NIPPON STEEL TECHNICAL REPORT No. 80 JULY 1999

UDC 621 . 73 . 011 : 669 . 14 - 42

Advanced Forging Technique with Bar and Wire Rod

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Abstract

High precision forging is required to decrease machining tips and to form complex-shaped products. In putting these requirements into practice, forging conditions become severe for workpiece and tools. It is, therefore, necessary to select suitable conditions easily and quickly. Recently, computer capabilities have rapidly developed, and Computer Aided Engineering (CAE) has become popular. Especially, computer simulation using Finite Element Method (FEM) analysis is available for making suitable forging processes, and a computer simulation system that combines FEM and a data-base of steel materials has been developed by Nippon Steel. In this paper, flow stresses used in the forging simulation system are introduced, and ultra high temperature forging to form complex-shaped products is introduced that considers forgeability.

1. Introduction

Some of the many issues relating to forged parts for automobiles include the reduction of weight to reduce fuel consumption and a strengthening for collision safety with regard to structure, and a reduction of costs by omitting machining processes with regard to productivity. To solve these issues, it is necessary to form high strength materials into complex-shaped parts, and the workpieces and tools used in forging must be even stronger under the current difficult conditions. Rapid and precise optimum process designs are preferred such as in the application of new steel types that can reduce the tool load, the changing of tool shape, and process distributions. With regard to that, in recent years the use of CAE (Computer Aided Engineering) has been spreading, along with the extension of computer capabilities.

This report introduces the future trends of forging process simulations that use FEM (Finite Element Method) analysis which is the nucleus of CAE, and it describes a computer aided system for analyzing mechanical behavior of steel bars and wire during forging that was developed by Nippon Steel. In addition, ultra-high temperature forging technology as the next-generation of technologies for forming complex-shaped parts is introduced.

2. Extensions of CAE in forming processing of bars and wire rods

2.1 Extension of forging simulation

Recent improvements in computer capabilities are eye-opening, and in the forging industry there has been a rapid expansion in the use of CAD/CAM and CAE, such as expert systems[1] that support the forging process designing using AI technologies, and forging simulations that analyze the deformation behavior of material during forging. Forging simulations can be classified as those using FEM group and those using UBET (Upper Bound Element Technique)[2].

This paper will introduce FEM in which more detailed information of workpiece properties can be handled. Some of the representative FEM simulation programs that are capable of analyzing forging processes are the commonly sold MARC, ABAQUS, NIKE, and DYTRAN-F programs for elastic-plastic FEM; and for rigid FEM there are the DEFORM[3], RIPLS-FORGE[4], PLUM[5] programs. NASKA[6] (Kobe Steel, Ltd.) and SHPSS[7] (Sanyo Special Steel Co. Ltd.) have been developed also by steel manufacturers. For forging processes, rigid FEM is more widely used than elastic-plastic FEM.

As the workpiece receives a large strain in forging, it is possible

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to keep the accuracy of FEM analysis even when ignoring the amount of elastic strain. Also rigid FEM is considered appropriate for forging processes in which deformation is large because it can obtain large incremental steps in comparison to elastic-plastic FEM, and because it does not give stress as an incremental mode. Further, there has been progress made in three-dimensional analyses recently, and connecting rod deformation analysis is being carried out using three dimensional FEM programs, such as GRADE/Forge[8], in which the Euler element and dynamic explicit method are combined. However, the dynamic explicit method is for increasing calculation speed without solving simultaneous linear equations. It is thought that more detailed investigation in evaluating internal stress is necessary, rather than other implicit methods with solving simultaneous equations.

In this way, there have been many researches and developments regarding forging process simulators by FEM, but there are hardly any that combine workpiece property data that can affect the accuracy of analysis. In this report, the authors describe a computer aided system for analyzing mechanical behavior of steel bars and wire during forging to clarify the performance of steel for forging by analyzing the mechanical behavior of steel bars by combining rigid FEM and data on the mechanical properties of steel[9].

2.2 Computer aided system for analyzing mechanical behavior of steel bars and wire during forging

This system consists of (1) the cold forging simulation system that combines rigid FEM analysis of deformation behavior with a database of the characteristics of steels for cold forging, and (2) a warm and hot forging simulation system that combines rigid FEM with heat analysis and a database of isothermal flow stress for warm and hot forging. The characteristics of steels for cold forging in the part of (1) are the flow stress and the forging limit; those are estimated from the results of tensile test and the composition of the steel. And, in the part of (2), heat distribution in the workpiece is evaluated by FEM by converting the plastic work to heat energy. The heat transfer to the tools is considered in the FEM analysis assuming that the tool temperature is constant during deformation. After the deformation analysis, heat distribution in each element is calculated after which it is calculated step by step using the subsequent deformation analysis using the isothermal flow stress at the temperature of each element.

Input data describe the shape of workpieces, the composition of steel, heating temperatures, shape of tools and the pre-heat temperature of tools and friction conditions, etc. Steel characteristics such as flow stress and forging limit are converted to mechanical constants through the database. Forging simulation is carried out using these mechanical constants and rigid FEM, and the forging load, workpiece failure, tool pressure and metal flow, etc. are judged to find the optimum steel materials and forging conditions by trial and error.

2.3 Characteristics of forged steels

2.3.1 Flow stress curves of the steels for cold forging

Measurements of the flow stress of steels for cold forging under large deformation and high speed deformation were carried out by the upsettability test using concentric platens[10], and the results were entered into a database[9]. Bars and wire rods are often drawn to the predetermined material diameter after rolling or annealing, and then they are forged. **Fig. 1** shows the flow stress curves of normalized JIS S15C and pre-drawn JIS S15C. There is an increase in flow stress as the reduction in area by drawing increases in the small strain region, but with equivalent strain $\bar{\varepsilon}_p \geqq 0.5$, flow stress is the same as that of normalized JIS S15C without dependence on the reduction in area by drawing (R_d). In other words, if there was an influence from strain by pre-drawing under the actual upset conditions, it indicates a flow stress for which it has disappeared. It is known that this phenomenon appears in other steels. A discussion of the mechanism is conveyed in other literature[11]. Also, the flow stress curve is presumed by considering the forging history from the tensile strength or the composition of the steel, and this is used in FEM analysis.

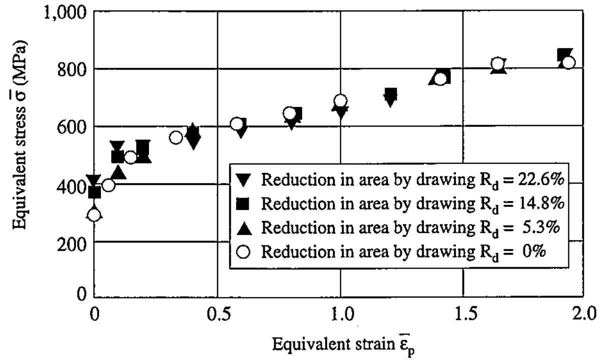

Fig. 1 Flow stress curves of JIS S15C wire material

2.3.2 Judging workpiece failure during cold forging

In the workpiece failures that occur in cold forging, voids often occur around metallic inclusions such as MnS and grow to become cracks. Also, there are cases of voids occurring in destroyed cementite not around metallic inclusions. Equation (1) is the ductile fracture criterion proposed by Oyane et. al[12]. The left side shows the volume ratio that considers the growth of voids, and the fracture occurs when this integrated value reaches the c value. This equation was derived by the mechanical theory, and it is valid in predicting the fracture limit of general steel. c and a_0 are material constants that are determined by the forging limit and structure. These constants can be found by regression from results of tensile test and the material composition in this system. Also, the integrated value is calculated using $\bar{\varepsilon}_p$, σ_m, σ obtained by FEM, and workpiece failure is predicted.

$$\int_0^{\varepsilon_f} \left(1 + \frac{1}{a_0}\frac{\sigma_m}{\bar{\sigma}}\right) d\bar{\varepsilon}_p = c \quad \cdots\cdots(1)$$

Here, ε_f: failure strain, σ_m: mean normal stress, $\bar{\sigma}$: equivalent stress.

2.3.3 Isothermal flow stress for warm and hot forging

With regard to steel flow stress in strain rates (1 to 10/s) corresponding to actual warm and hot forging processes, in the large strain region there is almost no data of flow stress whose is strongly affected by such factors as friction force, heat generation or heat transfer. Flow stress corresponding to the temperature during deformation is necessary for numerical analysis. The isothermal flow stress curves assuming that the flow stress is determined by temperature and strain during deformation are effective. However, in general compression tests, the only flow stress accompanying the temperature changes during deformation has been obtained. Therefore, the influences on flow stress by the friction force, heat generation and heat transfer during compression test were evaluated by using the rigid FEM with temperature calculation, and the results of simple compression test were modified. Easier methods were proposed[13] to obtain the accurate flow stress for the actual warm and hot forging conditions, and in using this method, isothermal flow stress of various steels for forging were calculated and entered into a database.

Fig. 2 shows the relationship of a nominal flow stress dividing

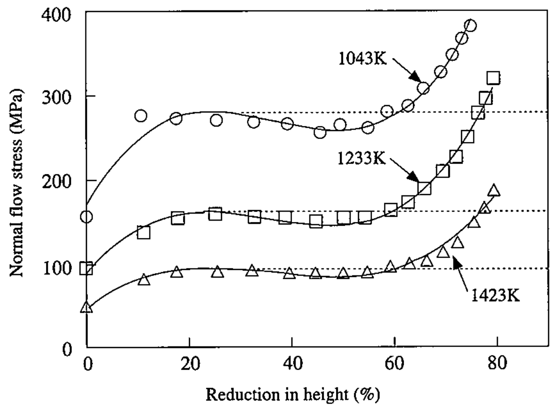

Fig. 2 Nominal flow stress achieved from upsettability test (JIS S55C, strain rate 10/s)

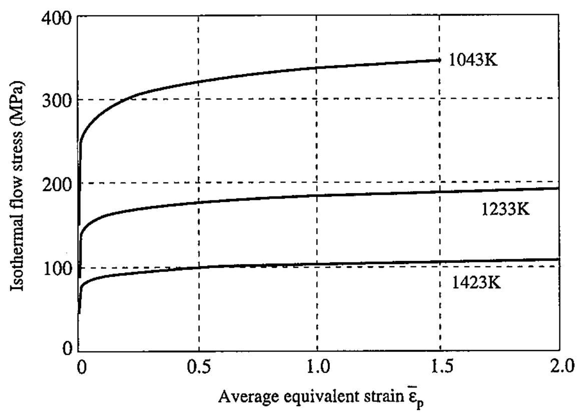

Fig. 3 Isothermal flow stress of JIS S55C rolled material (strain rate 10/s)

the load by the cross section area after compression and reduction in height as rolled S55C steel. This flow stress includs effects such as the friction between the tools and the workpiece, heat generation, heat transfer, and so on. These effects on the flow stress are extremely high in the region of great reduction of height. Up to now, flow stress was constant without depending on the reduction of height up to 20%, and was often taken as the dotted line shown in the figure. Using the experimental values as a base, the authors found the modification coefficient by dividing the flow stress calculated from FEM considering the effect of friction, heat transfer and heat generation into the experimental values. And **Fig. 3** shows the curve of the isothermal flow stress obtained by supplementing the results of the test. The figure shows the results with the strain rate of 10/s. The increase in flow stress by the friction in a high strain region has been removed.

2.4 Example of application of the system

2.4.1 Predicting failure of flange bolts

The heading of flange bolts is a severe process for steel, and failure often occurs at the flange. Element division of workpiece after pre-upsetting in FEM analysis and the shapes through the deformation are shown in **Fig. 4**. When a workpiece is pressed, the material is extruded around the upper portion of the punch when the flange is formed. The areas most easily cracked are the lower area of the free zone of the flange. The element of the position that has been studied where the cracking occurs is enlarged in the same figure.

In order to study the occurrence of cracks in the elements, the

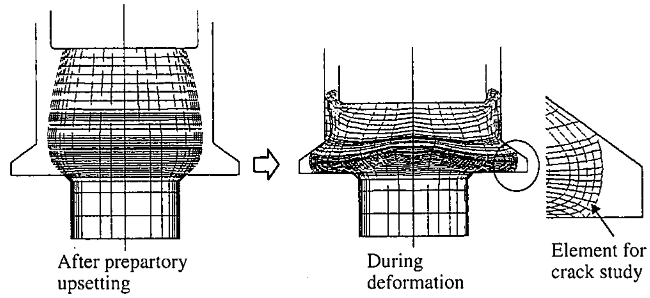

Fig. 4 Element positions for studying flange bolt forming and cracking

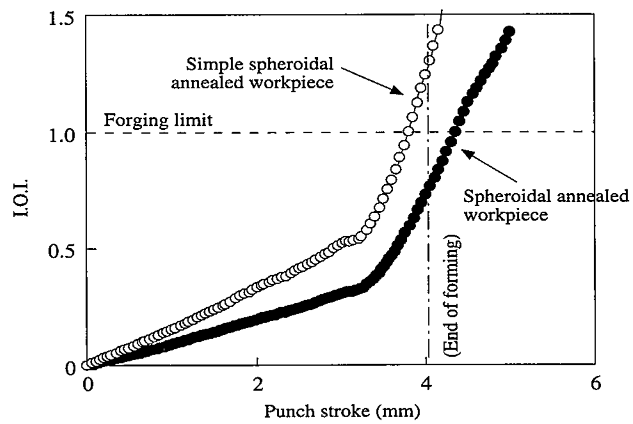

Fig.5 Prediction of workpiece failure by difference in annealing conditions

vertical axis is the I.O.I. (Index of Oyane's Integral) in which the integrated value of eq. (1) was divided by value c. **Fig. 5** shows its relationship with the punch stroke. This means that when I.O.I. is more than or equal to 1.0, material reaches the forging limit. The ○ plot in the figure represents the case of using a simple spheroidal annealed S45C steel. It has reached the limit just before damage by punch stroke at the end of the stroke. The ● plot shows the case of using the spheroidal annealed steel with high ductility which has not reached the damage limit at the end of the stroke. In this way, it is possible to extremely easily predict, through simulation, the safety when changing the steel characteristics. Also, it is possible to easily study the forging conditions like the shape of the heading to prevent cracking from occurring at the end of the stroke in easily annealed materials or the means for improving materials.

2.4.2 Warm backward extrusion

Fig. 6 shows an example of predicting load in warm backward extrusion. The figure shows the load-stroke line for backward extrusion with a reduction in area of 44%, extruded blank is 30 mm in diameter, of rolled S55C steel and heated at 1043K. The thick line in the figure is the prediction by FEM using the isothermal flow stress shown in Fig. 3; the fine line is the one using the flow stress obtained from the conventional method indicated by the dotted line in Fig. 2; and the ○ plots are the experimental results. The new method using the isothermal flow stress has about 20% improvement over the conventional method.

Tool life can also be greatly affected by differences in the load on them. Also, when selecting machines to use for forging it is necessary to find the absolute value of the tool loads with high accuracy. Therefore, in order to estimate accurate tool loads, it is important to evaluate precisely the work hardening characteristics of steel materials.

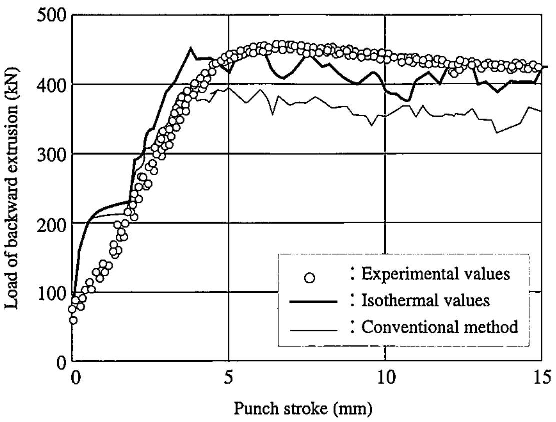

Fig. 6 Prediction of load under backward extrusion

3. Near Net Shape forging of bar and wire rod

Near Net Shape forging of complex-shaped parts can omit the forging and machining processes. However, there are many problems to be solved such as rapid increases of forming load and lowering of tool life caused by large deformation of material. To increase the forgeability of material by heating to ultra-high temperatures could possibly realize Near Net Shape forging of complex-shaped parts. In this report, ultra-high temperature forging near the solidus line, which is higher than that of normal hot forging, was carried out.

There are several reports[14, 15] relating to mushy-state forging in the liquid-solid region. Many of them report with regard to aluminum alloys and magnesium alloys for which the melting range is lower than steel, but there are virtually no reports regarding higher-strength steel for important safety parts of automobiles and construction machinery.

This report introduces the basic study of ultra-high temperature forging of carbon steel[16,17]. First, flow stress of steel at ultra-high temperatures are measured to compare them with conventional temperatures of hot forging. This is one of the features of ultra-high temperature forging. Then the forward extrusion with high reduction in area is carried out as an example of high-strength parts.

3.1 Study of flow stress at ultra-high temperatures

In order to estimate the degree of improvement of forgeability in ultra-high temperature forging, an upsettability test using concentrically grooved platens was carried out to measure flow stress. The specimen of rolled S45C, shown in **Table 1**, was machined to 20 mm in diameter and 30 mm in height. The specimen was heated to the predetermined temperature and upsetted to various strains at a constant punching speed of 200 mm/s. During this process, the average strain rate was about 10/s.

Fig. 7 shows the calculated isothermal flow stress at equivalent strain $\bar{\varepsilon}_p = 0.5$ based on the method described above. The isothermal flow stress at 1,613K, under the solidus line, was lower than that at 1,403K in a hot forging temperature range by about 45%, and that at 1,633K, just above the solidus line, was lower than that at 1,403K. It was found that there was a noticeable decrease in flow stress by forging above the solidus line of the material.

In the case of the starting temperature of 1,633K in upsetting, cracks occurred in the side surface of the specimen when formed for more than a 45% reduction in height. **Photo 1** shows an internal structure of cracks. It was thought that tensile hydrostatic stress working on the side free surface caused cracks, because grain boundaries melted above the solidus line.

Table 1 Test material composition (wt%) and temperature of solidus line and liquidus line (K)

	C	Si	Mn	P	S	T_S	T_L
S45C	0.44	0.20	0.67	0.016	0.012	1615	1768
S55C	0.53	0.20	0.65	0.029	0.016	1575	1761

T_S: Solidus line, T_L: Liquidus line

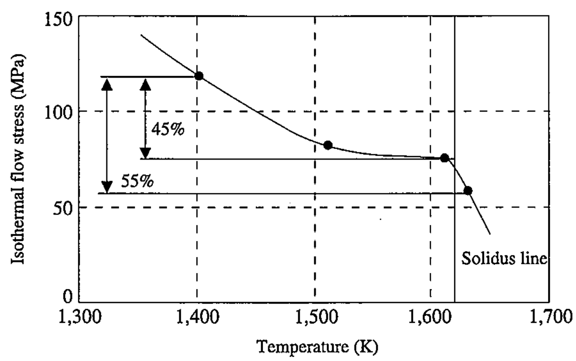

Fig. 7 Isothermal flow stress at equivalent strain 0.5

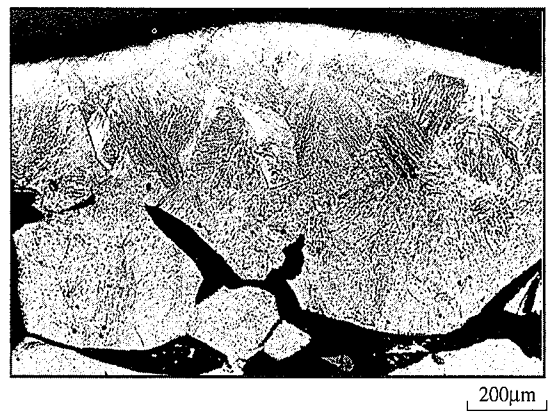

Photo 1 Internal cracking during upsetting

3.2 Forward extrusion

It is thought that the large compressive hydrostatic stress working on the material is effective to prevent the fusion cracks that occur in the solid-liquid region. In this section, a forward extrusion of a high reduction in area is carried out.

3.2.1 Experimental conditions

The diameter of a container was 20 mm and a die half-angle was 45°. Reduction in area in extrusion (R_d) was 19% to 96%. The specimen of rolled JIS S55C, shown in Table 1, was machined to 19 mm in diameter and 30 mm in height. Starting temperature in extrusion was 1,613 K (just above the solidus line) and 1,423K (hot forging temperature). The die was preheated to 573K and the heated specimen was extruded at a constant punching speed of 200 mm/s.

3.2.2 Experimental results

Fusion cracks occurred in the upsettability test at the solid-liquid region, but they were not found in either R_d excluding the front part of the specimen, because the compressive hydrostatic stress worked on the specimen.

Fig. 8 shows the relationship of R_d and the maximum extrusion load. The extrusion load at the solid-liquid region was lower than that at the normal hot forging temperature.

There is a fear of decreasing mechanical properties with the ul-

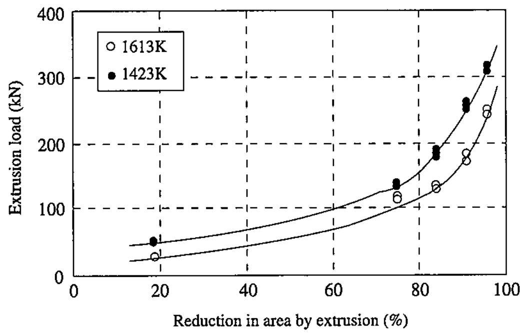

Fig. 8 Effects of forging temperature and reduction in area by extrusion on extrusion load

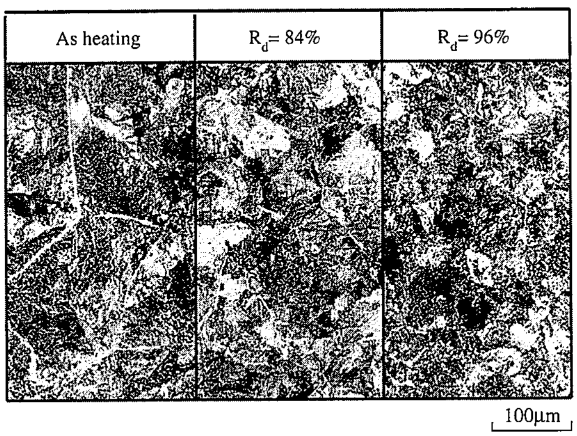

Photo 2 Internal microstructure after extrusion

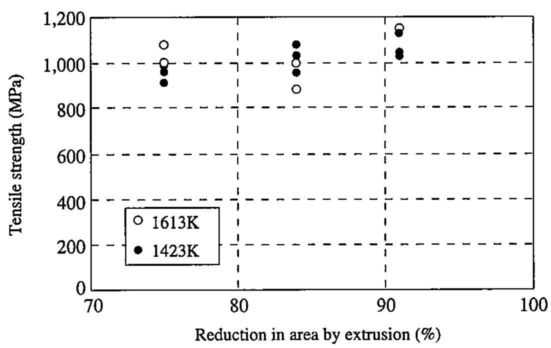

Fig. 9 Effects of forging temperature and reduction in area by extrusion on tensile strengths

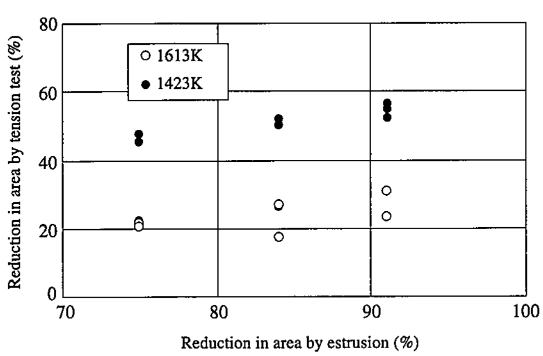

Fig. 10 Effects of forging temperature and reduction in area by extrusion on reduction in area by tension test

tra-high temperature forging, because the ultra-high temperature coarsened the grain structure. The microstructures were observed and their mechanical properties were evaluated. **Photo 2** shows the microstructure at the starting temperature in extrusion of 1,613 K. The structure of the heated specimen was coarsened to the order of several hundred mm. On the other hand, the structures of the specimen extruded more than R_d = 84% was refined. Also, the structures of the specimen extruded at 1,423 K were finer than at 1,613 K in each R_d.

Fig. 9 shows the tensile strength and **Fig. 10** shows the reduction in area by tensile test. They increase with R_d. There was almost no effect of the temperature in extrusion on the tensile strength. But the reduction in area by tensile test for 1,613 K was large at about half of that of 1,423 K. It is thought that this is a reflection of the grain size. Also, hardness of the center in the radial direction of the specimen was almost not affected by the temperature in extrusion the same as the tensile strength.

4. Conclusion

Because of the improvements in complex-shapes of forged parts and the precision of products, it is thought that there will be further spreading of process design using forging CAE. The use of three dimensional analysis lags behind in forging because it cannot be pseudo-three dimensional using shell elements like thin sheet forming, and it is non steady state forming. However, with the improvements in computer capabilities, it will slowly begin to spread over time. Nippon Steel is also using FEM analysis for three dimensions. Moreover, there are developments not only in forging, but in shearing[18] as pre-processing and in hot strain simulation after forging. It is also considered that the use of virtual forging trials is no longer a dream. With that as a background, it is important to increase the accuracy in evaluating the material forming characteristics to determine the accuracy of analysis. It is believed that it is necessary to develop this approach for both the analysis methods and material characteristic evaluation methods.

Also, ultra-high temperature forging enabling the forming of complex-shaped parts at one time with compression forming is one of the next generation forming technologies and that it is necessary to develop steel materials that match that. There will probably be developments in related steel materials and forming technologies and that forging technologies will be raised to yet a higher level.

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