

Development of Advanced Analysis System for the Production of Parts with Bar and Wire Rod

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Abstract

Through the many types of manufacturing processes in customers, special steel bars and wire rods are manufactured to the auto parts such as engine and power train. For the manufacturing process to produce the final part of steel, Nippon Steel is working on technology development, including both the steel and manufacturing technology. This paper introduces the efforts of technology solutions for special steel bars and wire rods is important in that position, and then some of examples of analysis such as prediction of die stress in forging process, prediction of material properties after hot forging, and prediction of thermal distortion in heat treatment process.

1. Introduction

Special steel bars and wire rods that are shipped as rolled products from the steelmaker are made into various automotive parts, such as the engine and powertrain, by the parts makers using different manufacturing processes. For example, a hot-forged automotive part is manufactured by the following processes: blast furnace → ironmaking → steelmaking → continuous casting → rolling → heat treatment → cutting → hot forging → machining → surface hardening → finishing. As the steel goes through the above processes, its properties change gradually, thereby influencing the manufacturing process characteristics that ultimately determine the performance of the finished product. In order to provide steel products and establish manufacturing processes that ensure the desired performance of the parts, it is important not only to pay attention to the individual steel materials and individual manufacturing processes but also to develop an integrated parts manufacturing system that embraces all the essential components, from steel materials to production methods.

As part of its interest in promoting such integrated parts manufacturing, Nippon Steel Corporation has been developing various new systems with a focus on CAE-based solution technology. In this

technical report, we introduce the solution technology that the company—a supplier of steel materials—has developed paying due attention to the material properties that impart the maximum performance to the parts. A few examples of applications of the solution technology are also given.

2. Solution Technology for Specific Parts Manufacturing Processes

With the exceptions such as valve springs and suspension springs, most of the automotive parts made of special steel are manufactured by subjecting the steel material (bar/wire rod) to hot or cold forging, heat treatment for surface hardening, and finishing, as shown in **Fig. 1**. The variety of automotive parts and steel materials used to produce them is large, and as the steel material goes through the various manufacturing processes, its shape and properties continue to change. In order to efficiently design a manufacturing process that imparts the desired strength characteristics to the final product, CAE-based solution technology can be applied to improve the manufacturing process.

Nippon Steel Corporation has been engaged with the development of solution technology mainly for the processes shown in the

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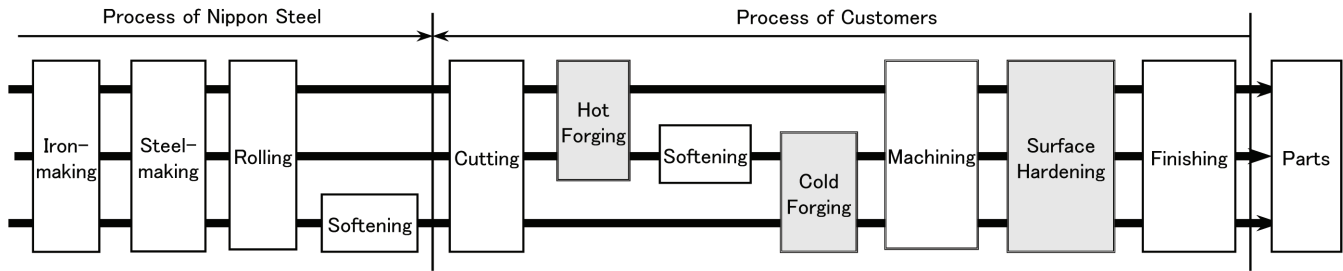


Fig. 1 Manufacturing process to produce the final parts of steel

Table 1 Consideration in the manufacturing process, analysis techniques and the necessary material data

	Hot/cold forging	Prediction of material properties	Surface hardening
Consideration	<ul style="list-style-type: none"> • Forging load • Forged shape • Fracture of parts • Tool life 	<ul style="list-style-type: none"> • Material properties of parts 	<ul style="list-style-type: none"> • Hardness • Fraction of microstructure • Thermal distortion • Residual stress
Analysis techniques	Rigid-plastic FEM Elastic-plastic FEM Heat transfer analysis	<ul style="list-style-type: none"> • Neural network 	<ul style="list-style-type: none"> • Elastic-plastic FEM • Heat transfer analysis • Phase transformation analysis
Material data	<ul style="list-style-type: none"> • Flow stress • Ductile fracture database 	<ul style="list-style-type: none"> • Experimental database of material properties and forging conditions 	<ul style="list-style-type: none"> • Phase transformation database • Coefficient of thermal expansion • Transformation plasticity coefficient

half-tone dot-meshed area in Fig. 1—hot forging, cold forging, and heat treatment for surface hardening. **Table 1** shows the major design considerations in each of the above processes, together with the applicable analytical techniques and necessary data for the process design.

In the design of a forging process, the major considerations are the forging load, tool durability, and material cracking, as well as the change in material shape. In cold forging, deformation analysis is generally performed using the rigid-plastic or elastic-plastic finite element method (FEM). In hot forging, together with deformation analysis, temperature analysis using the heat conduction FEM is often carried out. Computer software for these FEM analyses is readily available in the market. It should be noted, however, that implementing an accurate analysis requires reliable data about the material deformation characteristics, boundary conditions, thermal properties, etc. The forging analysis is described in detail in Section 3.

For hot forging, microalloyed steel has been developed. In this process, the cooling rate of the forged part is controlled by natural cooling, slow cooling, etc., to impart the material properties to the forged part, thereby omitting the subsequent quenching and tempering processes. This process is widely used to manufacture knuckles, connecting rods, crankshafts, etc. In this case, it is necessary to impart the appropriate microstructure and strength to the part in the forging process, since the material properties after the forging directly affect the performance of the finished product. The prediction of the material qualities after forging is described in detail in Section 4.

Gears, bearings, etc., whose surfaces are required to have an especially high strength, are subjected to a suitable surface-hardening treatment such as carburized quenching or high-frequency induction hardening. In the surface-hardening treatment, the part is first heated

to cause austenite transformation to occur and then cooled down rapidly for martensite transformation. These processes of quench cracking, thermal distortion, residual stress, etc., need to be considered in the process design. Since quenching accompanies a phase transformation, it requires an analysis that takes this phase transformation into account in addition to the deformation and temperature analysis in the forging process. The heat treatment analysis is described in detail in Section 5.

3. Forging Analysis

Here we describe data relating to the working characteristics of the steel materials used in the analysis of cold/hot forging. Nippon Steel's database of the working characteristics of steel materials contains data on the flow stress curve of steels for forging and on the working limit of steels for cold forging.¹⁾ These data are converted into dynamic constants on the basis of the forging steel conditions (chemical composition of steel, heat-treatment conditions, forging temperature, etc.) before being used in the forging analysis. For the flow stress curve database, the strains appropriate to specific forging conditions and the deformations at specific strain rates measured in compression tests were collected. The warm/hot flow stress curve data are converted in terms of the isothermal flow stress curve, which is useful in the deformation-temperature analysis. For data on the working limit of steels for cold forging, the material constants of working limiting values were obtained by applying Cockcroft-Latham's generalization equation (1), which is an equation for the prediction of ductile fracture, or Oyane's equation²⁾ (2), to the critical upsetting ratios obtained by upsetting tests³⁾.

$$D_f = \int \frac{\sigma^*}{\sigma} d\bar{\epsilon} \tag{1}$$

- D_f : Damage value
- σ^s : Maximum principal tensile stress
- $\bar{\sigma}$: Equivalent stress
- $d\bar{\epsilon}$: Equivalent strain increment

$$\int \left(1 + \frac{1}{a} \frac{\sigma_m}{\bar{\sigma}} \right) d\bar{\epsilon} = C \quad (2)$$

- a, C : Material constants
- σ_m : Mean stress
- $\bar{\sigma}$: Equivalent stress
- $d\bar{\epsilon}$: Equivalent strain increment

Next, as an example of analysis of cold forging, we consider cold forging of pinion shafts. Formerly, pinion shafts were in many cases manufactured by forming case-hardening steel, such as JIS S50C, into toothed shafts of the prescribed shape by machining or cold forging and then subjecting them to carburized quenching and finally to finishing. In recent years, however, there is a growing tendency to substitute high-frequency induction hardening for carburized quenching to cut the cost of heat treatment and omit the finishing process. In this case, it is necessary to use a high-carbon steel, such as JIS S50C, as the material so as to secure the required hardness after induction hardening. Since S50C has a higher strength and lower working limit than S50C, it can increase the forging load, shorten the tool life, and break the material being forged.

In view of this, we compared the results of forging obtained by using spheroidized S50C and spheroidized S50C. Assuming that cemented carbide nibs are to be reinforced with a double ring, the press-in interference was set at 0.45% of the diameter for each ring. Fig. 2 shows the distribution of the maximum principal stress acting on the tool. For both S50C and S50C, the maximum principal stress acting on the toothed part of the nib was between the applied

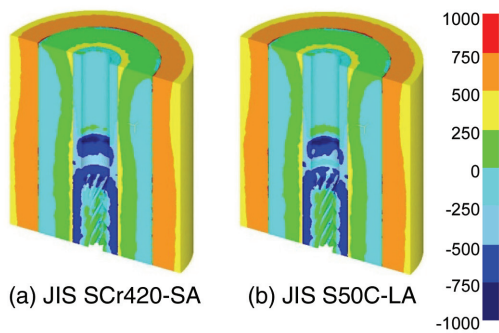


Fig. 2 Maximum principal stress distribution during forging

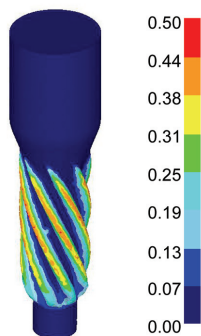


Fig. 3 Prediction of ductile fracture during forging

compressive stress and near zero. Thus, the possibility of the tool breaking is considered low. Fig. 3 shows the damage values calculated by using Cockcroft-Latham’s generalization equation. The maximum damage occurs at the tooth tip, and the critical upsetting ratio, within which no cracks occur, is 65%. On the other hand, the critical compression ratio of S50C is about 70%. Thus, even when S50C is forged into pinion shafts, it is considered that material cracking will not become a major problem.

4. Predicting the Material Properties of Hot-Forged Parts

Advanced prediction technology is available for the prediction of material properties, especially for steel sheets and plates. The material properties of steel sheets/plates are predicted by using a so-called physical model of the sequential prediction type.^{4,5} First, the expected heated γ grain size is estimated from the heating temperature, heating time, and precipitation condition of the precipitates. Second, the recrystallized or unrecrystallized γ grain size and residual dislocation density are estimated from the predicted γ grain size and the rolling pass schedule. Third, the microstructure factors such as volume fraction, grain size, and shape during transformation, are estimated by using the above-estimated values and the cooling conditions. Finally, the material properties are predicted from the microstructure factors. In the national project “R&D Project on Innovative Foundation for Enhancement of Strengths and Functions of Steel Materials,” Nippon Steel Corporation has also been engaged in the building of a material properties prediction model for forging with emphasis on the precipitation and precipitation hardening of vanadium carbides in medium- to high-carbon steels.⁶

Additionally, the company has approached the prediction of material properties using a neural network,^{7,8} rather than a physical model.⁹ The prediction system is outlined in Fig. 4. The database for the prediction of material properties contains mathematical equations and coefficients that express the relationships between the material composition, including histories of temperature, strain, and strain rate and the material properties.

The system uses commercially available FEM software to perform a deformation-temperature analysis in order to obtain histories of temperature, strain, and strain rate during forging and cooling and to predict the material properties so as to obtain the hardness distribution. As an example of an analysis, Fig. 5 shows the predicted hardness distribution in 0.3C–0.1 V microalloyed steel that was subjected to natural cooling after forging. It was confirmed that the predicted hardness distribution not only in the product proper but also in the burred part agrees well with the measured hardness distribution.

5. Analysis of Heat Treatment

Carburized quenching, induction quenching, etc., are all phenomena involving phase transformations: ferrite \rightarrow austenite \rightarrow martensite. Combining deformation analysis, temperature analysis, and heat treatment analysis while taking the phase transformations into account requires a variety of data about steel materials.¹⁰ For deformation analysis and temperature analysis, the flow stress curve, specific heat, density, thermal conductivity, etc., are required. For heat treatment analysis, the continuous cooling transformation curve or isothermal transformation curve, the heat/transformation expansion coefficient, transformation plasticity coefficient, etc., are needed. In addition, in carburized quenching, since the carbon concentration of the steel can change from 0.2% to 0.8% (in the surface

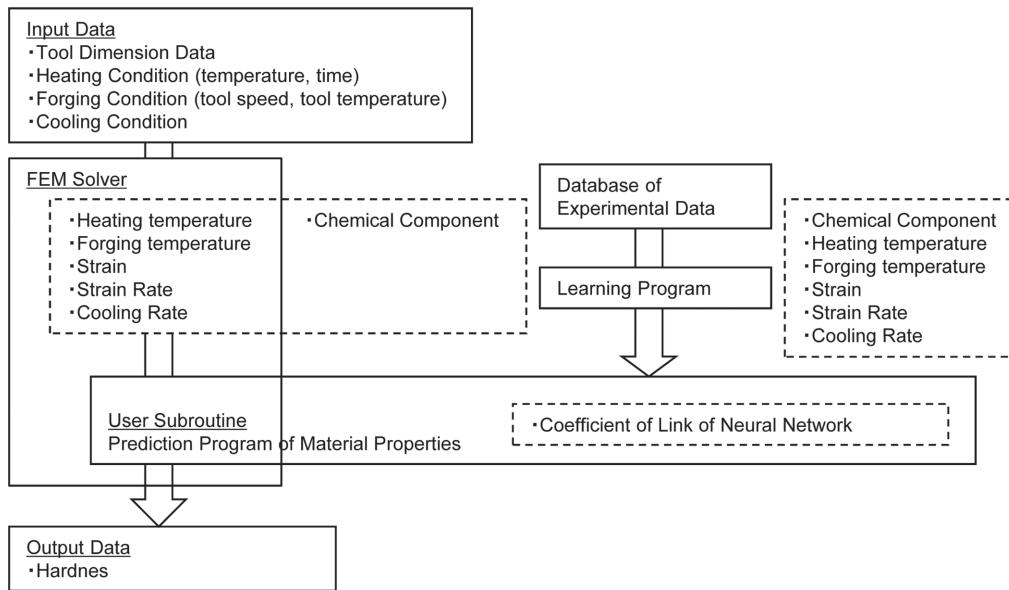


Fig. 4 Prediction of material properties of forged parts

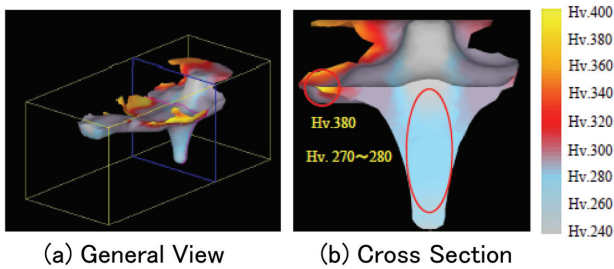


Fig. 5 Hardness distribution of forged parts

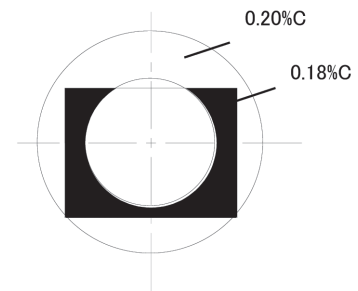


Fig. 6 Carbon distribution in cross section of ring part

layer) after carburization, it is necessary to consider the carbon concentration dependence for each of the above data parameters.

As an example of heat treatment analysis, the deformation of a ring-shaped part having negative segregation in the interior after carburized quenching is described below. For JIS SCr420 steel (0.2%C), it was assumed that the carbon concentration of the negative-segregated part was 0.18%. The center of that part was shifted from the center of the ring as shown in Fig. 6. Regarding the boundary conditions for carburized quenching, the thermal conductivity depends on the type and temperature of the coolant used. Since the flow of the coolant is influenced by the shape of the part and the position of the part being quenched. Here referring to the literature where the thermal conductivity was determined from measurements of the cooling rate obtained with a silver cylinder,¹¹⁾ the analysis was made in two different patterns, as shown in Fig. 7. In one pattern, the entire ring was subjected to uniform cooling, while in the other pattern, the ring was divided into two halves in the circumferential direction and the thermal conductivity of each half was doubled.

Fig. 8 shows the roundness of the inside and outside diameters of the ring-shaped sample. At a given thermal conductivity, both inside and outside diameters showed an ovality of about 5 μm. Thus, the negative segregation had a minimal effect on the deformation during carburized quenching. On the other hand, when thermal con-

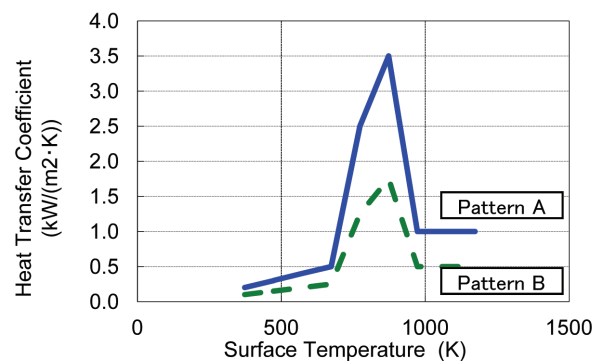
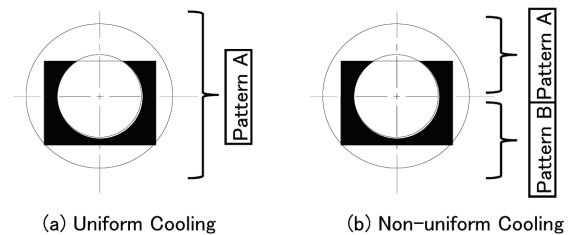


Fig. 7 Condition of heat transfer coefficient

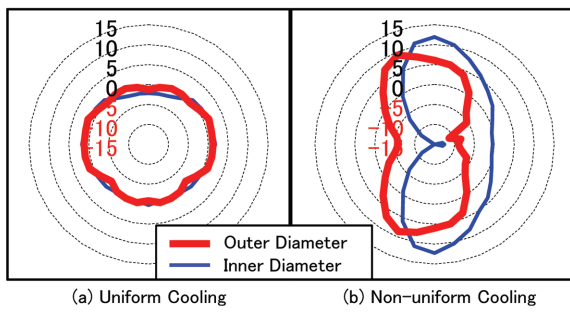


Fig. 8 Roundness of ring part after carbonized quenching

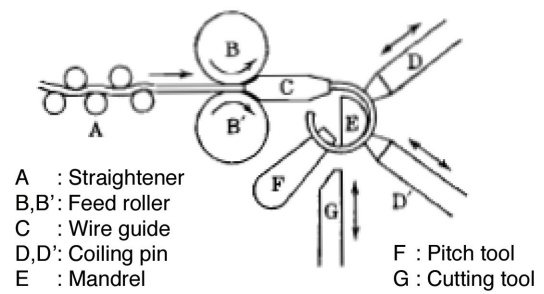


Fig. 9 Coiling mechanism

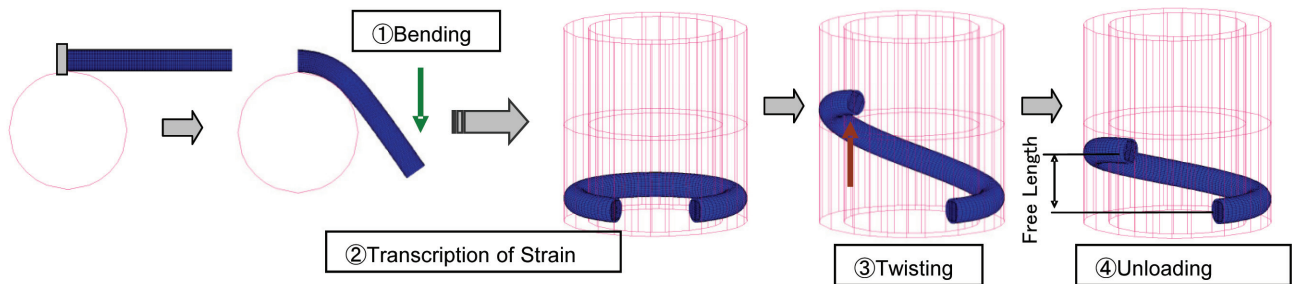


Fig. 10 Coiling process modeling

ductivity was doubled, the ovality was about $20 \mu\text{m}$, which is larger than the value obtained when only negative segregation was considered. Namely, the thermal distortion of the parts during carburized quenching is influenced more by the quenching conditions, such as nonuniform cooling, than by the steel material factors, such as variance in chemical composition.

6. Valve Spring Forming Analysis

As mentioned earlier, many automotive parts are formed by forging. However, there are various other manufacturing processes for auto parts. For example, valve springs, and suspension springs are manufactured by using a coiling machine. Nippon Steel's solution technology based on numerical analysis is applied to the coiling process as well. Here an example of the application of the solution technology in the forming of valve springs is described.

When coiling valve springs, the variance in free length is used as one of the production control indexes. The variance in free length is affected by the variance in the treatment during the coiling process and the variance in the strength of the wire rod used for the valve spring. The variance in strength includes the difference in strength along the length of the wire rod and across the wire rod. Segregation can be cited as one of the causes of the difference in strength across the wire rod. With the aim of clarifying the effect of segregation on the variance in the free length of the valve spring the following analysis was carried out.

6.1 Analytical procedure

The valve spring coiling mechanism is shown in Fig. 9.¹²⁾ The wire rod is first bent to the prescribed curvature by the coiling pins D and D'. It is then adjusted to the prescribed pitch by the pitch tool F. For the analysis, the coiling process was modeled as shown in Fig. 10.

- ① Bend the wire rod to the same diameter as the inside diameter of the valve spring to be formed.

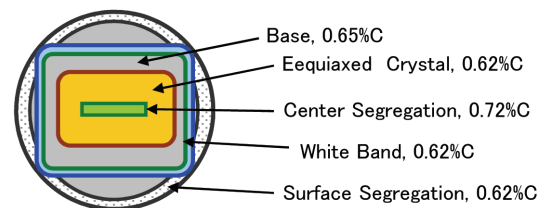


Fig. 11 Modeling of the cross-section of the wire

Table 2 Mechanical properties by the amount of carbon

Carbon (%)	Yield strength (MPa)	Tensile strength (MPa)
0.62	1,771	1,933
0.65	1,820	1,987
0.72	1,934	2,112

- ② Form the bent wire rod into a ring taking into account the bending strain that occurred in Step ①.
- ③ Adjust the pitch by pulling up one end of the ring with the other end kept fixed. (In this step, the wire rod is subject to a torsional deformation.)
- ④ Remove the load and measure the residual displacement (free length).

In light of the mode of macrosegregation in actual springs, the cross section of wire rod was modeled as shown in Fig. 11. The carbon concentration was assumed to be 0.65% for the base, 0.72% for the center segregation, and 0.62% for the white band, the equiaxed crystal, and the surface segregation. On the basis of this carbon concentration, the mechanical properties of each of the above parts were estimated as shown in Table 2. In the analysis, the bending dis-

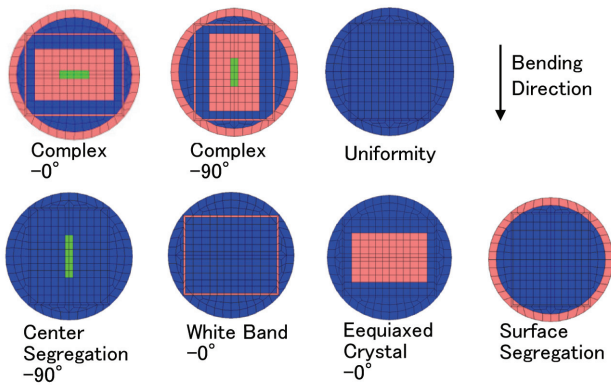


Fig. 12 Analysis model

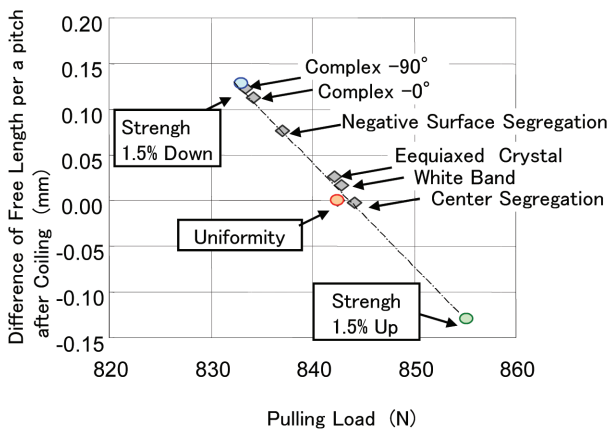


Fig. 13 Relationship between the pulling load and difference of free length per pitch after coiling

rection was varied between 0° and 90°, as shown in Fig. 12, since for the complex that corresponds to an actual wire rod, consideration is given to the directivity of the segregation. In the analysis, the degree of contribution of each of the above factors (center segregation, etc.) to the valve spring free length was studied by using a homogeneous material (0.65%C) as a reference.

6.2 Analytical results

Fig. 13 shows the relationship between the pull-up load during pitch adjusting and the difference in spring free length (the difference in free length from the homogenous steel material). The above relationship between the pull-up load and the difference in spring free length is almost linear. Of all the factors affecting steel material segregation, negative surface segregation has the largest effect on spring free length (Fig. 13). The reason for this is that since bending is performed in the direction in which the wire rod is bent and pitch adjustment is performed in the direction in which the wire rod is twisted, the segregation in the neighborhood of the surface layer that contributes greatly to the flexural and torsional rigidity of the wire rod strongly manifests itself. Even with the same complex, spring free length changed when the direction of bending in the coiling process was varied. This would account for the variance in spring free length that occurred even though the same lot of wire rods was used, although this variance is negligibly narrow.

7. Conclusion

Of the parts manufacturing processes using steel bars and wire rods, Nippon Steel’s solution technology applicable to forging, material properties prediction, and heat treatment has been described, together with some application examples. In particular, the application of the solution technology to valve spring forming was described. In order to study optimum parts manufacturing processes taking into consideration the properties of the finished parts, it is important to thoroughly understand not only the manufacturing processes itself but also the steel material properties that continue to change as the steel material is processed. In the future, we intend to continue developing advanced new steel materials and expanding the existing database of boundary conditions such as lubricant properties and thermal conduction. In addition, we plan to develop new solution technology, including deformation analysis taking nonmetallic inclusions into consideration.

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