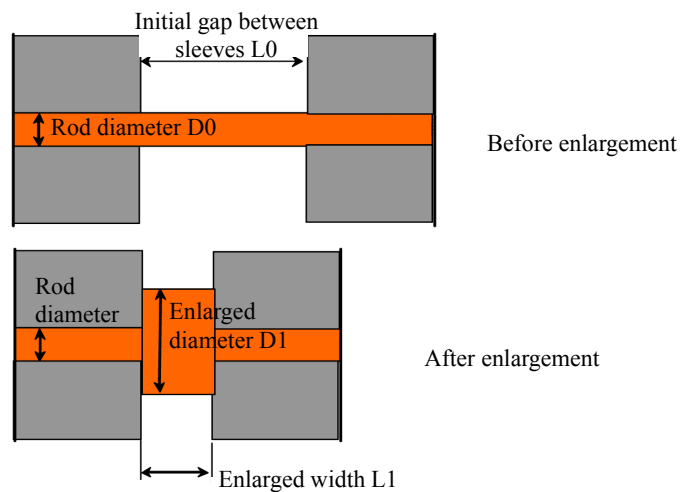
$$k = \frac{D_1}{D_0}$$

$$m = \frac{L_1}{D_0}$$

Fig. 7 Shapes before and after diameter enlargement
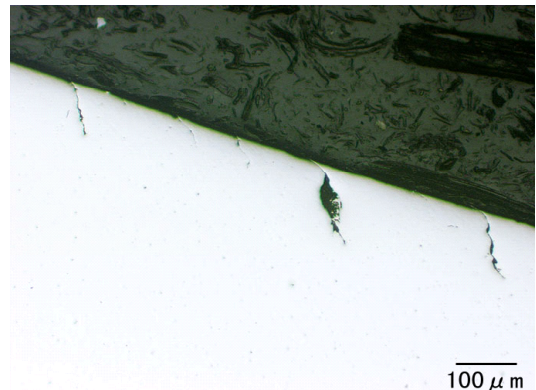
3.1 Forming Limits on Cracking

Cracking (a crack generated in fillet) is a crack that generates along the periphery of the rising part of enlargement (**Fig. 8**).

Fig. 9 shows the distribution of main shearing stresses when pressure of 540kN and a bending angle of 3° are applied. The maximum main shearing stress is detected in the rising part of enlargement (fillet).

The fillet is subjected to compressive and tensile stresses in each turn of the shaft. The stresses are large and a cracking develops on the surfaces of the fillet after a certain count of revolutions due to low cycle fatigue. For this reason, an S-N diagram has to be prepared for each material used to evaluate limits for cracking. Evaluation of limits on cracking of alloy steel with a carbon content of 0.14% is presented in the following. Hard materials with a high carbon content develop cracking early compared with soft materials and a test was made using a material with an upper limit of 0.18% in carbon content.
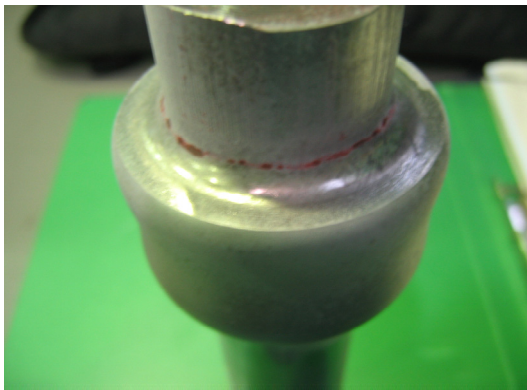
| (a) Cracking in fillet (red line part) | (b) Radiographic image of a cracking (Depth 0.1 to 0.2 mm) |

Fig. 8　Cracking in enlarged fillet
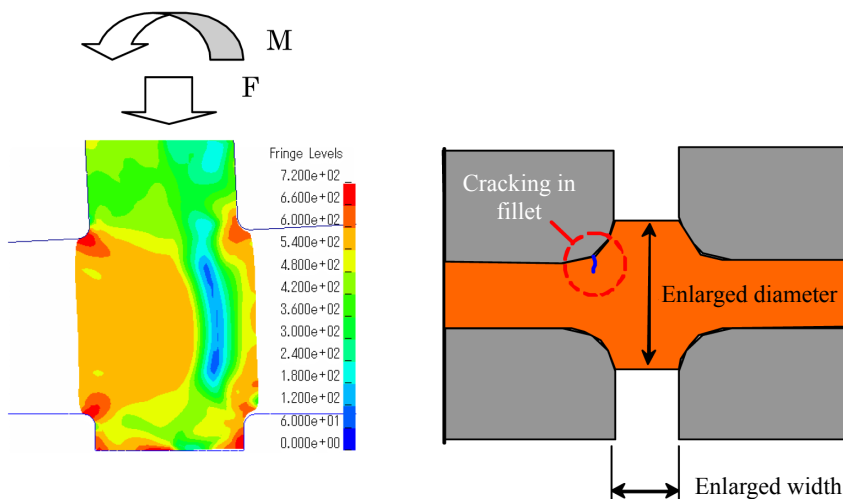
Fig. 9　Distribution of maximum shearing stress during diameter enlargement
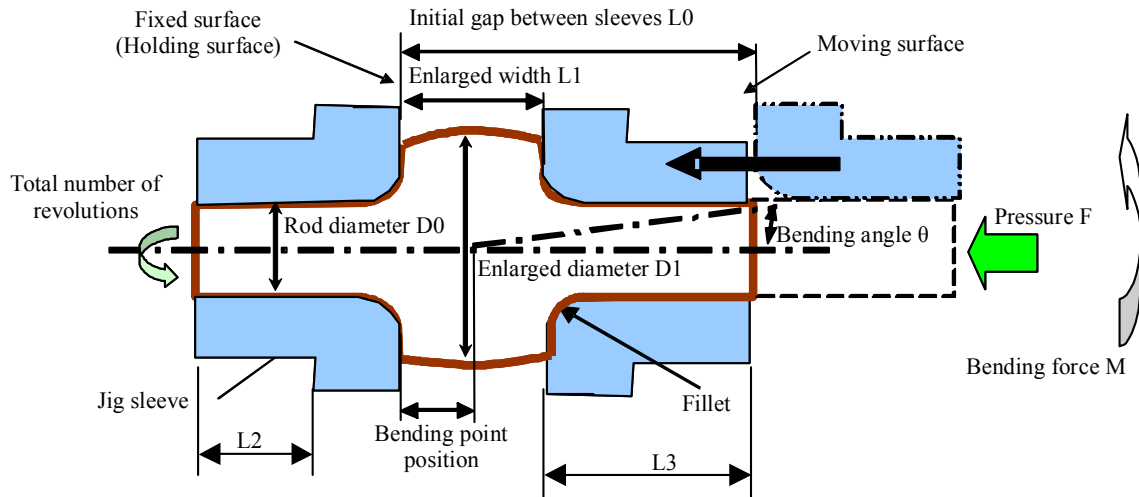
(1) Test conditions
　(a) Dimensions
　　• Rod diameter　　　　　　　　D0: 42 in diameter
　　• Diameter enlargement ratio　D1/D0: 1.2 to 2.0
　　• Width enlargement ratio　　D1/D0: 0.83
　　• Retained width　　　　　　　L2: 40mm, L3: 46 mm
　(b) Forming conditions
　　• Pressure　　　　　　　　　600 to 1400kN
　　• Bending angle　　　　　　1 to 6°

(2) Results S-N curves were plotted based on the foregoing test
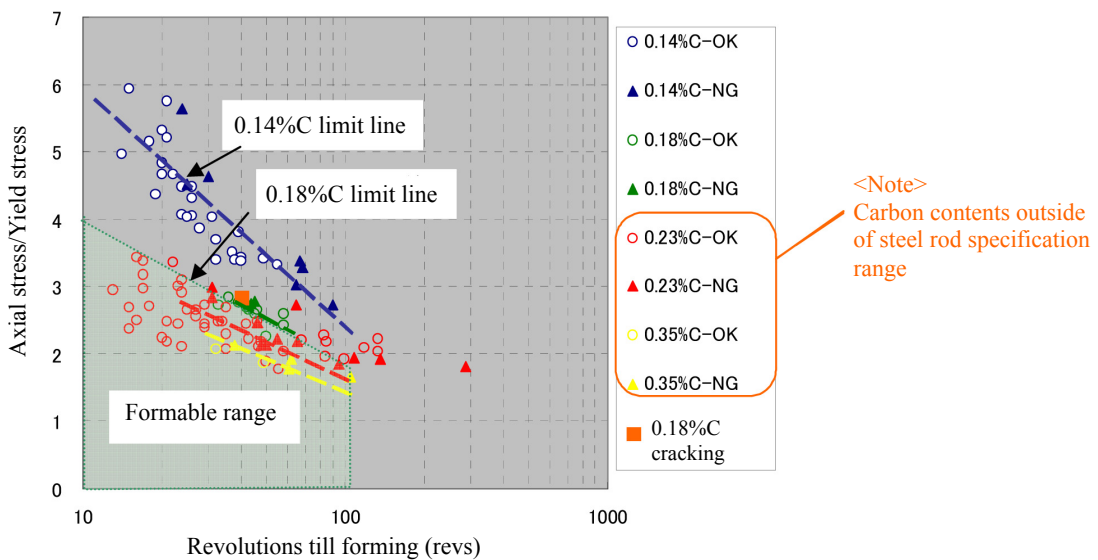conditions.

Fig. 10　Relation between axial stress indicator and forming revolution count

Limit lines of 0.14%C (blue) and 0.18%C (green) are shown in **Fig. 10**. (Even though not within the specified range of carbon content, values for 0.23%C and 0.35%C are also plotted as supplemental information) The limit line of 0.18%C is the forming limit line for the applicable alloy steel.

The number of revolutions till diameter enlargement and volume of diameter enlargement have a correlation. The S-N curve seems to assure shaft diameter enlargement to a certain diameter enlargement volume without cracking.

Steel rod diameter — Enlarged diameter — Enlarged volume — Equivalent enlarged width
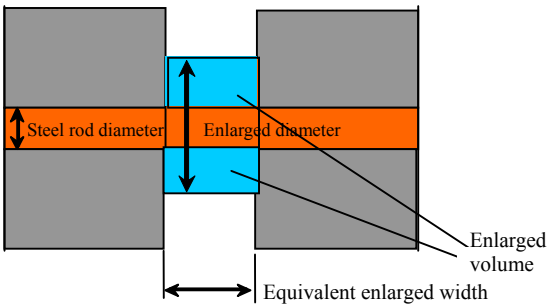
The enlarged volume can be calculated by the following formula.

$$V = \frac{\pi D_0^{\,3}}{4} m(k^2 - 1)$$

The enlarged volume increases the larger rod diameter is. The normalized enlarged volume indicator Vn is defined as follows.

$$V_n = m(k^2 - 1)$$

Based on the limit line for 0.18%C shown in the S-N diagram in **Fig. 10**, the limit value for Vn is 1.3.

3.2 Limit of Forming on Buckling (Eccentricity)

Plastic buckling is generally expressed as follows.

(σ c) buckling criticality = $16\pi^2 E'/(L0/D0)^2$ ...(3-1)

(E' is inclination of the stress strain diagram in the plastic region)

When Load F works onto a circular long column whose length is L0 and diameter, D0. The critical buckling stress is determined by L0/D0. Before diameter enlargement, the round rod is gripped as illustrated in **Fig. 11**. As mentioned above, the rod buckles when pressure is applied if L0/D0 is large. For this reason, L0/D0 that causes buckling was evaluated.

The following processing conditions were set.
Processing conditions:
Pressure 1200kN, bending angle 3°, spindle rotation speed 40rpm
Diameter enlargement ratio D1/D0 1.4
Two alloy steels 0.14%C and 0.22%C as materials

L0/D0 was set beginning at 2.0 with an interval of 0.5 and eccentricity after forming was measured. "L0" is the gap between the sleeves as a rod is set (**Fig. 11**).

Sleeve on drive side — Lo — Sleeve on pressure and bending side

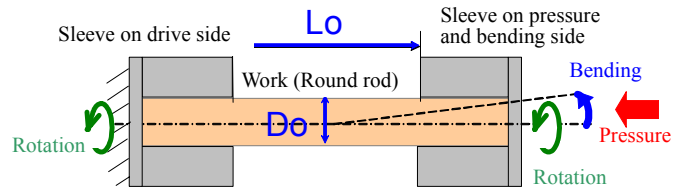Work (Round rod) — Bending — Do — Rotation — Pressure — Rotation

Fig. 11 Definition of L0/D0 in diameter enlargement processing

The eccentricity was controlled below 1mm till L0/D0 was 2.75 irrespective of the carbon content and was negligible in practical use.

At L0/D0 > 3.2, the eccentricity rapidly increased, exceeding 3mm. Finally, as in L0/D0 = 3.75, corner buckling was caused due to buckling, resulting in rupture (**Figs. 12** and **13**).

Rupture by corner buckling

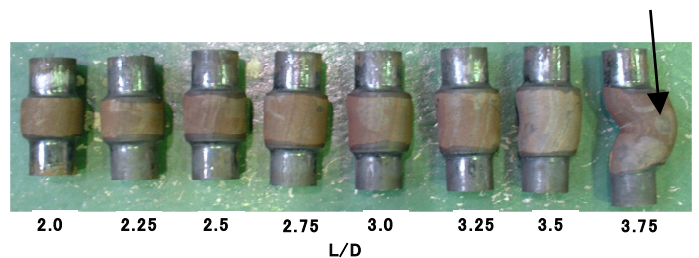| 2.0 | 2.25 | 2.5 | 2.75 | 3.0 | 3.25 | 3.5 | 3.75 |

L/D

Fig. 12 Shaft diameter enlargement by L/D

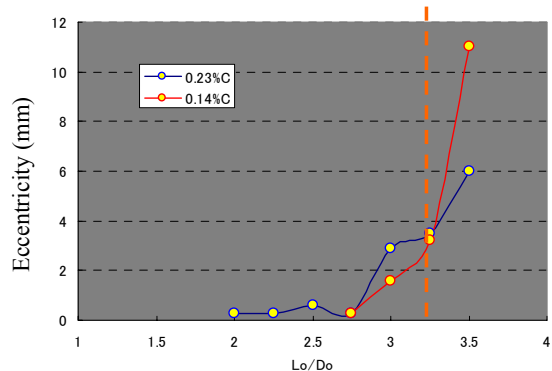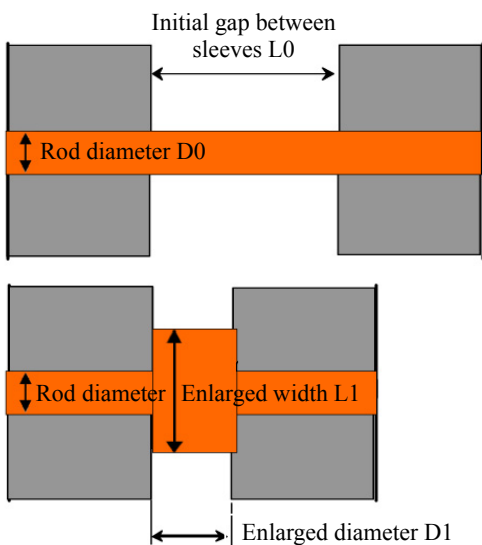**Fig. 13** Eccentricity after diameter enlargement

In this research, eccentricity of 3 mm or more is defined as buckling and L0/D0 of 3.2 or less is defined as the limit value.

The enlarged volumes before and after diameter enlargement are constant in volume.

$$\frac{L_0}{D_0} = k^2 m$$

$$k = \frac{D_1}{D_0}$$

$$m = \frac{L_1}{D_0}$$

Initial gap between sleeves L0

Rod diameter D0

Rod diameter | Enlarged width L1

Enlarged diameter D1

3.3 Forming Limits by Diameter Enlargement Shape

As mentioned earlier, the critical values of cracking and buckling limits are calculated based on the shape of diameter enlargement.

Cracking limit $\quad V_n = m(k^2-1)$

Buckling limit $\quad \dfrac{L_0}{D_0} = k^2 m$

Limit of diameter enlargement ratio $\quad k$

Therefore, plotting the diameter enlargement ratio k (D1/D0) on the axis of ordinates and enlarged diameter ratio m (L1/D0) on the axis of abscissas, based on the calculated limit values, the limit lines can be plotted as shown in **Fig. 14** for an alloy steel with 0.14% carbon content.

The limit for the diameter enlargement ratio can be calculated at 1.6 or less as a region without cracking based on the data used in the S-N diagram.

Thus, by calculating the diameter enlargement ratio and enlarged width ratio from the shape after diameter enlargement, evaluation of cracking, buckling and enlarged width can be made. Regions where the enlarged width ratio is large are in a buckling rate-determining step, whereas regions where the enlarged width is small are in an enlargement ratio rate-determining step. In other regions, the step is a cracking rate-determining step.
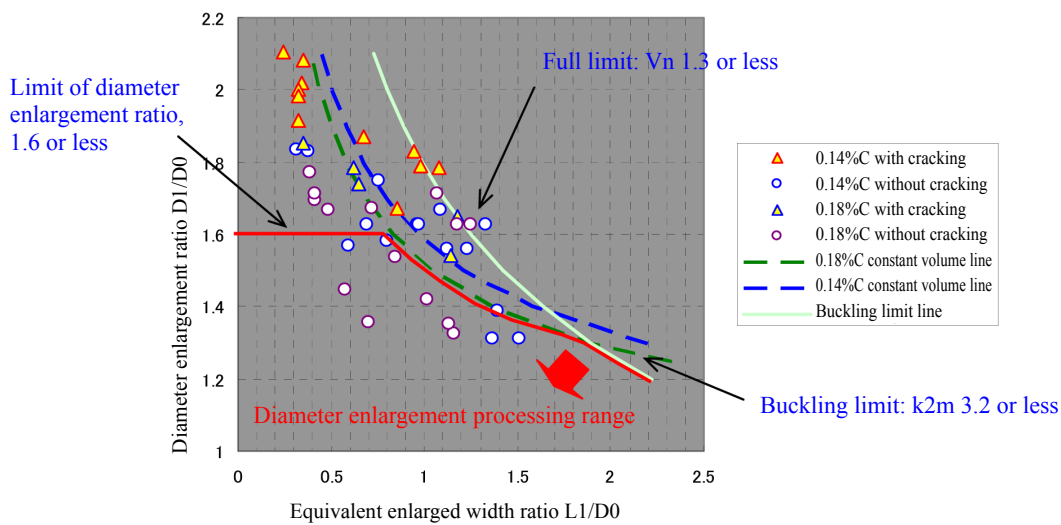
Fig. 14 Forming limits by diameter enlargement ratio and enlarged width ratio (0.14%C alloy steel)

4. Process Ability

Dispersions of the shape after diameter enlargement of rods by this technology were checked.   Especially the diameter enlargement direction is not constrained at all and dispersions in that direction are potentially large.   To check this possibility, a test was conducted.

1) Level of process ability test

The test level is specified in **Table 1**.   (Rod diameter 36) Rods of alloy steels containing 0.16% and 0.22% of carbon were tested.

Table 1 Test level

Rod carbon content (%)	Rod diameter (mm)	N number
0.16	35.5	30
	36	30
0.22	35.5	30
	36	30
	36.5	30

2) Forming conditions
　　Pressure　　　　　650kN
　　Bending angle　　　3°

3) Results

(1) Under the foregoing forming conditions, a crack was not developed at the test levels of N = 30 each shown in Table 1, verifying that the forming conditions were appropriate.

Fig. 15 shows the structures near the fillet.   A color check showed that a crack was not developed in all the levels. Anomalous plastic flow was not detected.

(2) Dispersions of formed dimensions were evaluated.
　　a) Dispersion of enlarged width　　　±0.19mm (3σ)
　　b) Dispersion of enlarged diameter　　±1.22mm (3σ)
　　c) Flatness of enlarged diameter　　　±1.73mm
　　d) Eccentricity of enlarged part　　　Max. 0.54mm

Compared with other items, the enlarged width dispersed less as pressurizing was stopped when a preset value was reached by sensing the travel distance on the pressurizing side. The diameter enlargement exceeded 1mm in dispersion as the diameter enlargement direction was free of any constraint. The "flatness" is defined as the difference between maximum and minimum diameters (See shape of enlarged part in **Fig. 16**).

(a) 0.16%C Rod diameter 36.0

(b) 0.22%C Rod diameter 36.0
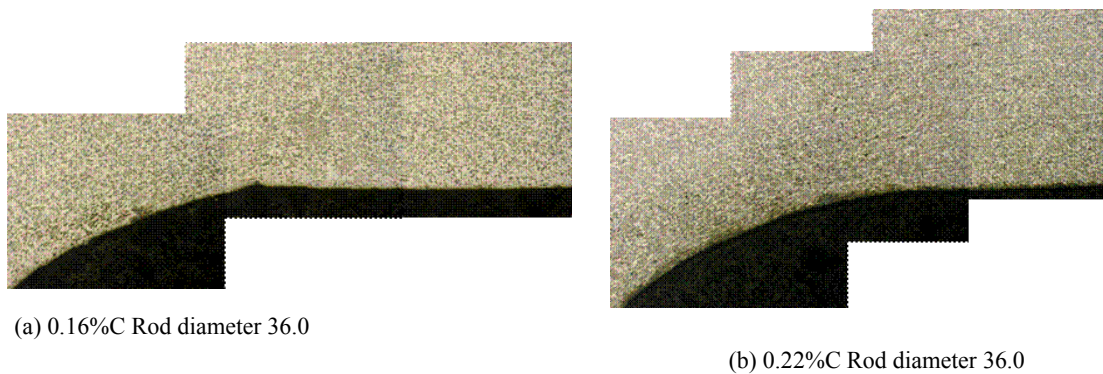
Fig. 15　Structure near fillet on pressurizing side
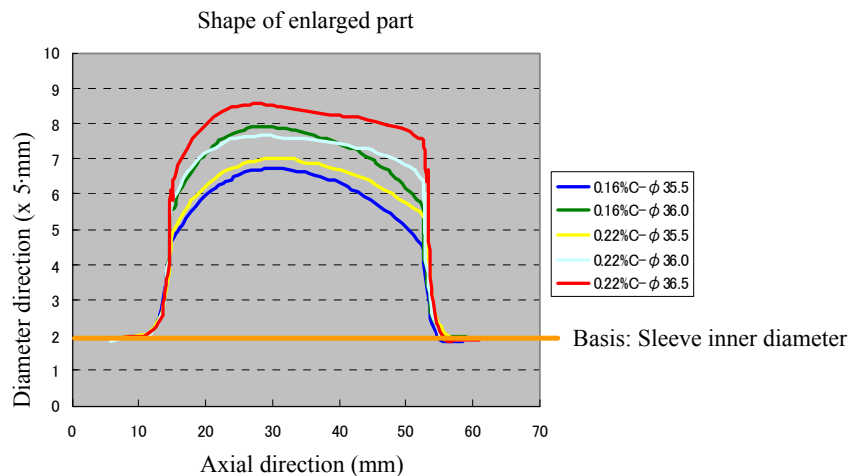
Fig. 16　Profile of enlarged shape

(3) Characteristics of formed shape
a) The enlarged part becomes like a barrel. Enlargement at both ends is restrained as both ends are semi-constrained due to friction with the sleeves.
b) The greater the enlarged diameter the larger the rod diameter is. The clearance between the sleeves and rod is relatively small and the enlarged diameter is less affected by deformation inside the sleeves.
c) The volume varies constantly and has no correlation with the carbon content.

In the case of this rod, the total error in the direction of the diameter of the enlarged part is ±4.7mm. Dispersions were determined in this manner and the shaving allowance in the downstream process was decided accordingly.

5. Application Case

Forming limits of the rods to be formed and conditions for principal control parameters were determined and application of this technology to shafts for gear pumps totaling several hundred items was performed.

As many items were involved, the rod diameter varied between 32 and 60mm, varying in enlarged diameter and width as shown in **Fig. 17**.

The application of this technology improved the material yield of blank rods before gear cutting by approximately double compared with rod shaving. The processing time also was shortened by about 20% (**Fig. 18**). At present, a high-volume production line from round rod cutting to shaft diameter enlargement, to heat treatment (normalize tempering) and to lathing is being built.
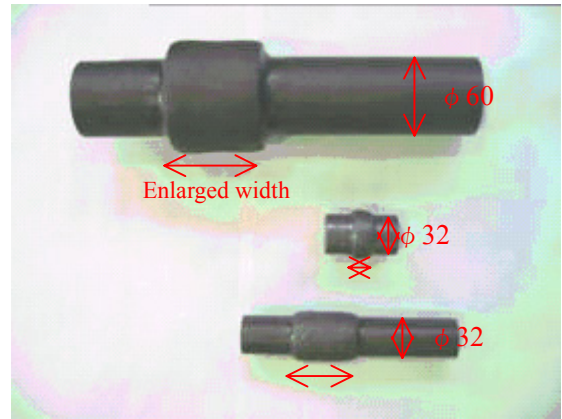

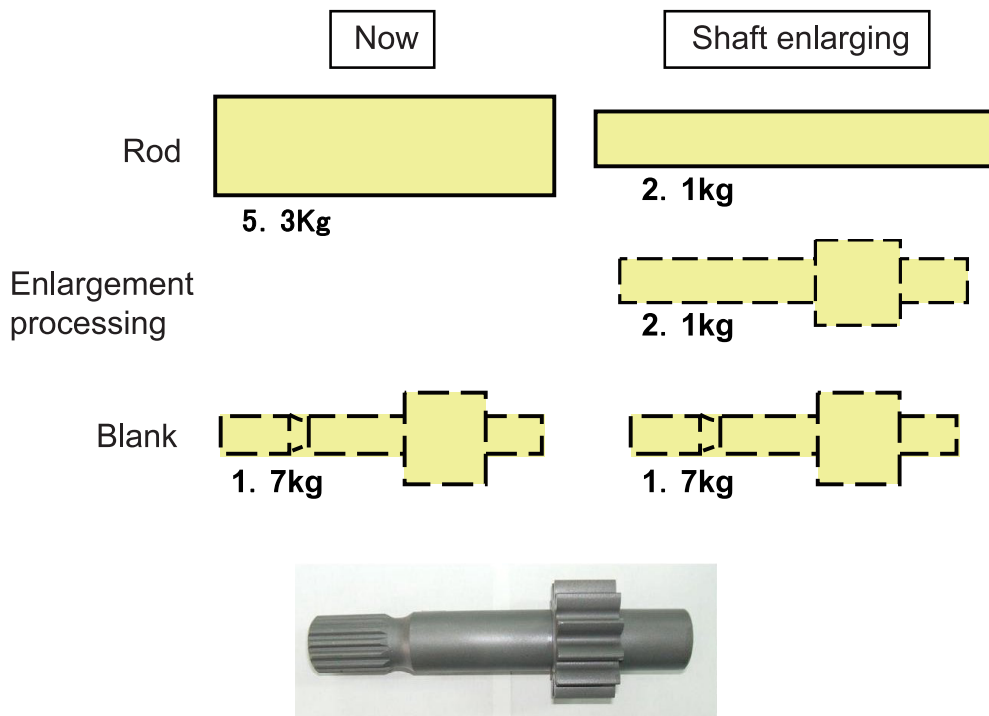**Fig. 17** Example of diameter enlargement

Fig. 18 Example of diameter enlargement of shaft with face width of 31.5 mm and outer diameter (gear part) of 62.5 mm

6. Conclusion

The plastic processing method could not be adopted in some cases because of cost consideration for dies and other elements due to requirements of having to produce a large variety of parts in small quantities. Nevertheless, plastic processing is suitable for enhancing material yields. The technology can be used if dies are hardly used and the partial diameter enlargement technology suits this purpose. In this sense, this technology is an excellent technology that can widen the application range of plastic processing. On the other hand, this technology does not need dies and is suitable for the production of a large variety of items in small quantities. However, nothing constrains the shape in the diameter direction in which rods are enlarged, making control of enlargement in the diameter direction difficult. For this reason, determination of forming conditions for a large variety of items will be difficult unless the enlargement mechanism is understood and forming conditions based on the enlargement mechanism are defined. To deal with this problem, this research has defined the procedures to set forming limits for the manufacture of a large variety of components in small quantities. It is believed that this technology has removed the great barrier to employing plastic processing in the production of components. Plastic processing is now employed in manufacturing gear pump parts that total several hundred items in number.

Introduction of the writer

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[A few words from the writer]

Aside from understanding characteristics of the materials and mechanisms of processing, this research required new ideas on system design and operation such as system setup and strength setting for parts and areas onto which a high load is applied. More new ideas seem to be needed to automate the process. However, a wealth of knowledge could be gained by studying the theme as a process that includes a hardware system. The characteristic of this technology contributed to its application to plastic processing, which was considered impossible to adopt. It will be important to continue approaching and devising new ideas that are free from the limits of common sense as in this research and in other researches.