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Development of Solution Technology for Parts Production Using Steel Bars and Wire Rods

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Abstract

Process and design technology as well as development of new steels are indispensable for development of new products using steel bar and wire rod which satisfy various demands. Then, research and development for solution technology in production has been promoted in our company, in order to develop new products successfully utilizing throughout metallurgy, process technology and design optimization. This report describes research topics concerning both basic technology and development of forging process for new products, and a research topic concerning manufacturing of stranded wire.

1. Introduction

After shipment from a manufacturer, steel bars and wire rods undergo various manufacturing processes on the user's side for use in the production of automobiles, construction machines, construction materials, and other finished products. In order to comply with the increasingly strengthened fuel consumption regulations for global environmental protection, and to meet the demand for workability improvement of steel products provided by steel manufacturers, we are striving to find methods to boost our ability to reduce weight, increase strength, and sophisticate steel products. As bar and wire rod products undergo various processes until they reach their final form, satisfying a higher level of requirements for them means that instead of mere expansion of steel types, consistent product development is required, involving the creation of a new steel type and processing methods suitable for such steel type.

Against this backdrop, Nippon Steel & Sumitomo Metal Corporation has conducted R&D projects related to the manufacturing solution technology of steel components as part of the consistent product development initiatives by integrating both the development of new steel and that of new processing methods. **Figure 1** shows the process workflow conducted in highly functional product development to satisfy the higher level of requirements from markets. In order to realize a highly functional or cost competitive product, the steel type and process development performed in cooperation with users is considered effective, starting from the design stage.

One of the most important processes in the manufacture of bar and wire rod products is forging, in view of the direct influence it has not only on the component cost, but also on the component function. For the product development, Nippon Steel & Sumitomo Metal conducts experiments including cold forging test production and utilizes numerical analysis technology. As part of such initiatives, we are conducting a variety of experiments. This report describes some examples using large servo press machines, for which unique experiments are conducted to test various enclosed die forging methods and other methods with varied processing conditions while rendering the production test condition as close to the actual production condition as possible, and working on the technology for forging with high shaping ability.

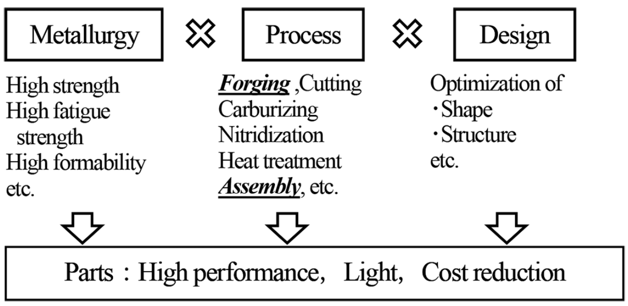

Fig. 1 Development process of high performance parts produced with steel bar and wire rod

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Furthermore, steel cords, which are some of our main wire rod products, have been studied in pursuit of further increasing the strength in response to recent market demand. Amid this, the breakage of wires during the twisting process in the manufacture has been an issue. To this end, we are studying a wire twisting method capable of reducing the percentage of broken wires.

This paper describes examples of researches that have been conducted at Nippon Steel & Sumitomo Metal regarding cold forging of bars and wire rods including the development of element technology and processing technology, and also a study on a wire twisting method of the steel cord manufacture using numerical analysis.

2. Steel Material Fracture Prediction Method by Numerical Analysis

When a highly functional steel component is developed, the actual realization of an idea requires the creation of forging technology. To create forging technology, first, it is important to check whether the designed manufacturing process is appropriate through numerical analysis. Since one of the most important issues for the validity evaluation of a manufacturing process is the fracture of steel materials that occurs in the course of processing, demand for the technology that allows for steel material fracture prediction through numerical analysis is strong. **Table 1** shows various fracture prediction methods used for forging.[1–11] In recent years, Nippon Steel & Sumitomo Metal has been studying a prediction method using the fracture limit curve on the equivalent plastic strain-stress triaxiality plane on which an actual fracture phenomenon, varied by the stress triaxiality, can be accurately evaluated.[6–9] In this paper, pertaining to such study, we describe the results of the research examples regarding the effect of the multiaxis stress state on the fracture limit above,[9] and those of the verification of the prediction accuracy for inner cracking in the shape of a chevron (hereinafter referred to as "chevron cracking"), which is seen when forward extrusion is performed.[8]

2.1 Effect of multiaxis stress state on fracture limit[9]

Assuming the possibility that the multiaxis stress state may affect the fracture limit curve described above, prediction method construction considering Lode angle parameter ξ, which is a function of the third deviatoric stress invariant, has been pursued.[10] The multiaxis stress state is expressed as ξ $(-1 \leq \xi \leq 1)$. When $\xi=1$, the stress state is that of uniaxial tension; when $\xi=0$, the plane strain stress state; and when $\xi=-1$, the equibiaxial tension stress state. While many evaluations have been conducted for the ductile fracture limit in the uniaxial tension stress state and plane strain stress state, research examples in the equibiaxial tension stress state are rare. Given this, the fracture limit under the equibiaxial tension stress, in addition to the uniaxial tension stress and plane strain stress, was evaluated to study the effect of the multiaxis stress state on the fracture limit.

Figure 2 shows the shape of the specimens used. The tested material was a round bar of SCr420H that had undergone spheroidizing annealing (tensile strength: 475 MPa). The specimens were prepared such that the tensile direction became 90° to the tested material rolling direction. The biaxial tensile test specimen designed shown in Fig. 2(c) was characterized by the depression in the shape of a round bottom provided at the center of the specimen, which would maintain the center point in the equibiaxial tension stress state until ductile fracture occurred, with its curvature radius controlling the stress triaxiality. **Figure 3** shows the history of stress triaxiality during the test with the biaxial tensile specimen designed. The specimen's shape demonstrates the deformation with different stress triaxiality under the same equibiaxial tension stress. **Figure 4** shows

Table 1 Fracture prediction method for forging

Clasification	Method	Characteristics
Ductile fracture model	Cockcroft-Latham Oyane, etc.	• Application is limited to some simple fracture.
Equivalent strain-stress triaxiality	Experimental method	• High versatility • Procedure for determination of fracture limit is not simple.
Bifurcation theory	Hill, S-R, 3-D bifurcation theory	• Possibility for application to fracture under complex strain path. • Few verification examples in forging.

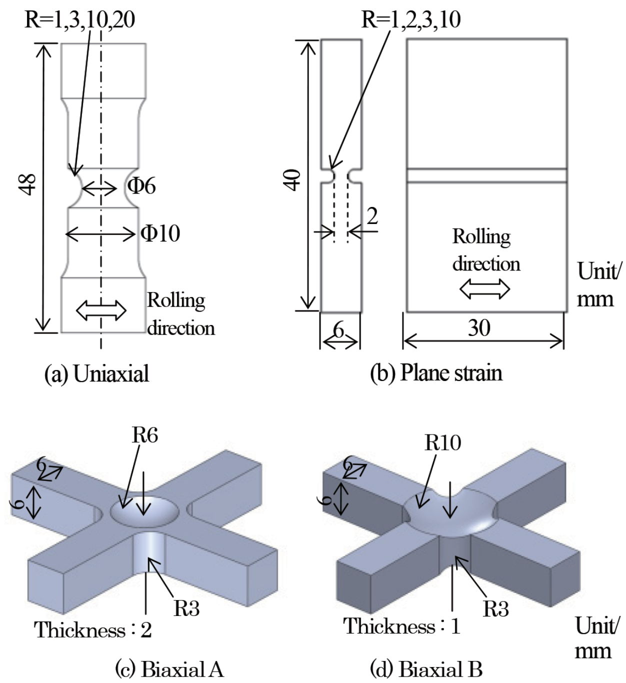

Fig. 2 Specimen for evaluation of fracture criterion

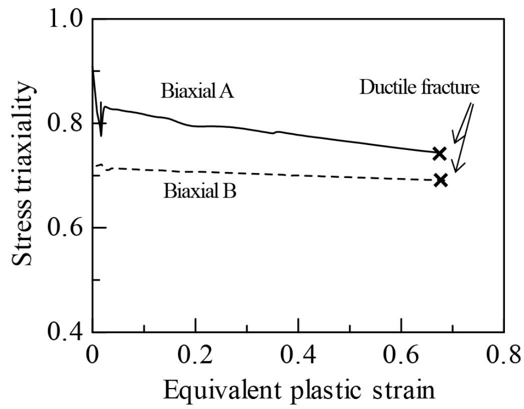

Fig. 3 Effect of specimen profile on stress triaxiality

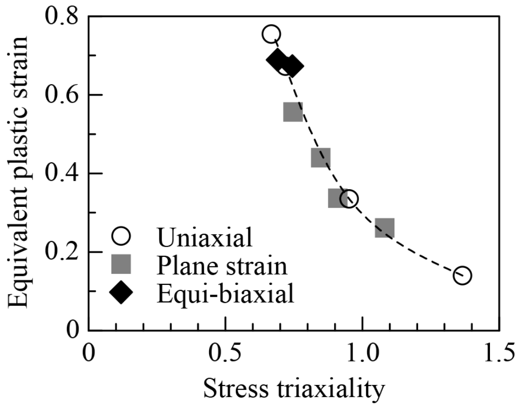

Fig. 4 Effect of multiaxial stress condition on fracture criterion in equivalent plastic strain-stress triaxiality

the influence of the multiaxis stress state on the fracture limit strain on the equivalent plastic strain-stress triaxiality plane. The fracture limit can be seen roughly on the same curve under different multiaxis stress.

The above results show the fracture limit defined on the equivalent plastic strain-stress triaxiality plane under the conditions of this test was not influenced by the multiaxis stress state. In the future, we will continue to study the fracture modes under the conditions of fracture phenomena during real operations conducting verifications in a similar manner.

2.2 Fracture prediction examples using the equivalent plastic strain-stress triaxiality curve[7, 8)]

Furthermore, we examined the possibility of the chevron cracking prediction, which is needed in many cases, in order to verify the validity of the fracture limit as defined using the equivalent plastic strain-stress triaxiality plane.

Figure 5 shows a schematic view of the forward extrusion as performed in the test, and the blank used and specimen that underwent the forward extrusion in the test. The tested material was as-rolled S43C. In the test, forward extrusion with multi passes was performed. The extruded specimen was cut at each pass to check the presence of fracture. For the determination of fracture, the fracture limit curve of as-rolled S55C, which has the C concentration equivalent to the center (the fracture starting point) of the specimen was used.

Figure 6 and **Fig. 7** show the fracture prediction results using the limit curve on the equivalent plastic strain-stress triaxiality plane, and the observation result of chevron cracking in the test, respectively. From Fig. 6, the potential to cause fracture was seen in the 3rd pass. The result image of the 3rd pass in Fig. 7 shows fracture, which accords with the prediction. The fracture gradually grew with each pass until it became a large chevron crack after the 9th pass.

Thus, we have verified that chevron cracking is predictable using the fracture limit that is defined using the equivalent plastic strain-stress tri-axial plane.

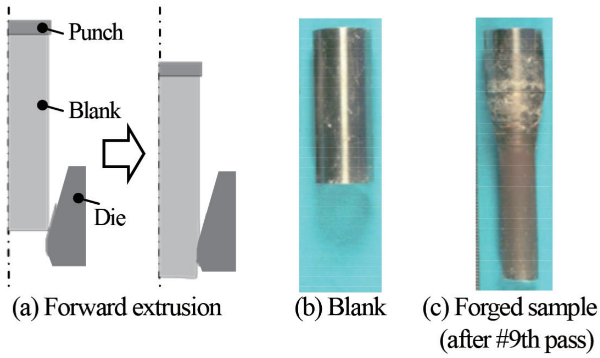

Fig. 5 Forward extrusion test

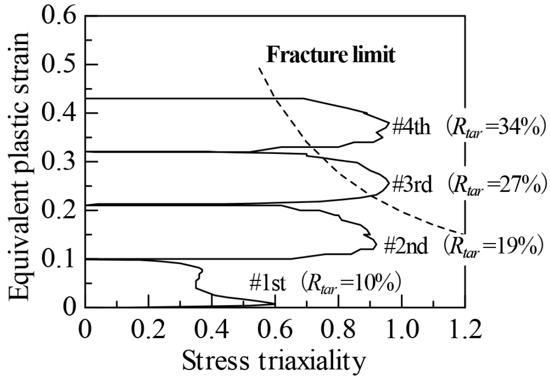

Fig. 6 Fracture prediction using fracture criterion on equivalent plastic strain-stress triaxiality

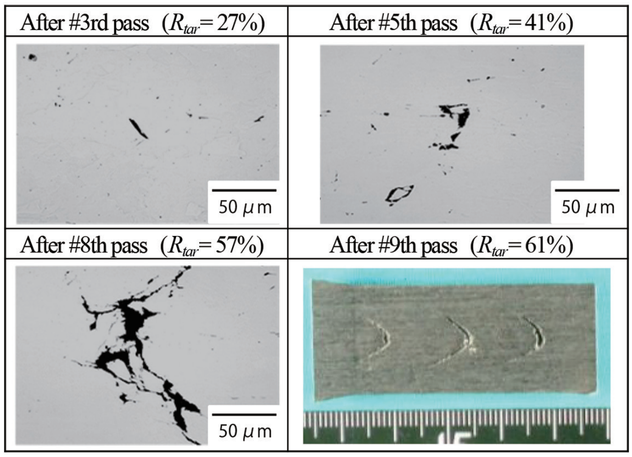

Fig. 7 Generation and growth of chevron crack

3. Technology for Anti-seizure Ability Evaluation[12, 13)]

When a processing method involving large strain introduction during cold forging of high strength steel is performed, the interface temperature between the die and workpiece increases, and the surface area of the workpiece is significantly widened as well. For this reason, the lubricant used for cold forging is required to have the frictional property and anti-seizure ability under the conditions of high temperature and large rate of area increase. To date, many evaluation methods of the anti-seizure ability, one of the important factors, have been proposed.[14, 15)] In such a situation, Nippon Steel & Sumitomo Metal has set out the initiatives to establish an evaluation method during backward extrusion, which is a typical forging process.[12, 13)] Specifically, this is a method to detect seizure based on a sudden change found in the extrusion load during backward extrusion.

Figure 8 shows a schematic view of the backward extrusion performed in this test. The tested material was one equivalent to S10C that had been annealed, from which a specimen machined to the size of 27 mm in diameter × 52 mm in length was obtained. After shot blasting and sulfuric acid pickling, zinc phosphate was used for the chemical conversion treatment, and sodium soap was used for lubrication. In order to verify the validity of the above method, as shown in **Fig. 9**, we compared the depth of the bored hole when a quick change occurred in the extrusion load with that when seizure was visually confirmed on the specimen after the test. To prevent the specimen from being damaged when the punch was pulled out after the backward extrusion was completed, the punch was stopped at the bottom dead center to remove the punch and processed specimen. Then, they were cut in half on the longitudinal cross-section to observe the seizing condition on the inner surface. As Fig. 9 shows, the portion at which the sudden change in the extrusion load occurred accorded with the depth of the bored hole in the seizure position as visually confirmed. Moreover, although not shown in the figure, it was confirmed that the anti-seizure ability was improved

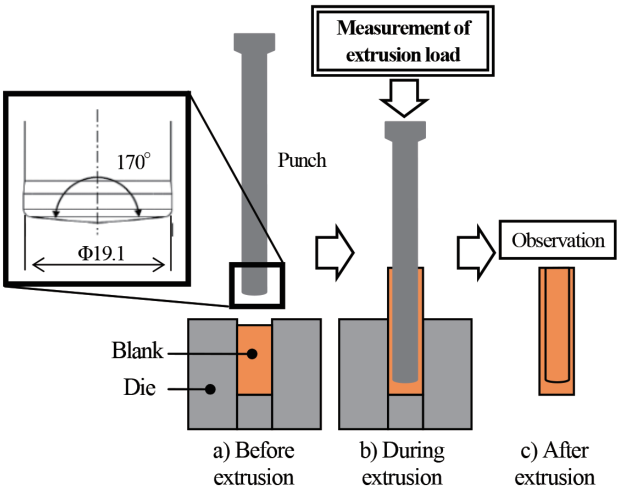

Fig. 8 Schematic drawing of evaluation method of galling resistance characteristics

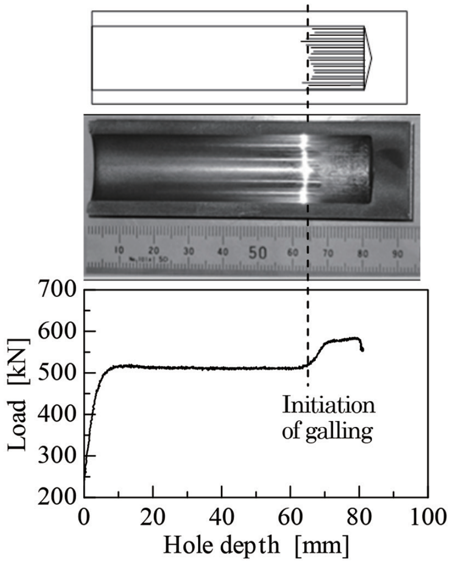

Fig. 9 Example of evaluation results of galling resistance characteristics by means of suggested method

through this method along with an increase of the amount of the phosphate film.[13)]

Thus, the validity of the method devised for detecting seizure occurrence through a sudden change in the extrusion load during backward extrusion was confirmed.

4. Technology for Processing Components with a Long Hole in the Center

Currently, the long holes in the center of shaft parts and other steel components that have a central long hollow are generally formed by cutting. It is an effective method in terms of cost, productivity and production equipment if the deep hollows can be formed by cold forging. However, if value L/D (quotient obtained by dividing hole depth L by hole diameter D) exceeds 4, the risk of damaging the die (punch) due to buckling when the deep hole is formed by cold forging is increased. Against this phenomenon, in order to reduce the punch load, a countermeasure technology using tension application to the workpiece was proposed,[16)] allowing for deep boring with L/D of approx. 11.[17)] Meanwhile, Nippon Steel & Sumitomo Metal is studying technology for processing steel components with a central long hole using a different method from these. Specifically, we considered a processing method in which a round bar undergoes backward extrusion from both end faces and subsequent punching to be formed into a shape with a hole in the center ($L/D \approx 10$) that in turn is elongated by forward extrusion.[18)]

Figure 10 shows the shape of the steel component in this study. The tested material was a round bar of S43C that had undergone spheroidizing annealing. Fracture that occurs on the inner diameter part of a steel material during forward extrusion is one of the issues involved in this method. **Figure 11** shows Cockcroft-Latham damage value D_f based on the numerical analysis results and a photograph of the inner surface of the specimen extruded in the test for

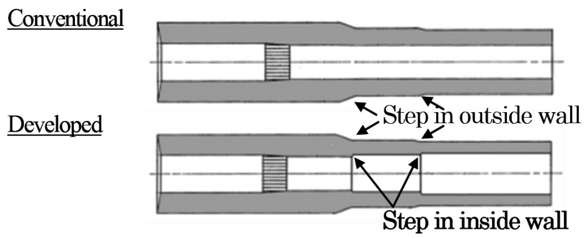

Fig. 10 Test sample of parts with long hole in the center

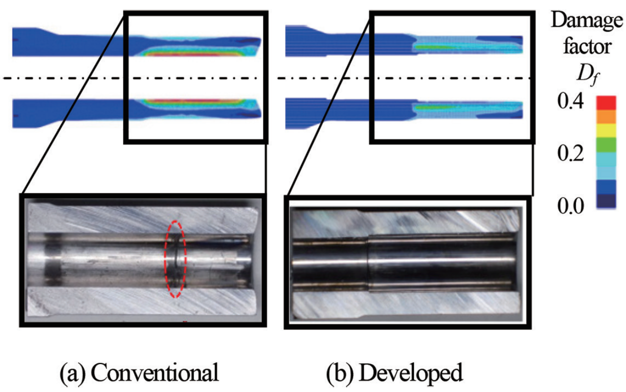

Fig. 11 Countermeasure against fracture along inside wall during forging of parts with long hole in the center

each normal forward extrusion (conventional method) and developed method described later. In Fig. 11 (a), visible fracture can be seen on the inner surface of the specimen extruded using a conventional method. Based on the numerical analysis results, the cause of the inner surface fracture above was confirmed to be the tension on the inner diameter part due to the material deformation speed difference between the inner diameter part and outer diameter part.

Given this, we have devised a new method for preventing inner diameter surface cracking. This is a method in which the inner diameter is expanded while the outer diameter is decreased in order to reduce the material deformation speed difference between the inner diameter part and outer diameter part (devised method). From the FEM result in Fig. 11 (b), the devised method was confirmed to have an effect on reducing damage value D_f along with the reduction of the tension on the inner diameter part. During the test as well, prevention of fracture on the inner diameter part was confirmed.

These results confirm that the processing method devised from the perspective of decreasing the material deformation speed difference between the outer diameter part and inner diameter part that occurs during forward extrusion is capable of preventing fracture on the inner diameter part during the forward extrusion process of a steel component with a long hole in the center. The use of this method allows for cold forging manufacture of stepped steel components with a long hole in the center with L/D equal to or larger than L/D of those made using conventional methods.

5. Analysis of Steel Cord Twisting

Steel cords used for reinforcing tires are manufactured by twisting multiple wires. These wires are made from wire rods 5 mm in diameter that are dry and wet drawn to be approx. 0.2 to 0.3 mm in diameter. An important issue involved in the steel cord manufacture using high strength wires is the reduction of the percentage of broken wires. This chapter describes a numerical analysis study of the influence of the twisting method difference on the breakage, focusing on single twist bunching and tubular stranding for the inner stress working during the twisting processes of these methods. Knowledge of the deformation history during the wire twisting process is important not only for the reduction of the percentage of broken wires, but also for the estimation of the cord properties and even tire performance.

Figure 12 shows schematic views of single twist bunching and tubular stranding. When the untwisted wire ratio y[19] is defined as the quotient obtained by dividing the rotating rate of the strand in the opposite direction of the revolution around the steel cord central axis by the revolution speed around the steel code center axis, $y=0$ for single twist bunching and $y=1$ for tubular stranding.

We used numerical analysis models each of which had four straight wires of 0.23 mm in diameter and 12 mm in length that were arranged in parallel, and were completely fixed at one end face and twisted in a revolving motion around the central axis formed by the four wires bundled at the other end faces (hereinafter referred to as the "revolution center"), simulating steel cord twisting of 1×4. When revolving around the central axis at the other end faces, no rotation was allowed during single twist bunching (the end face positions remain unchanged relative to the revolution center), and rotation at the same speed as the revolution speed in the opposite direction to the revolution direction was allowed during tubular stranding. The wires were those of elasto-plastic, and a stress strain curve equivalent to that of steel with tensile strength TS=3 200 MPa was used. Even though tension is also an important factor during twisting processes, we excluded tension from the consideration.

Figure 13 is a comparison of the numerical analysis results of principal stress distribution during the twisting process between single twist bunching and tubular stranding. In the figure, the upper left image in each cell indicates the maximum principal stress distribution on the $L/2$ cross-section; the center image indicates the maximum principal stress distribution of the entire twisted wire; and the lower left image indicates the wire positional relationship viewed from the wire end faces on the revolution side. As both end faces of the wires were fixed in a vertical manner, the analysis did not consider the phenomenon in which wires tilt when being twisted occurring at both end faces. Given this, we considered that stresses higher than those in reality would be shown in the vicinity of the fixed end faces and the other end faces on the side of revolution. In contrast, in the vicinity of the center in the longitudinal direction of the models, we thought that the stress distribution in the longitudinal direction would not change, representing the states seen in twisting processes. For this reason, the stress distribution in the vicinity of the center in the longitudinal direction of the models was evaluated. Moreover, **Fig. 14** shows a chart on which the influence of stranding pitch on the maximum value of the maximum principal stress at the central cross-section in the longitudinal direction of the models is plotted. If this maximum principal stress exceeds the fracture stress, a wire will break. It can be used as a guideline for wire breakage prevention when wires are twisted. Figure 14 shows that as the twisting pitch became shorter, the stress rapidly increased.

In view of Fig. 13 and Fig. 14, when the stress distribution at the

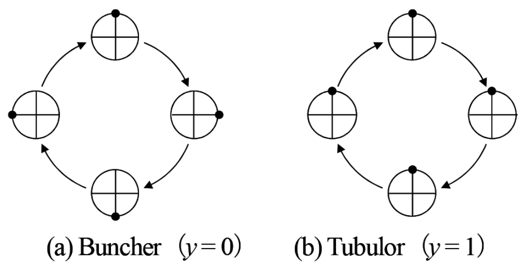

Fig. 12 Schematic view of buncher bunching and tubelor bunching

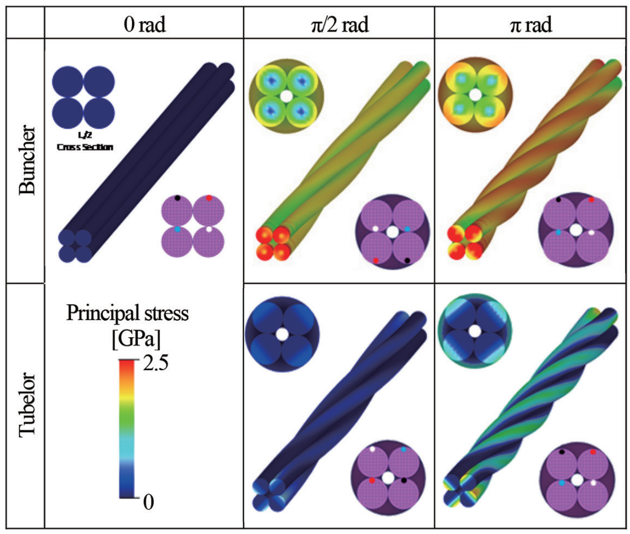

Fig. 13 Comparison of principal stress distribution between buncher bunching and tubelor bunching

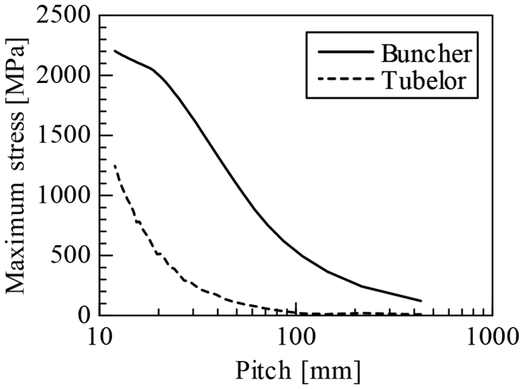

Fig. 14 Effect of strand pitch on maximum stress

center in the longitudinal direction is compared between single twist bunching and tubular stranding, the maximum principal stress during tubular stranding is smaller at all rotation angles. In Fig. 13, concentric high stresses can be seen at the circumference of each wire, because each wire is twisted once per revolution during single twist bunching. In addition, as each wire is three-dimensionally deformed in a helical manner, stresses work at the strand circumference. When these stresses are superimposed, the stresses are distributed as seen in Fig. 13. As torsional deformation does not occur during tubular stranding, the stress works on the strand circumference due to three-dimensional deformation alone. Thus, it is more difficult for wire breakage to occur with tubular stranding than single twist bunching, in terms of the positive effect regarding the issue of wire breakage due to large stresses generated from strong processing force.

Therefore, this study quantitatively clarified the influence of the difference in the twisting method and that of the twisting pitch on the occurrence of wire breakage through an analysis of steel cord twisting.

6. Conclusion

In this paper, we described examples of researches that have been conducted at Nippon Steel & Sumitomo Metal regarding cold forging of bars and wire rods including the development of element technology and processing technology, and also a study on a wire twisting method of the steel cord manufacture using numerical analysis.

(1) As part of the development of technology for steel fracture prediction required for the development of highly functional product forging technology, the validity of a method that uses the fracture limit strain on the equivalent plastic strain-stress triaxiality plane was confirmed in terms of the prediction accuracy for fracture occurrence under the conditions of basic research and real operations.

(2) As part of the development of technology for anti-seizure ability evaluation, which is important for cold forging of high strength steel, the validity of a method developed by us for seizure detection based on a sudden extrusion load change during backward extrusion was demonstrated.

(3) The forging method developed by us taking note of suppressing the material deformation speed difference between the outer diameter part and inner diameter part during forward extrusion allowed for cold forging manufacture of stepped steel components with a long hole in the center with L/D equal to or larger than L/D of those made using conventional methods.

(4) In order to reduce the percentage of wires broken in the course of the twisting process, an issue to be solved for the steel cord manufacture in which achievement of a higher strength level has been pursued, the influences of the twisting method difference and twisting pitch on wire breakage occurrence were quantitatively clarified through numerical analysis.

Acknowledgments

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