IMPROVING THE EFFICIENCY OF THE ROUND BAR FORGING PROCESS BY FOUR-DIE FORGING DEVICE (FDFD)

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Japan Steel Works M&E, Inc. installed a Four-Die Forging Device (FDFD) designed by Lazorkin-Engineering, LLC on a 30 MN hydraulic press. The FDFD enables four-side radial forging using the existing conventional open-die hydraulic forging press. FDFD can efficiently forge bar-shaped materials while suppressing horizontal expansion. To maximize the forging efficiency of the FDFD, it is effective to introduce the FDFD from the beginning of the forging process. However, there are void defects inside the ingot, so FDFD must be used to close them during the process of forging. We derived void closure criteria in the FDFD by FEM analysis and our experiences of void closure in a minimum forging ratio. Then we verified the possibility of void closure using the FDFD only based on the criteria. As a result of performing the void closure process in the finishing process with the FDFD only, the forging time was reduced by approximately 41% compared to conventional methods without deteriorating the internal quality.

KEYWORDS: OPEN-DIE FORGING – FOUR-DIE FORGING DEVICE – FDFD – VOID CLOSURE – VOID CONSOLIDATION – FEM ANALYSIS – REDUCTION OF FORGING TIME

INTRODUCTION

There is a strong demand for cost reduction in mass-produced circular-section shafts, such as simple round bars and stepped round bars. To solve this problem, we have implemented a Four Die Forging Device (FDFD) from Lazorkin Engineering (LE). The FDFD makes it possible to mechanically disperse vertical forces to the four directions (top, bottom, left, and right) and enables highly efficient four-face forging with less lateral bulging (Figure 1).

A FDFD has been shown to be effective in reducing press time in cogging and finishing rounding processes [1], but there are still many unresolved issues regarding the ability of FDFD to close void defects (hereinafter referred to as "voids") inside steel ingots, and there are few cases where the void closure effect of FDFD has been evaluated. Therefore, we conducted a quantitative evaluation of the void closure effect of FDFDs using FEM analysis and we verified the void closure using only FDFDs. This report describes a case in which the forging time of a circular cross section product was significantly improved by forging from void closure to finishing using only FDFD.

Fig.1 - Appearance of FDFD

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1. ESTABLISHMENT OF VOID CLOSURE METHOD USING FDFD

1-1. Study of void closure minimum forging ratio

To make void closure using FDFD simpler and more reliable, an actual test was conducted to verify the minimum forging ratio required for void closure. Figure 2 shows an overview of the test. The test sample were three steel ingots with a body weight of approximately 27 tons each (2.5CrMoV). The shape of all three test ingots was φ1495 mm (Top side) × L 2360 mm. After raising the temperature to 1270°C, the test ingots were cogged 1040 mm sq. (condition ①), 960 mm sq. (condition ②), and 890 mm sq. (condition ③) using a 450 mm wide flat die in a 30 MN press with an die contact ratio (Definitions are shown in Figure 2. The larger this ratio, the higher void closure effect.) of 90% and press reduction amount of 90 to 100 mm for each forging pass. As a result of void prediction based on solidification analysis, the diameter at the maximum size void position of this test ingot was φ 1364 mm, and the forging ratio calculated from this diameter was 1.42S for condition ①, 1.66S for condition ②, and 1.92S for condition ③, respectively. After the forging was completed, the material was annealed, and then the surface was ground in a total of 4 strips of 400 mm width in the longitudinal direction. The internal defects just below the hatched area in Figure 2 were evaluated from 4 directions by ultrasonic flaw testing (hereinafter referred to as UT). Figure 3 shows the UT results. UT indications were detected in conditions ① and ②, but not in condition ③, and the MDFS (= Minimum Detectable Flaw Size) of the shaft center was approximately φ2.5 mm. In order to confirm whether the detected indications were unclosed voids, we analyzed the initial location of the indication. Figure 4 shows the results of the analysis under conditions ① and ②. The areas of UT indications detected in conditions ① and ② coincided with the void areas (φ3.0 mm or larger) predicted from the solidification analysis. Therefore, the indications detected under conditions ① and ② are considered to be unclosed voids. As a result, it was found that the void could be closed at a forging ratio of 1.92S, which omitted the void closing process, and under conditions without strong reduction.

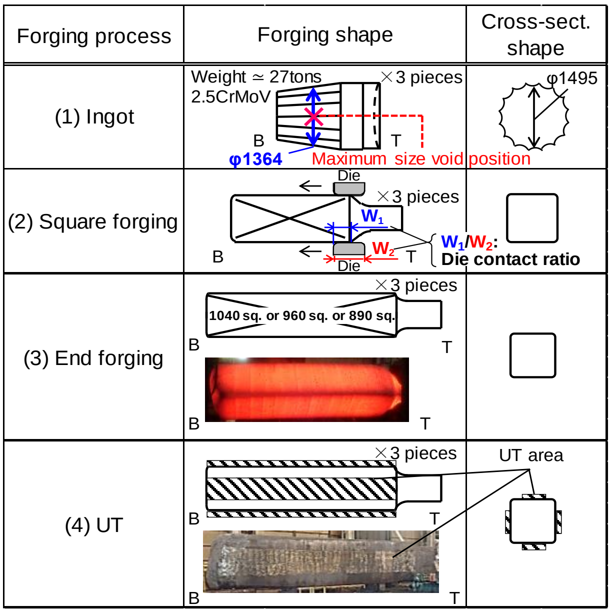

Fig.2 - Void closure verification test overview

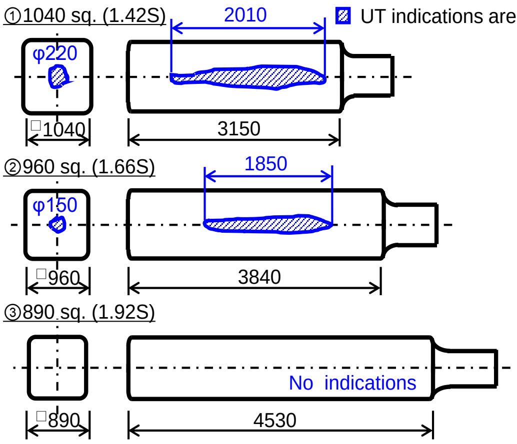

Fig.3 - Test sample UT results

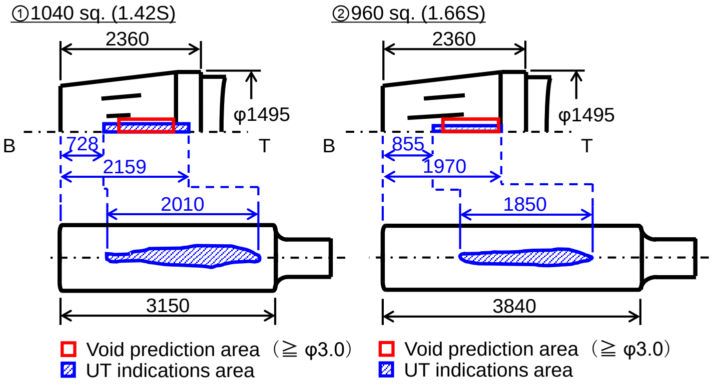

Fig.4 - Initial location analysis result of UT indications

1-2. Quantitative evaluation of void closure criteria

The void closure criteria of the shaft center under condition ③ was derived by FEM analysis using Abaqus 6.14-1. Table 1 shows the analysis conditions. Figure 5 shows the initial model for the FEM analysis. The initial model for analysis had a cylindrical shape with φ1364, which is the diameter at the maximum size void position of test ingot for condition ③. We evaluated the void closure effect at the shaft center directly below the center of the die using the integral of hydrostatic stress, G_m, and void volume reduction ratio, R_v, which our company uses as parameters for void closure. The integral of hydrostatic stress, G_m, and void volume reduction ratio, R_v, are defined by Equations (1) and (2) [2]. Here, ε_f is the equivalent strain at the end of forging at the void position, p is the hydrostatic stress, ε_{eq} is the equivalent plastic strain, σ_{eq} is the equivalent stress, and C_{ij} is the coefficient of the n-th order simultaneous multi-nodal equation (C_{00}, C_{10}, C_{11}, ····· C_{0n}, C_{n0}). Table 2 shows the coefficients of the multiple regression equation obtained by extracting explanatory variables with large variance values in equation (2) [2].

$$G_m = \int_0^{\varepsilon_f} \left(-\frac{p}{\sigma_{eq}}\right) d\varepsilon_{eq} \fallingdotseq \sum_{i=1}^{n} \left(-\frac{p}{\sigma_{eq}}\right)^i \Delta\varepsilon_{eq}^i \qquad (1)$$

$$R_v = \sum_{i=0}^{n} \sum_{j=0}^{n-j} C_{ij} \varepsilon_{eq}^i G_m^j \qquad (2)$$

Regarding the material properties, we adopted the properties of 3.5NiCrMoV steel, which is a similar material to the test sample. The initial temperature of the analysis model was set to a uniform 1270°C. And a temperature distribution similar to that of the actual press was reproduced by sequentially performing heat conduction analysis on the end shape of each forging pass. Figure 6 shows the output results of the void closure criteria for condition ③. As a result of accumulating the individual close indices for each pass, it was found that the criteria for void closure in a 27t steel ingot (hereinafter referred to as criteria A) is as follows.

$$\left.\begin{array}{l} \text{Integral of hydrostatic stress } G_m \geqq 0.708 \\ \text{Void volume reduction ratio } R_v \geqq 0.589 \end{array}\right\} \text{Criteria A}$$

Tab.1 - FEM analysis conditions

Item	Conditions
Analysis code	Abaqus6.14-1
Element	Eight-node hexahedral linear element (C3D8)
Material	3.5NiCrMoV
Initial diameter [mm]	φ1364
Initial temp. [°C]	1270
Press speed [mm/s]	50
Die width [mm]	450
Die chamfer shape [mm]	R50
Die contact ratio [%]	90
Press reduction amount [mm]	≃100

Tab.2 - Coefficients of equation (2) [2]

i ＼ j	0	1	2	3
0	0.011	1.488	-0.480	-
1	-0.291	-0.911	0.295	
2	1.164	-		
3	-0.382			

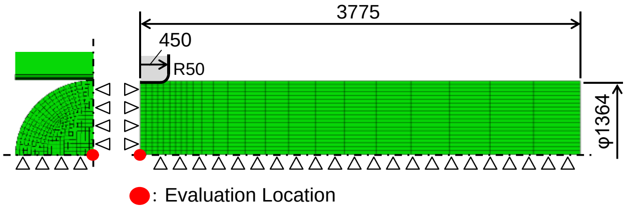

Fig.5 - FEM analysis initial model

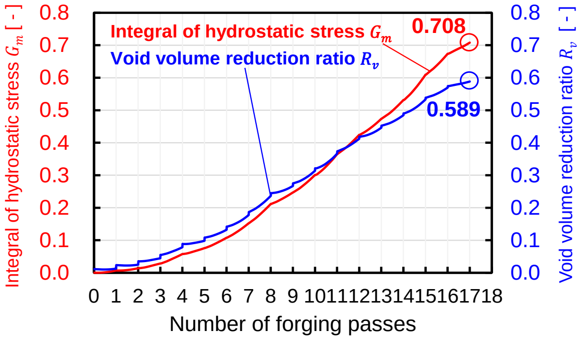

Fig.6 - Void closure parameter output result for condition ③

1-3. Verification of void closure effect using FDFD

Based on the above results, we verified whether void closure is possible using FDFD only. We performed an FEM analysis simulating the cogging process of forging a round bar from a steel ingot using FDFD to evaluate the closure effect. The initial model for analysis was a simulated cylindrical shape with φ868 which is the diameter at the maximum size void position of test ingot. We verified the forging ratio that provides a closure effect equal to or higher than criteria A using FDFD with an die contact ratio of 50%. Table 3 shows the analysis conditions. The method of FEM elastoplastic analysis is as shown in Section 1-2. Figure 7 shows the analysis output results for criteria A. As a result of accumulating the integral of hydrostatic stress G_m and void volume reduction ratio R_v for each reduction pass schedule, it was found that the void closure parameter of the shaft center became equal to or higher than that of criteria A at the opposite side dimension of 500 mm. The forging ratio was calculated to be 2.86S.

We verify whether the voids would close in an actual forging press using FDFD only by imparting a void closure effect greater than criteria A. The test sample was one steel ingot (Top side φ955 mm × L 2040 mm) with a body weight of approximately 10 tons (1.8NiCrMoV). After the steel ingot was heated to 1200°C, it was cogged an octagonal shape with a diagonal dimension of 500 mm using an FDFD with an die width of 600 mm under an die contact ratio of 50% and a reduction amount of 50 to 90 mm. Figure 8 shows an overview of the void closure forging test using FDFD only. As in Section 1-1., after annealing, UT was performed on the hatched areas in Figure 8. The UT result was No-indication, and the MDFS of the shaft center was φ1.6 mm. Therefore, it was concluded that void closure is possible by cogging using FDFD only.

Tab.3 - FEM analysis conditions (FDFD only)

Item	Conditions
Analysis code	Abaqus6.14-1
Element	Eight-node hexahedral linear element (C3D8)
Material	3.5NiCrMoV
Initial diameter [mm]	φ868
Initial temp. [°C]	1200
Press speed [mm/s]	50
Die width [mm]	600
Die chamfer shape [mm]	R50
Die contact ratio [%]	50
Press reduction amount [mm]	≃ 50

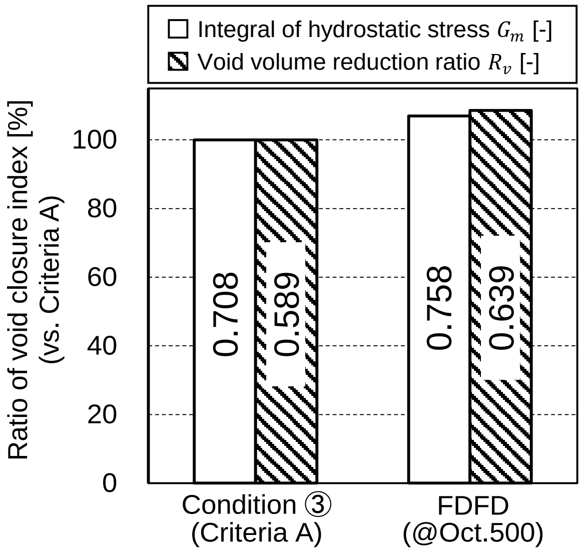

Fig.7 - Void closure parameter output results for FDFD (vs. Criteria A)

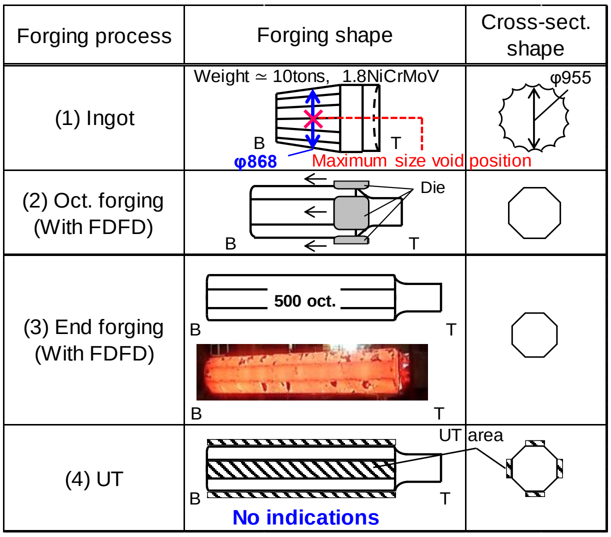

Fig.8 - Overview of forging tests with FDFD only

2. ACTUAL PRESS FORGING USING FDFD ONLY

The method using FDFD was applied to an actual press from the void closure process to the final rounding process. Applicable products are round bars $\varphi 450^{+15}_{-0}$ mm × L 5500 mm forged from steel ingots (Top side φ955 mm × L 1675 mm) with a body weight of approximately 7.4tons (SCM432). After the steel ingot was heated to 1250°C, it was upset using a 30 MN hydraulic press until the diameter of the bottom side reached 810 mm to ensure a 3S forging ratio. At an die contact ratio of 50% or more using FDFD with an die width of 600 mm, the ingot was forged into an octagonal shape with a width across flats of 480 mm for a reduction amount 50 mm or more. After that, rounding is performed with FDFD and finished into a round bar of $\varphi 450^{+15}_{-0}$ mm × L 5500 mm. Figure 9 shows the appearance of a round bar that has been FDFD forged throughout the entire forging process. Figure 10 shows the press time reduction effect compared to the average for conventional products. The objects of investigation for conventional products are a total of four round bars of the same shape, which are subjected to a closure process and a leveling and rounding process using upper and lower R-shaped dies. When the entire process was forged using FDFD, it was possible to reduce the press time by approximately 41% compared to the average of conventional products while maintaining external and internal quality.

Fig.9 - Appearance of round bar
(All forging processes use FDFD)

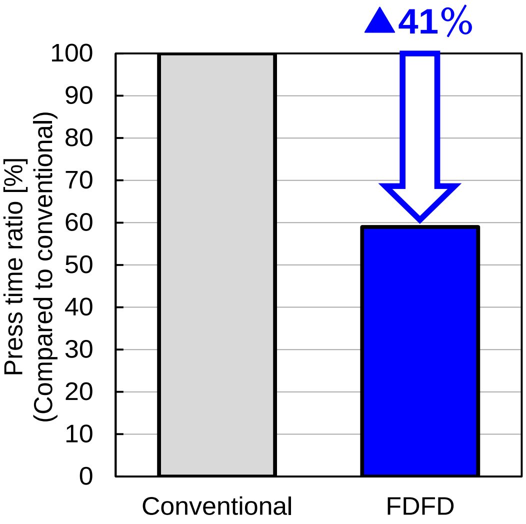

Fig.10 - Pressing time reduction effect
(All forging processes use FDFD)

3. CONCLUSION

The results of this study are summarized below.

1. We derived the minimum void closure criteria and obtained the following values.
   Integral of hydrostatic stress $G_m \geqq 0.708$
   Void volume reduction ratio $R_v \geqq 0.589$
2. We achieved void closure by using FDFD only according to the above criteria.
3. We succeeded in reducing forging time by approximately 41% using FDFD.

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