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Cold Forging Technology for Steel Bars and Wire Rods

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Abstract

Cold forging, which is excellent in productivity, processing accuracy, and material yield is one of the processing methods indispensable for the manufacturing of automotive parts made of steel bars and wire rods. As a measure against technical problems of cold forging, study cases of evaluation of ductile fracture limit in the low stress triaxiality region, development of a ductile fracture-suppressing method in forward extrusion of hollow members, and performance evaluation of phosphate coating with soap are introduced.

1. Introduction

Steel bars and wire rods for automotive parts are shipped from steelmakers as rolled steels. Then, customers process them in various ways such as wire drawing, annealing, forging, machining, and surface hardening heat treatment to turn them into parts of engines, powertrains, and others. The characteristics and production costs of these parts are significantly affected not only by steel products (materials) but also by manufacturing processes. Therefore, to improve strength, functions, and price competitiveness of automotive parts, approaches from the perspectives of both steel products and manufacturing methods are required. Under this concept, Nippon Steel Corporation has been researching and developing technologies for manufacturing parts in addition to steel products themselves, and promoting technology development for every phase from steel products to manufacturing methods.[1–3]

One manufacturing method that is essential in the manufacture of automotive parts from steel bars and wire rods (materials) is forging with high productivity and material yield. Forging is classified into several types depending on the processing temperature: cold forging, warm forging, hot forging, and mashy-state forging: This section organizes the characteristics of cold forging and hot forging that are often used for steel in **Table 1**. As advantages of cold forging, the dimensional accuracy and the surface condition after forging are excellent and finishing by machining and grinding can be omitted or simplified. Therefore, after the technology was introduced into Japan from Europe and the U.S., various types of parts have been formed by cold forging. In the present situation where the technology has advanced, cold forging is also applied to high-accuracy parts in complicated shapes such as gears and spiders.[4, 5]

Nippon Steel has developed various types of steel (e.g., high-ductile steel, soft steel, and coarse-grain-prevention steel) that are

Table 1 Comparison of steel cold forging with steel hot forging

	Cold forging	Hot forging
Process temperature	Room temperature	1000–1250°C
Material flow stress	High	Low
Forging pressure	High	Low
Annealing before forging	Necessary	Unnecessary
Material deformability	Low	High
Shape of forgings	**Complex in some cases**	Complex
Dimensional accuracy of forgings	**High**	Low
Surface condition of forgings	**Fine**	Oxidized and decarburized
Lubricant	Phosphate coating plus metal soap, etc.	Graphite, etc.

suitable for cold forging to solve its technical problems from the perspective of steel products.[6, 7] In addition, Nippon Steel has been working to improve cold forging technologies and is prototyping and developing high-value-added cold-forged products using laboratory equipment (e.g., double-acting servo press) and numerical analysis. This paper introduces Nippon Steel's researches on ductile fractures, processing of hollow members, and lubrication in cold forging of steel bars and wire rods as examples.

2. Ductile Fracture Limits in the Low Stress Triaxiality Region

In cold forging where materials are processed at room tempera-

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ture without heating, ductile fractures (cracks) tend to be made on the surface or inside of forged parts. When a ductile fracture is found, countermeasures (e.g., review of the manufacturing processes and the shape of the forged part) are sought through trial and error, so techniques for predicting ductile fractures at high accuracy need to be established from the perspective of work period shortening and cost reduction.

Generally, to predict a ductile fracture in cold forging, ductile fracture conditional equations represented by Cockcroft and Latham's formula[8] and Oyane's formula[9] are used. In recent years, Nippon Steel has been studying a prediction method using ductile fracture limit lines on stress triaxiality-equivalent plastic strain planes that are considered able to evaluate ductile fracture limits more accurately. Stress triaxiality is a dimensionless number obtained by dividing the mean stress (σ_m) by the equivalent stress (σ_{eq}). It is considered that the higher the stress triaxiality is, the more void growth (one process in a ductile fracture) is encouraged.[10] It is known that, in a region where the stress triaxiality is 0.6 or higher, when a ductile fracture advances mainly in tension mode from the inside of the material, the higher the stress triaxiality is, the lower the ductile fracture limit is.[11–14]

Meanwhile, for cases when a ductile fracture advances from the surface of the material in a region where the stress triaxiality is 0.0 or higher and lower than 0.6, various results have been reported. Specifically, some researchers have reported that the ductile fracture limit is not affected by the stress triaxiality and determined only by the equivalent plastic strain.[11, 15] Some other researchers have reported that the higher the stress triaxiality is, the higher the ductile fracture limit is.[16] Still other researchers have reported that the higher the stress triaxiality is, the lower the ductile fracture limit is.[17, 18] Thus, it cannot be said that ductile fracture limits in the low stress triaxiality region have been fully understood. Therefore, the authors clearly distinguished differences in deformation mode, which may hinder sound understanding, and then studied ductile fracture limits in the low stress triaxiality region.[19, 20]

As the test material, JIS S55C carbon steel for machine structural use that had been subject to spheroidizing annealing was used. **Figures 1** and **2** show the shapes of test specimens. Each test specimen was cut from the test material parallel to the rolling direction. **Table 2** lists test conditions. In the notched-bar tensile tests (test Nos. 1 to 4), the stress triaxiality at the center of (inside of the material of) each test specimen that serves as the starting point of ductile fracture was changed depending on the size of the radius of the notch. In the notched-bar torsion tests (test Nos. 5 to 9), the test specimen was not only simply twisted but also twisted while applying compressive load or tensile load/displacement to change the stress triaxiality at the bottom (surface of the material) of the notch that serves as the starting point of ductile fracture. The stress triaxiality and equivalent plastic strain in the tests were calculated by elasto-plastic analysis using the finite element method analysis software Marc (version 2014).

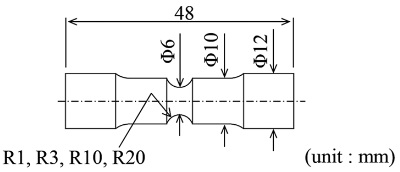

Fig. 1 Geometry of notched-bar tensile specimen

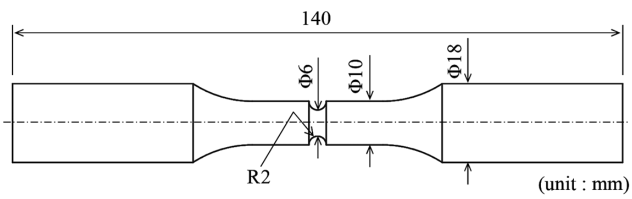

Fig. 2 Geometry of notched-bar torsion specimen

Figure 3 shows the stress triaxiality and equivalent plastic strain at the fracture origin when a ductile fracture occurred in each test. When a ductile fracture develops from the inside of the material in tension mode in the region with a stress triaxiality is 0.6 or higher, the higher the stress triaxiality is, the lower the ductile fracture limit is, as is the case with past reports. When a ductile fracture develops from the surface of the material in the low stress triaxiality region mainly in shear mode, which is the focus of this study focuses, the ductile fracture limit can be organized using the stress triaxiality and equivalent plastic strain. That shows that the higher the stress triaxiality is, the lower the ductile fracture limit is. In addition, it has been found that ductile fracture limits vary between the case where the fracture was mainly generated in shear mode and the other case where the fracture was generated in tension mode.

The results above show that, when a ductile fracture develops from the surface of a material mainly in the shear mode in the low stress triaxiality region, the higher the stress triaxiality is, the lower the ductile fracture limit is, as is the case in the high stress triaxiality region. In addition, because the ductile fracture limits vary depending on the deformation mode, it may be important to evaluate ductile fracture limits in the same deformation mode as that of a target,

Table 2 Test conditions

Test number	Test pattern	Notch radius	Tensile rate	Torsion rate	Load
1	Tensile	1 mm	0.3 mm/min	–	–
2		3 mm			
3		10 mm			
4		20 mm			
5	Combined tension and torsion	2 mm	0.3 mm/min	0.5 deg/s	–
6			–		11 kN
7	Torsion				–
8	Combined compression and torsion				−3 kN
9					−6 kN

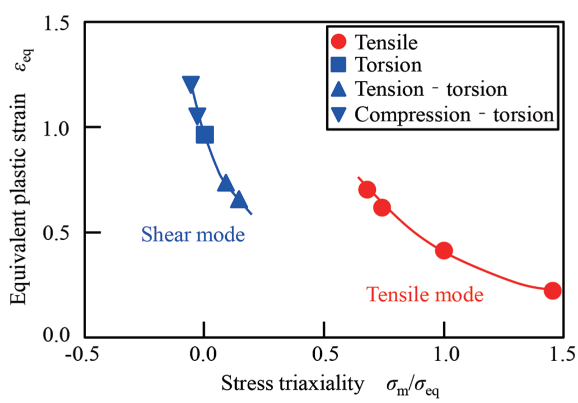

Fig. 3 Ductile fracture limit

in order to predict ductile fractures more accurately.

3. Technologies for Processing Long Hollow Members

For weight saving, many hollow automotive parts whose inside is partly or entirely cored by cold forging have been manufactured. In coring by cold forging, a round hole is formed at the center by forward extrusion or backward extrusion in most cases. In such cases, when the ratio (L/D) of the hole depth (L) to the hole diameter (D) exceeds 4, the risk of punch failure by buckling increases, so it is difficult to form long hollow members with a deep hole with a large L/D by cold forging. Currently, long hollow members are cored by machining using a gun drill in general, but the productivity and material yield are low. Therefore, technologies for forming hollow members by cold forging need to be advanced and types of parts to which such technologies can be applied need to be expanded.

Buckling of punches in boring by forward extrusion or backward extrusion can be suppressed by reducing the contact pressure of the punches. Some researchers have actually reported that a deep hole whose L/D is 11 can be formed by applying can extrusion with auxiliary tension[21] as a method to reduce the contact pressure of a punch.[22] Meanwhile, Nippon Steel has been working to form long hollow members by cold forging using a method different from such methods. Specifically, a solid material is cored (by forming a hole); then the diameter of the obtained hollow member is made smaller and the member is extended by forward extrusion. However, this method tends to cause a ductile fracture on the inner periphery (hereinafter "inner surface crack") in forward extrusion of the hollow member. Cracks may not be sufficiently suppressed only by adjusting the die angle and the reduction of area. To solve this problem, Nippon Steel developed a new method to suppress inner surface cracks and carried out an experiment to check the effects.

As the test material, JIS S43C carbon steel for machine structural use that had been subject to spheroidizing annealing was used. **Figure 4** shows the shapes of forged parts before and after forward extrusion. Sheared round bars were processed by hole forming from both ends and then punching. The obtained hollow members (Fig. 4(a)) were formed into three types of stepped hollow members in different shapes (Fig. 4(b) to Fig. 4(d)) by forward extrusion. Figure 4(b) shows a stepped hollow member formed by the conventional method. When the outer diameter was made smaller, the inner surface plastically deformed under the tensile stress caused by differences in the drift velocity of the material between the outer peripheral section and inner peripheral section. Therefore, the smaller the outer diameter is made, the greater the risk of an inner surface crack is.

Therefore, to reduce differences in the drift velocity of the material between the outer diameter section and inner diameter section that cause tensile stress, the authors developed a new method to suppress inner surface cracks in which when the outer diameter is reduced and the inner diameter is enlarged at the same time. Figure 4(c) shows a stepped hollow member to which the new method was applied in the second reduction of the outer diameter. Effects on suppression of inner surface cracks and the influence of angles for diameter expansion on the effects were studied. Figure 4(d) shows a stepped hollow member to which the developed method was applied twice to suppress inner surface cracks to the extent possible.

Figure 5 shows the experimental results. With the conventional method (Fig. 5(a)), an easily visible inner surface crack was formed. On the other hand, in the case where the developed method was applied in the second outer diameter reduction (Fig. 5(b)), the smaller the size of the crack was, the lower the occurrence ratio of the crack also was. These results show that the developed method can suppress inner surface cracks. In addition, it has been found that the larger the angle for diameter expansion is, the higher the effect of reducing cracks is. Furthermore, applying the developed method twice could suppress inner surface cracks completely (Fig. 5(c)).

As described above, the authors developed a new method to suppress inner surface cracks on hollow members in forward extrusion

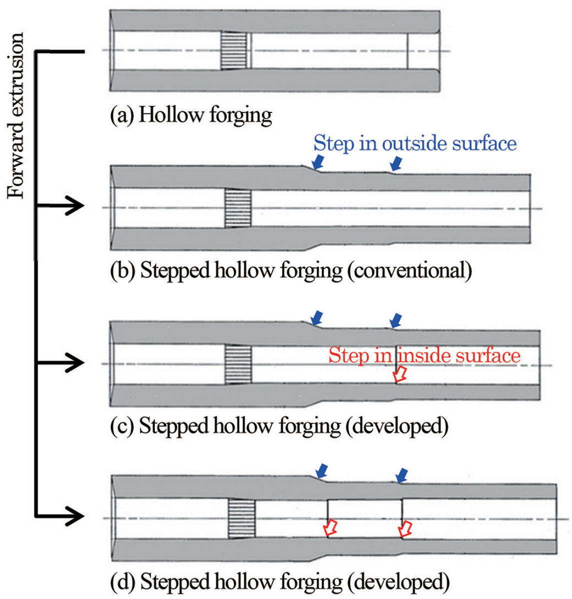

Fig. 4 Geometries of forgings before and after forward extrusion

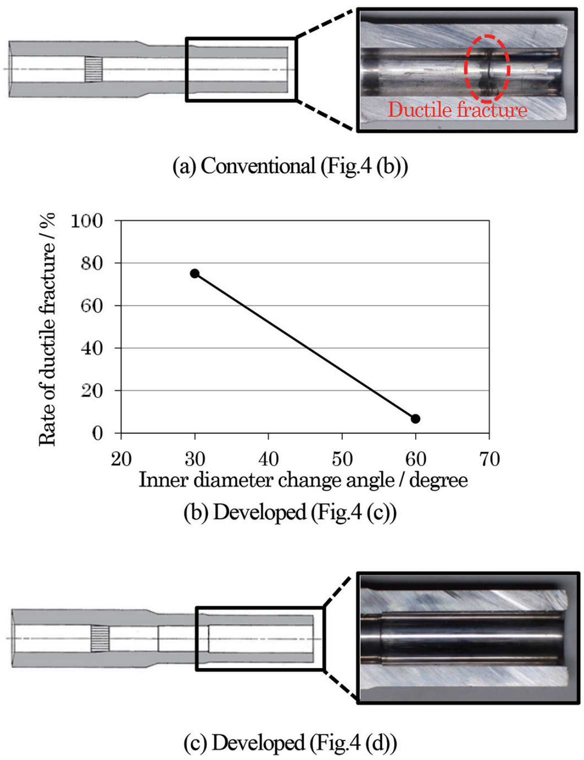

Fig. 5 Experimental result

and proved the effects. Applying this method makes it possible to form long hollow members with deep holes by cold forging whose L/D is larger than that of existing parts.

4. Evaluation of the Lubrication Properties of Phosphate Coating with Soap

Lubricants used in cold forging must prevent galling between materials and dies and reduce friction coefficients even under severe conditions such as steep temperature increase due to deformation and friction heat, significant surface expansion, and high contact pressure. To that end, phosphate coating with soap has been often used in cold forging, where phosphate coating with excellent anti-galling ability is subject to soap treatment to reduce the friction coefficient.

It is known that various factors affect the lubrication properties of phosphate coating with soap. For example, some researchers have reported that the coating weight affects the anti-galling ability[23] and others have reported that the temperature and surface expansion ratio affect the friction coefficient.[24] Nippon Steel has developed its particular method to evaluate anti-galling ability and has evaluated the properties of phosphate coating with soap.[25, 26] However, there are very few cases where the influence of various factors was systematically evaluated including roughness of dies. Therefore, the authors changed the coating thickness, roughness of the friction tool, interface temperature, contact pressure, and sliding speed to evaluate their influence on the friction coefficient and anti-galling ability.[27]

As the test material, normalized JIS S10C carbon steel for machine structural use was used. A Bowden-Leben friction test was performed to evaluate lubrication properties. A zinc phosphate coating with soap with an initial thickness of approximately 5 μm was expanded by forward extrusion with a counter-punch having a square cross section. The coating thickness was adjusted to 0.10 to 0.94 μm. A commercially available steel ball (material: JIS SUJ2 bearing steel) was used as the indenter. The reduced peak height (Rpk) on the indenter was set to 0.007 to 0.300 μm by re-polishing. The test temperatures were 25 to 250°C, the test loads were 9.8, 29.4, and 68.6 N, and the test speed was 1, 5, and 10 mm/s. The friction coefficient was evaluated using the average one of 10 times of sliding. The anti-galling ability was evaluated using the sliding distance ($L_{\mu 0.2}$) until the friction coefficient exceeded 0.2.

Figure 6 shows influence of the temperature on the friction coefficient. The plotted data in Fig. 6 and **Fig. 7** are the experimental results and the lines are prediction formulas to be mentioned later. From room temperature to 200°C, as the temperature increases, the friction coefficient decreases and, at 250°C, it rapidly increases. Figure 7 shows influence of the surface roughness of the indenter on the friction coefficient. The lower the roughness is, the lower the friction coefficient is. Figures 6 and 7 show that the coating thickness hardly affected the friction coefficient. In addition, the contact pressure and sliding speed hardly affected the friction coefficient although it is not shown as a figure. The highly influential temperature (T) (°C) and the reduced peak height (Rpk) of the indenter (μm) were used to formulate the friction coefficient (μ). Formula (1) is the obtained formula. The data at 250°C at which the coating broke and the function stopped were not used for the formulation. As shown in Fig. 6 and Fig. 7, formula (1) matches the experimental data well and it can potentially be used for numerical analysis considering changes in the friction coefficient due to temperature changes.

$$\mu = 0.338\,(1.05\,\mathrm{Rpk} + 0.975)\,\mathrm{T}^{-0.373}. \quad (1)$$

Figure 8 shows influence of the temperature on the anti-galling ability. It is considered that the longer sliding distance ($L_{\mu 0.2}$) until the friction coefficient exceeds 0.2 is, the higher the anti-galling ability is. From 25 to 150°C, the higher the temperature is, the lower the anti-galling ability is. **Figure 9** shows influence of the surface roughness of the indenter on the anti-galling ability. The lower the roughness is, the higher the anti-galling ability is. Figures 8 and 9 show that the thicker the coating is, the higher the anti-galling ability is. The contact pressure and sliding speed had almost no influence although it is not shown as a figure.

The results above show that the interface temperature and roughness of the tool significantly affect the friction coefficient of phosphate coating with soap and that the interface temperature, rough-

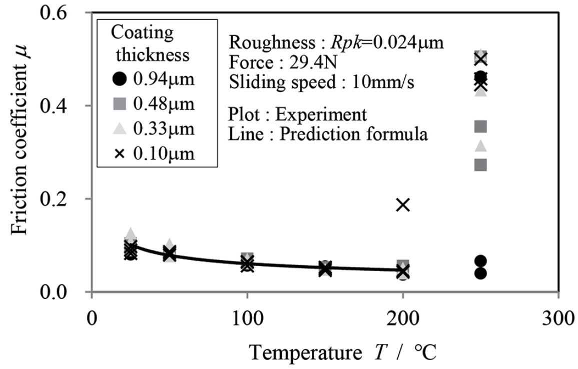

Fig. 6 Influence of temperature on friction coefficient

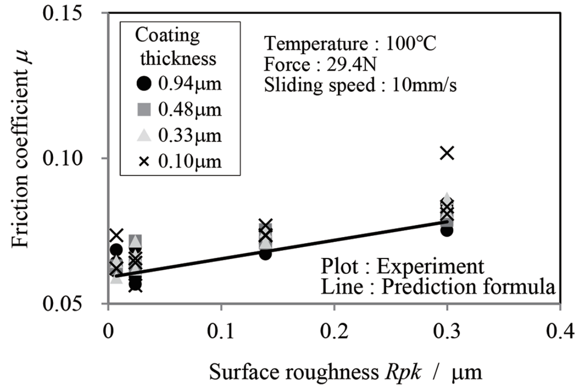

Fig. 7 Influence of contact surface roughness on friction coefficient

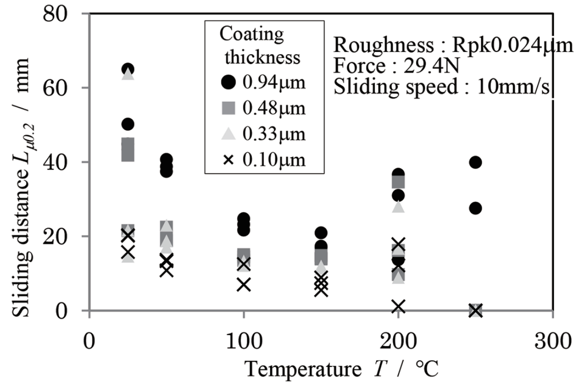

Fig. 8 Influence of temperature on anti-seizure ability

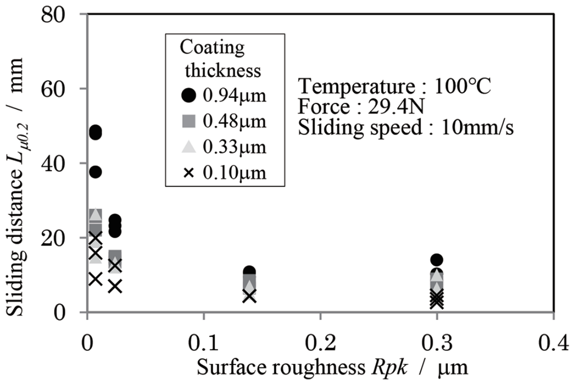

Fig. 9 Influence of contact surface roughness on anti-seizure ability

ness of the tool, and coating thickness significantly affect the anti-galling ability.

5. Conclusions

(1) It has been found that when a ductile fracture develops from the surface of a material mainly in shear mode in the low stress triaxiality region, the higher the stress triaxiality is, the lower the ductile fracture limit is, as is the case in the high stress triaxiality region.

(2) The authors developed a new method to suppress cracks as a countermeasure against inner surface cracks on hollow members in forward extrusion. The new method expands the inner diameter at the same time as the outer diameter is reduced. The effects were proved.

(3) It has been found that the interface temperature and roughness of the tool significantly affect the friction coefficients of phosphate coating with soap and that the interface temperature, roughness of the tool, and coating thickness significantly affect the anti-galling ability.

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References

1) Todo, S., Sueno, H., Imataka, H.: Shinnittetsu Sumikin Giho. (406), 13 (2016)
2) Umehara, T., Yuya, M.: Abstracts of the meeting of the Japan Society for Heat Treatment. (80), 45 (2015)
3) Aiso, T.: Materia Jpn. 56 (6), 397 (2017)
4) Nakajima, M., Arai, S., Kondo, K.: J. Jpn. Soc. Technol. Plast. 50 (587), 1086 (2009)
5) Shinozaki, K.: J. Jpn. Soc. Technol. Plast. 57 (664), 406 (2016)
6) Monden, A., Miyanishi, K., Yamasaki, S., Ochi, T.: Shinnittetsu Giho. (393), 127 (2012)
7) Toda, M., Yoshida, S.: J. Jpn. Soc. Technol. Plast. 52 (600), 153 (2011)
8) Cockcroft, M.G., Latham, D.J.: J. Inst. Met. (96), 33 (1968)
9) Oyane, M: Trans. Jpn. Soc. Mech. Eng. 75 (639), 596 (1972)
10) Rice, J.R., Tracey, D.M.: J. Mech. Phys. Solids. (17), 201 (1969)
11) Kawabata, T., Arimochi, K., Ohata, M., Mochizuki, M., Toyoda, M.: Q. J. Jpn. Weld. Soc. 22 (4), 515 (2004)
12) Shimanuki, H., Furuya, H., Inoue, T., Hagiwara, Y., Toyoda, M.: Journal of the Society of Naval Architects of Japan. (186), 475 (2001)
13) Narumiya, H., Kada, O.: Proceedings of the 2016 Japanese Spring Conference for the Technology of Plasticity. 217 (2016)
14) Narumiya, H., Kada, O.: CAMP-ISIJ. 29 (1), 174 (2016)
15) Shoji, H., Ohata, M., Minami, F.: Tetsu-to-Hagané. 100 (5), 668 (2014)
16) Bao, Y., Wierzbicki, T.: Int. J. Mech. Sci. 46 (1), 81 (2004)
17) Shiga, A., Okubo, J., Tamura, K., Matsui, N., Neishi, Y., Higasida, M.: J. Jpn. Soc. Technol. Plast. 53 (613), 150 (2012)
18) Miyata, T., Otsuka, A., Okuyama, H.: J. Soc. Mater. Sci., Jpn. 37 (420), 1036 (1988)
19) Yamashita, T., Neishi, Y., Monden, A., Yamasaki, S., Noguchi, Y.: Proceedings of the 65th Japanese Joint Conference for the Technology of Plasticity. 255 (2014)
20) Yamashita, T., Neishi, Y., Shiga, A., Noguchi, Y.: J. Jpn. Soc. Technol. Plast. 58 (678), 617 (2017)
21) Shinozaki, K., Kudo, H.: J. Jpn. Soc. Technol. Plast. 14 (151), 629 (1973)
22) Murai, E., Mori, M., Nakayama, S., Kondo, Y.: Proceedings of the 2016 Japanese Spring Conference for the Technology of Plasticity. 119 (2016)
23) Saiki, H., Marumo, Y., Ruan, L., Ngaile, G.E.: J. Jpn. Soc. Technol. Plast. 41 (477), 1036 (2000)
24) Danno, A., Abe, K., Nonoyama, F.: J. Jpn. Soc. Technol. Plast. 24 (265), 213 (1983)
25) Kada, O., Wang, Z., Miyanishi, K., Yanagi, H., Nose, Y.: J. Jpn. Soc. Technol. Plast. 60 (696), 8 (2019)
26) Kada, O., Miyanishi, K., Nose, Y., Yanagi, H.: Proceedings of the 65th Japanese Joint Conference for the Technology of Plasticity. 277 (2014)
27) Kada, O., Wang, Z.: Key Engineering Materials. (767), 124 (2018)

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