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Technical Report

Material Properties and Evaluation of Formability of Thick Sheet Steel for Sheet Forging

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Abstract

Automotive industry has been facing the challenge of body-lightweight against the background of environmental issues. Near-net-shape and high-strength-steel has been progress in order to solve these problems, for which are being deployed the mission and power train as well as body-in-white. Therefore, thick steel plate is used for cold forging process not only by the steel bar and rod, so called the "sheet forging" which has been an increase in recent years. In this paper, it will be introduced the mechanical properties and the basic material properties of thick steel plate, the evaluation of formability of thick steel plate with thickness variation plate, and also introduced the three-dimensional local bifurcation theory with its effectiveness.

1. Introduction

In light of various environmental issues, the automotive industry has been striving to reduce the weight of cars. To that end, the industry has started using steel materials of higher strength for both car bodies and other components such as transmissions and power trains. Furthermore, near net shape (NNS) manufacturing has become increasingly popular in the industry. In recent years, both cold-forged automotive parts made from bar steel and sheet-forged parts made primarily from thick sheet steel have increased in number. In addition to the cost-cutting effects of NNS manufacturing, such as improvements in material yield through appreciable reduction of cutting allowances and efficient increases/decreases of blank thickness, sheet forging helps to improve the accuracy of forming and enhances the value added.[1, 2)]

When forging thick sheet steel, it is extremely useful to evaluate the material, tool shape, and process by means of FEM analysis. However, to evaluate the fracture limit and indicate measures suitable for the prevention of fractures, it is considered necessary to evaluate not only fracture timing but also fracture mode and direction.

This report describes the material properties required for forging of sheet steel exceeding 4 mm in thickness, describing, for example, factors that should be considered when choosing a material. In addition, we present a forming limit evaluation technique based on a 3D local bifurcation theory that is applicable even when the forging process involves a complicated mode of deformation.

2. Material Properties Required for Sheet Forging

Depending on the method used, sheet forming can be performed in combination with conventional deep drawing, pressing, bulging, stretch flanging, burring, or bending, among others. Therefore, the material to which sheet forming is applied must exhibit specific properties that vary according to the method used.[3, 4)]

Table 1 summarizes the important material properties required for sheet forming. As mentioned above, these differ according to the forming method used: elongation and r-value (Lankford value) are particularly important in deep drawing; plastic fluidity in pressing; elongation and n-value (work hardening index) in bulging; λ-value and local elongation (hole expansibility) in stretch flanging and burring; and local elongation in bending.

Auto parts that are required to have high strength are made by

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Table 1 Important factor of material properties in sheet forging

Material property	Effectiveness
Hardness-reduction	• Reduction of tool damage and press force • Hardness after quenching
Reduction of in-plain anisotropy	• Improvement of yield and roundness • Eccentricity, scatter-reduction in quenching
Elongation	• Improvement of formability
Stretch flange-ability	• Improvement of formability

forging material of relatively high strength, in which case the parts can be used directly; however, if the parts are difficult to form, they are made from a low-carbon steel material with good formability and subjected to carburizing or nitriding. Auto parts that require quench hardening are made from a high-carbon steel material and subjected to suitable heat treatment.

2.1 High-formability hot-rolled steel sheet and high-strength hot-rolled steel sheet of medium thickness

The sheet forging process is used to fabricate various parts for automobile driving systems, transmissions, and other components of the automotive industry. In sheet forging, unlike in conventional deep drawing or bulging, upsetting, extrusion, and ironing are applied to increase or decrease the thickness of the blank as required. Various working methods, such as feed-forward working by a multistage process[1)] and process streamlining using a multispindle press,[2)] can be employed.

These methods are applicable for various materials. For hard-to-form parts that demand a very high degree of formability, high-strength hot-rolled steel sheets for automotive parts are used (**Table 2**). In such cases, lower carbon contents provide better ductility, i.e., higher formability. Conversely, components made in this way may need carburizing or nitriding because of their inferior product strength.

Carburizing is a method of heat treatment whereby carbon enters the surface layer of steel. The steel sheet is first heated to 900°C or more to carburize its surface layer and is then cooled rapidly from the austenite region to harden only the surface layer, with the interior structure kept flexible. Thus, the method permits the forming of steel parts whose surfaces have both good wear resistance and high toughness.

It should be noted, however, that the steel sheet may be influenced by thermal strain during the carburizing treatment because it must be heated to 900°C or more. Furthermore, heat treatment is costly. Therefore, in recent years, there have been cases in which hot-rolled steel sheet was worked and high-strength hot-rolled steel sheet was subjected to sheet forging or fine blanking to impart the prescribed strength to the product by adding material strength or work hardening.

For such steel materials, increasing strength leads to deterioration in ductility. Thus, the fluidity of these materials deteriorates as they are worked on. Furthermore, even high-strength hot-rolled steel sheet does not always produce parts of desired strength. In such cases, it is recommended to use the high-carbon hot-rolled steel sheet described below.

Table 2 Chemical compositions of test materials (mass%)

C	Si	Mn	P	S
0.45	0.22	0.73	0.020	0.026

2.2 High-carbon steel sheet with medium thickness

Sheet forging is intended primarily to omit processes such as hot forging from the fabrication of auto parts and cut the production cost of parts by reducing cutting allowances, which is made possible by NNS manufacturing. In addition, it is expected that sheet forging (or cold working) will improve the surface properties of finished products. Steel materials for parts subjected to sheet forging are required to possess adequate durability, strength, wear resistance, and pitting resistance, among other properties. Therefore, many parts require a suitable heat treatment, such as quench hardening, after cold working by sheet forging.

High-carbon steel is used for such parts. **Fig. 1** illustrates the relationship between carbon content and maximum quench hardness of steel. The hardness of a steel material after quenching is closely related to its carbon content. In general, quench hardness increases with carbon content. The quenching temperature, too, has a significant effect on hardness. As shown in **Fig. 2** (which illustrates the relationship between quenching temperature and hardness), the quenching temperature at which maximum hardness is reached differs according to steel species. Therefore, it is necessary to apply the optimum quenching temperature for the steel under consideration.

The surface properties of high-carbon steel also differ depending on use. Both hot-rolled high-carbon steel sheets (e.g., skinned, pickled) and cold-rolled high-carbon steel sheets (e.g., hard-drawn, annealed) are available. However, hot-rolled and pickled steel sheets are used most commonly for sheet forging.

A suitable material is selected to ensure the strength required for a specific product. In general, the higher the carbon content, the

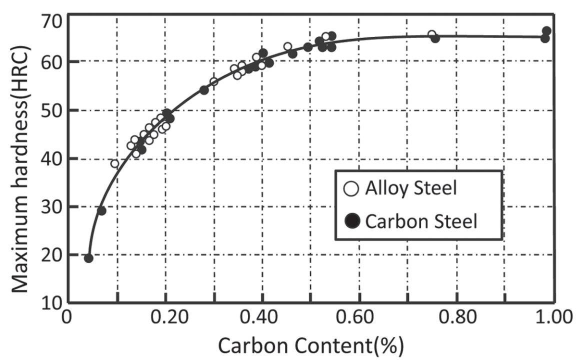


Fig. 1 Relationship between carbon content and quench hardness

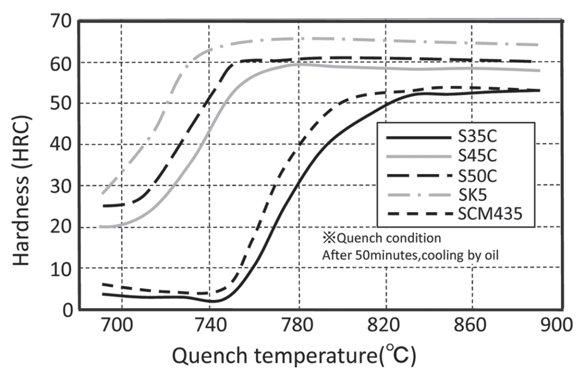


Fig. 2 Relationship between quench temperature and hardness

higher the quench strength and the lower the ductility. Therefore, the plastic fluidity of the material can deteriorate if an unsuitable material is used for sheet forging, which can cause a loss of material during upsetting. Similarly, an increase in material strength requires a larger forming load to avoid adverse effects on the durability of the tool. S35C is used most commonly in sheet forging. When selecting a material, it is desirable to study carefully the workability of each candidate material using, for example, FEM analysis.

2.3 Chrome/chrome–molybdenum steel sheet of medium thickness

As a heat treatment performed in atmosphere to increase the hardness of the surface layer of a steel material after working, nitriding is used as commonly as carburizing. Nitriding is applicable to chrome steel (SCR) or chrome–molybdenum steel (SCM) containing chromium, aluminum, and molybdenum to form nitrides. SCR and SCM are characteristic in that they can be subjected to both ordinary quenching and nitriding. By heat treating SCR (SCM) at about 470°C to 580°C in an ammonia or nitrogen atmosphere, it is possible to harden only the surface layer (up to HV 1,000 or more) while keeping the interior relatively soft. Thus, this heat treatment can produce parts with both good wear resistance and high toughness. As one of the heat treatment processes applicable after sheet forging, nitriding is subject to little thermal strain because the heat treatment temperature is lower than that in the carburizing or quenching processes.

3. FEM Analysis and Fracture Limit Evaluation Using Thick Steel Sheet

FEM analysis is useful in designing methods for and processes of sheet forging. It is important to evaluate accurately the forming limit by applying FEM analysis to the material properties that are suitable for sheet forging.

In FEM analysis of ordinary press forming, it is common practice to extrapolate a stress–strain diagram from experimental results up to the uniform elongation of the material in a tensile test, as shown by the solid line in **Fig. 3**. In press forming, the plastic strain region that is handled in FEM analysis is only up to about 0.5%; hence, a stress-strain diagram obtained using the above method offers sufficient analytical precision. Conversely, for material thickening in sheet forming, the plastic strain may reach as high as about 2.0%. In this case, the stress-strain diagram obtained by tensile tests illustrates a high degree of work hardening in the high-strain region. Thus, FEM analysis tends to highlight the difference in deformation behavior from the actual material.

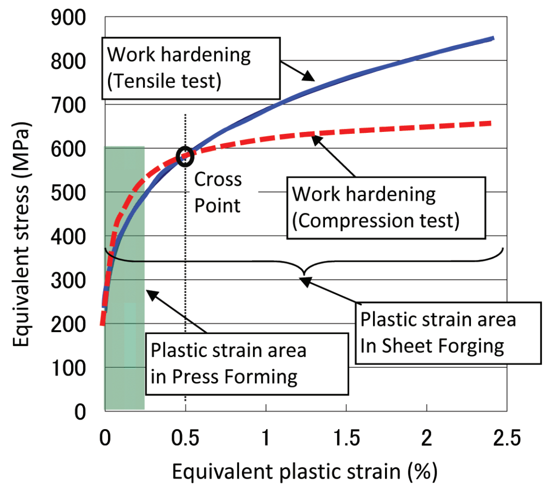


Fig. 3 Mechanical properties of hot rolled sheet in sheet forging

Therefore, in FEM analysis of sheet forging, it is advisable to use the material properties obtained by compression tests up to the high-strain region indicated by the broken line in Fig. 3 in order to evaluate the material deformation behavior that corresponds to the material thickening (compressive deformation). It is expected that using the material properties obtained by the compression test will improve the accuracy of FEM analysis of the material thickening process in sheet forging.

Conversely, several matters must be considered when evaluating the fracture limit in sheet forging. For example, a thin steel sheet fractures as follows. First, diffuse necking occurs as a result of homogenous deformation. Then, a shear zone accompanying a through-thickness deformation is formed at the neck in the thickness direction. Eventually, the shear zone leads to fracture of the steel sheet. However, necking in the thickness direction does not occur in the case of sheet forging of a thick steel sheet; rather, a local deformation starts from the formation of a shear zone. Therefore, using a model based on the 3D local bifurcation theory[5-8] in a form containing the thickness direction, it is possible to verify the modes in which a shear zone is formed and the possibility of these modes occurring in an actual material.

In such a model, a necking plane that takes the thickness direction into account is assumed to exist, and the orientation vector (n) perpendicular to the local necking plane and the orientation vector of necking velocity (m) are determined independently of each other (**Fig. 4**). Here, the shear mode in which the shear zone is formed within the necking plane (and in parallel with the sheet surface) is expressed as Mode SH (horizontal share), while the shear mode in which the shear zone is formed within the necking plane but in the thickness direction is expressed as Mode SV (vertical share). In addition, in the analysis of sheet forging, it is necessary to consider Mode N (normal), in which the shear zone is theoretically at right angle to the necking plane and whose effect has been considered negligible in press forming of thin steel sheet. In each of the above modes, the orientation vectors expressed using φ and ψ are as follows.

$$n = (\cos\phi\cos\psi, \sin\phi\cos\psi, \sin\psi) \quad (1)$$

$$\dot{m}_{SV} = (-\sin\phi, \cos\phi, 0)$$

$$\dot{m}_{SH} = (-\cos\phi\sin\phi, -\sin\phi\sin\psi, \cos\psi)$$

$$\dot{m} = \frac{\upsilon_1\dot{m}_{SV} + \upsilon_2\dot{m}_{SH}}{\sqrt{\upsilon_1^2 + \upsilon_2^2}} \quad (2)$$

where υ_1 and υ_2 are parameters indicating the contributions of Mode SV and Mode SH.

3.1 Test and analysis results

We conducted an axial compression test using cylindrical test pieces of different aspect ratio—diameter (D) to height (H) ratio—

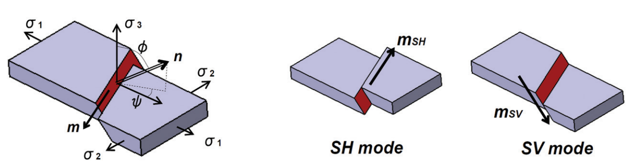


Fig. 4 3D localized bifurcation theory

to study the mode of cracking and the timing of surface cracking.[9] The material tested was S45C, the chemical composition of which is shown in Table 2.

As shown in **Fig. 5**, the test pieces were cylinders, each with a diameter (D) of 3 mm. The height (H) was varied between 1.5 mm and 7.5 mm; hence, the aspect ratio (D/H) was between 0.5 and 2.5. The axial compression test was conducted at a test speed of 1 mm/min using test equipment for load–stroke measurement (Instron). In addition, a microscope was used for in situ observations of surface cracking.

The dynamic explicit method LS-DYNA (axisymmetric element) was used for the FEM analysis associated with the axial compression test. The mechanical properties were derived from tensile test results to decide the Swift parameters (K-value, n-value) to be applied in the analysis. Conversely, the fracture limit was evaluated by post-treatment using the results of FEM calculations. In the post-treatment, the conditions for instability of cleavage in the local bifurcation zone were applied in addition to the 3D local bifurcation theory. The stress increment dependence parameter (Kc-value) in the constitutive equation of stress increment dependence[4] that is required for the 3D local bifurcation theory was also derived from the tensile test results.

Fig. 6 compares the results of in situ observations of surface cracking in the axial compression (aspect ratio H/D = 2.5) with the results of FEM analysis. Note that, in the figure, the 3D local bifurcation limit is associated with an index of 2 or more in the contour diagram and the cleavage instability condition is associated with a negative value (less than 0) in the contour diagram. In the experiment, the upsetting ratio when cracking occurred from the surface of a barrel-shaped test piece under axial compression was about 75%. Conversely, the upsetting ratio obtained by 3D local bifurcation analysis was about 56% (i.e., higher than the experimental result) and the upsetting ratio under the cleavage instability condition was about 72% (i.e., close to the experimental result). This is thought to occur for the following reason. Surface cracking in a cylinder under axial compression does not occur at the 3D local bifurcation limit, since even the surface is subject to deformation constraints from the inside; however, it is assumed that surface cracking occurs when the cleavage instability condition sets in. Furthermore, the mode of cracking was diagonal in the direction of the bifurcation interface, as confirmed by the experiment.

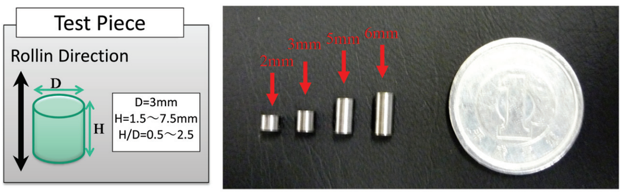


Fig. 5 Specimens for axial compression test

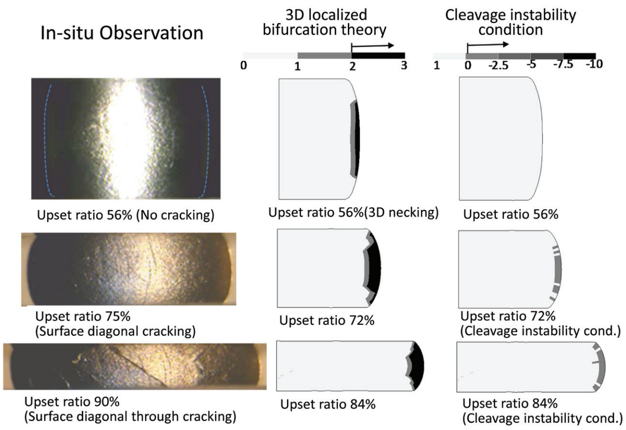


Fig. 6 Comparison with the fracture at the compression test (aspect ratio H/D = 2.5)

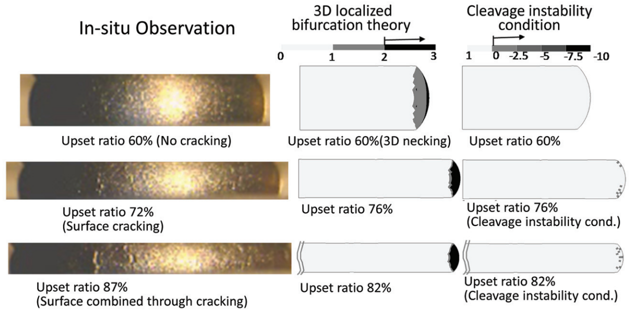


Fig. 7 Comparison with the fracture at the compression test (aspect ratio H/D = 1.0)

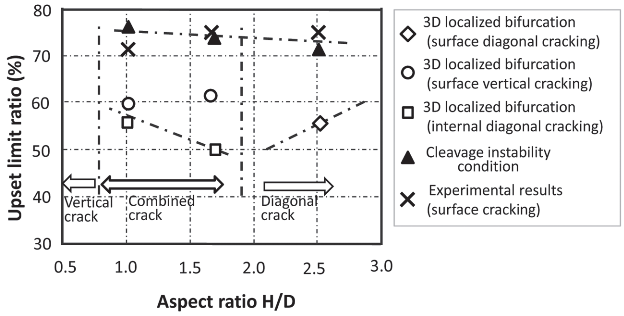


Fig. 8 Comparison experiment and analysis of crack initiation behavior at each aspects

Fig. 7 compares the results of in situ observation of surface cracking in the axial compression test (aspect ratio H/D = 1.0) in the conventional mixed mode of cracking with the results of FEM analysis of surface cracking. The 3D local bifurcation limit at the surface was reached at an upsetting ratio of about 60%; however, in the experiment, surface cracking was observed at an upsetting ratio of about 72%, close to that under the cleavage instability condition (76%). As can be seen from the experimental results in Fig. 5, the mode of cracking is a mixed mode in which surface cracking takes the form of a zigzag, as predicted by FEM analysis.

Fig. 8 summarizes the upsetting ratios for the occurrence of cracking according to the other aspect ratios, including the experimental and analytical results. Concerning the 3D local bifurcation condition, it can be seen that the mode of cracking is diagonal when H/D > 1.8, mixed when H/D = 0.5 - 1.7, and vertical when H/D < 0.5. As a whole, the surface cracking observed in the experiment was found to occur at an upsetting ratio about 10% higher than the 3D local bifurcation limit and nearly the same as the ratio under the cleavage instability condition.

3.2 Working analysis and fracture limit prediction taking anisotropy into account

From the experimental results described in the preceding section, we were able to confirm the validity of the 3D local bifurcation theory. However, the material appears oval in cross-sectional shape after deformation, depending on material properties. This is assumed to be due to the effect of the plastic anisotropy of the material. **Fig. 9** illustrates the conditions of cracking for the material conditions under which that occurs (material sampled in direction perpendicular to rolling direction; aspect ratio = 2.00). For this aspect ratio, diagonal cracking occurred at the outside of the material and a diagonal crack occurred at two points on the short sides of the material.

Thus, in the upsetting of a cylindrical material, it is possible that the fracture limit will be influenced by the oval cross section. Therefore, we evaluated the influence by 3-D FEM analysis, taking the material anisotropy into consideration.

3.2.1 Analytical conditions and results

An analytical model of quarter symmetry was used to consider the material characteristics. A 3D solid element that allows plastic anisotropy to be taken into account was used as the analytical element. The detailed analytical conditions are presented in **Fig. 10**. Since the aspect ratio is 2.00 (Fig. 10), diagonal cracking should occur at the outer surface of the material.

Fig. 11 summarizes the results of FEM analysis and the results of evaluation based on the 3D bifurcation theory in terms of the amounts of r0, r90, and r45 and the mean value of r. For r0 and r90, it is clear that the risk of fracture increases and the material cross

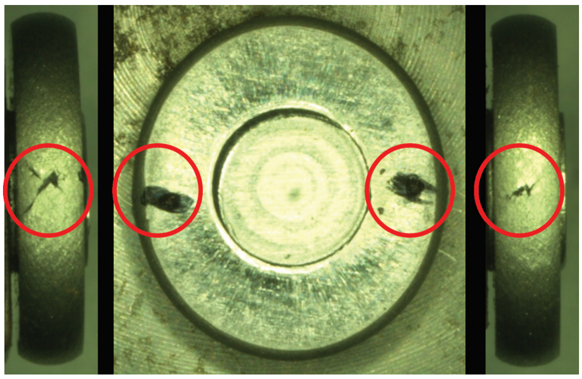
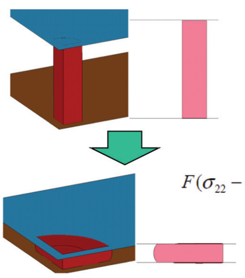


Fig. 9 Ovalized specimen after cracking



▹Solver/ LSDYNA
▹ Material model/ MAT103(Hill's 48 model)
▹ TP size/ D3.0mm x L6.0mm (1/4 model)
▹ Material/ Hot rolled steel 540MPa

$$F(\sigma_{22}-\sigma_{33})^2+G(\sigma_{33}-\sigma_{11})^2+H(\sigma_{11}-\sigma_{22})^2$$
$$+2L\sigma_{23}^2+2M\sigma_{31}^2+2N\sigma_{12}^2=\sigma(\varepsilon_{eff}^p,\dot{\varepsilon}_{eff}^p)$$

	F	G	H	L	M	N		r_0	r_{45}	r_{90}		ave_r	del_r
Case1	0.5	1	1	3	3	3		1	1.5	2		1.5	0
Case2	1	0.5	1	3	3	3		2	1.5	1		1.5	0
Case3	1	1	1	3	3	3		1	1	1		1	0
Case4	1	2	1	3	3	3		0.5	0.5	1		0.625	0.25
Case5	2	1	1	3	3	3		1	0.5	0.5		0.625	0.25
Case6	1	1	2	3	3	3		2	1	2		1.5	1
Case7	1	1	0.5	3	3	3		0.5	1	0.5		0.75	−0.5

Fig. 10 Analysis of cold upsetting of circular cylinder in consideration of material anisotropy

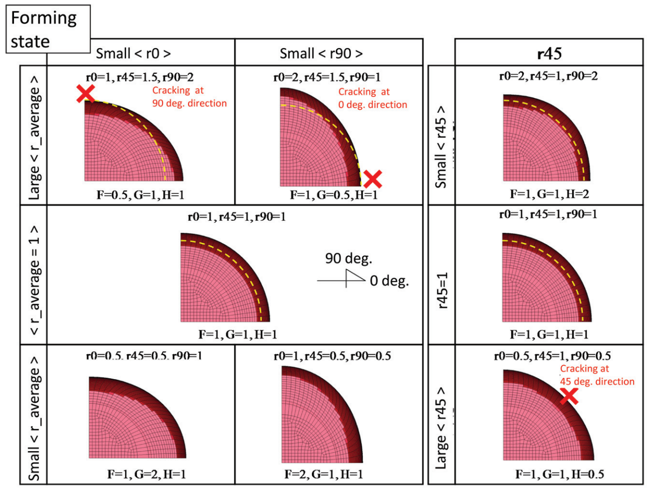


Fig. 11 Results of finite element analysis in consideration of material anisotropy (marking × on the predicted fracture point)

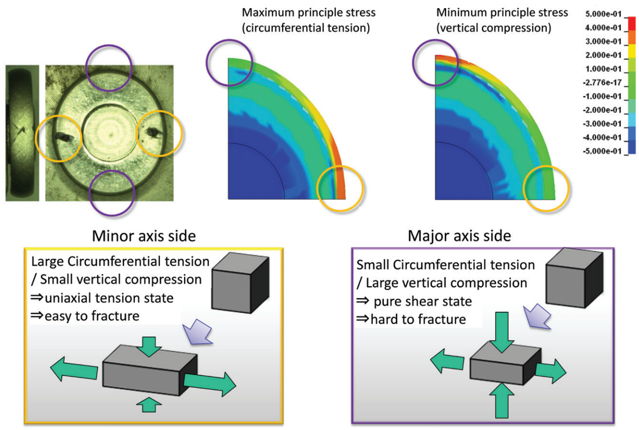


Fig. 12 Evaluation of stress state at long and short axis side

section becomes more oval for larger mean values of r, owing to the plastic anisotropy. This causes cracks to occur at the short axis side. Any increase in the mean value of r increases the stress of the material as a whole, which in turn contributes to the occurrence of a fracture. Conversely, the prediction of the occurrence of cracking at the short axis side confirmed the validity of the experimental results.

To evaluate the fracture limit according to the degree of ovality, we studied the stress state on both the short and long axis sides. The study results are shown in **Fig. 12**. At the long axis side, both the circumferential tensile stress and the axial compressive stress were sufficiently large to invite a "pure shear state" in which the fracture limit was high. However, at the short axis side, the axial compression stress in the longitudinal direction was small, although the circumferential tensile stress was large. Therefore, the stress state at this side became a "uniaxial tension state," in which the fracture limit was lower than in the pure shear state. The above information indicates that the ovality imparts a difference in stress state at the material outer surface between the short axis and the long axis sides, causing a fracture to occur more easily at the short axis side.

4. Conclusions

In this report, we conducted a fracture limit evaluation using 3D local bifurcation theory to illustrate the possibility of evaluating the fracture limit when a change in sheet thickness is involved and of determining the mode of fracture. In future, we intend to continue offering suitable steel materials in this particular field, evaluating their forming limits, and seeking new forming processes.

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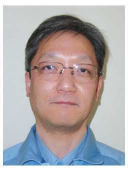

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