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Technical Report

Effect of Material Properties and Forming Conditions on Formability of High-Purity Ferritic Stainless Steel

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Abstract

Applications of high-purity ferritic stainless steels are expanding, because of the steels' excellent corrosion resistance and high r-value. This report shows that high-purity ferritic stainless steels present satisfactory formability better than SUS304 by selecting forming conditions to utilize the high r-value characteristic. It is desirable to change forming conditions from n-value dependent budge forming to r-value dependent drawing. Moreover, high-purity ferritic stainless steels indicate hole expanding ratio better than SUS304. The reasons are: 1) less deterioration of formability resulting from lower work-hardening at the time of hole punching, 2) good local elongation by high r-value.

1. Introduction

Compared with austenitic stainless steel, ferritic stainless steel has advantages such as lower prices and lower sensitivity to stress corrosion cracking because it does not contain Ni. Its applications are expanding because of the latest trend of resource saving, and demand for it is expected to grow significantly. However, the shapes of final products made of stainless steel are becoming increasingly complicated, and it is not easy for it to replace austenitic stainless steel, which has higher ductility and is capable of being formed into a wide variety of shapes.

A reduction in impurities such as C and N and addition of stabilizing elements such as Ti and Nb are widely considered effective in improving the formability of ferritic stainless steel[1-5], because these measures increase elongation and r-value to improve deep-drawability[6, 7]. Actual press forming work, however, includes not only drawing but also many other modes of plastic deformation such as stretching and stretch flanging[8, 9], and it is necessary to select the forming conditions best suited for the material and final product shape. In consideration of this, there has been much research and numerous reports on the forming conditions of ferritic stainless steel[9-13].

In view of the above, the authors focused attention on high-purity ferritic stainless steel, NSSC® 180, the applications for which have been expanding rapidly over the last few years, and analyzed the effects of forming conditions and material properties on formability. This paper reports the results of the study.

2. High-Purity Ferritic Stainless Steel, NSSC 180

2.1 Chemical composition and mechanical properties of NSSC 180

Table 1 shows typical chemical composition of NSSC 180 together with those of commonly used stainless steels, SUS304 and SUS430 under JIS. NSSC 180, which satisfies the specifications of JIS SUS430J1L, is characterized by excellent formability due to very low content of C and N and addition of Nb as a stabilizing element. **Table 2** shows the tensile test results of the steels shown in Table 1; here, JIS No. 13B test pieces cut out in parallel to the rolling direction were used. The total elongation of NSSC 180 is lower than that of SUS304, but higher than that of SUS430, which demonstrates the effects of its high purity and the addition of the stabilizing element. **Fig. 1** compares NSSC 180 and SUS304 in terms of the relationship

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Table 1 Chemical compositions

	C	Si	Mn	Ni	Cr	Cu	Nb	N
NSSC 180	0.013	0.5	0.1	0.3	19.3	0.5	0.4	0.0115
SUS430	0.078	0.3	0.6	-	16.1	-	-	0.0293
SUS304	0.056	0.4	1.1	8.1	18.1	0.2	-	0.0374

Table 2 Results of tension test (specimen: JIS13B, RD)

	0.2%PS (MPa)	TS (MPa)	El (%)	n-value
NSSC 180	331	505	31.4	0.19
SUS430	305	511	26.7	0.18
SUS304	325	757	50.8	0.46

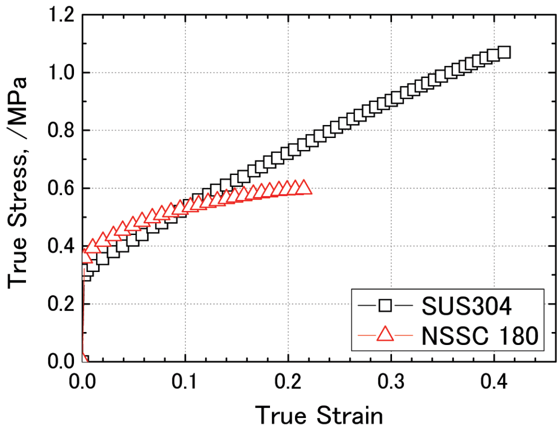


Fig. 1 True stress-true strain curves of SUS304 and NSSC 180

between the true strain and true stress during tensile tests using test pieces 0.8 mm in thickness. Whereas SUS304 exhibits significant work hardening due to transformation-induced plasticity (TRIP), the work hardening of NSSC 180 is smaller, and its uniform elongation is approximately twenty percent. In consideration of the relationship with total elongation, the local elongations of the two steels are substantially the same.

2.2 Deep-drawability and stretchability

2.2.1 Comparison in terms of limit drawing ratio and Erichsen value

Formability was evaluated by test of limit drawing ratio (LDR) and Erichsen test. **Photo 1** shows the test pieces after the LDR test using one punch diameter (40 mm) and different blank diameters (78 to 96 mm). The conditions for the cup drawing were: punch speed 6 mm/min, lubricant #122 wax, and blank holder force 10 kN. **Table 3** compares NSSC 180 and SUS304 in terms of average r-value and LDR, representative indicators of formability, and the Erichsen value, an indicator of stretchability. The LDR of NSSC 180 is higher than that of SUS304, reflecting the higher r-value of the former. On the other hand, the Erichsen value of NSSC 180 is lower than that of SUS304, reflecting the difference in ductility.

2.2.2 Test method and material properties

Using PAM-STAMP 2G[14], a solver for the dynamic explicit method, the authors calculated the material thickness distribution after the cup drawing tests (at a drawing ratio of 2.0) and after Hydraulic bulge tests. The results are illustrated in **Fig. 2**. Here, the cup test result on the left-hand side shows the distribution of sheet thickness, and the pressure bulge test result on the right-hand side shows that of

Photo 1 Sample after limit drawing ratio test

Table 3 r-value and forming properties

	r-value average	L.D.R.	Er value
NSSC 180	1.4	2.25	9.6
SUS304	1.0	2.05	13.1

thinning. Whereas, in the cup drawing test, the thickness change of NSSC 180 was small and quite different from that of SUS304, thinning occurred at the top area with both steels at the pressure bulge test, and the thickness distribution of the two was much more similar to each other, though the absolute rate of thinning was different. This indicates that, to expand the forming range of NSSC 180, it is effective to increase the deformation mode of drawing, by taking advantage of its high r-value.

2.3 Approach to formability improvement and evaluation test

2.3.1 Square drawing test

Sheet forming work is done mostly by pressing, leaving a flange around the formed part. This is to prevent the forming die from being damaged by the blank edge coming into the gap. Another reason is that it is difficult to define the shape of initial blanks to secure uniform material influx leaving a uniform and minimum flange for various forming shapes. It is appropriate, therefore, to leave a flange to evaluate drawability using drawing tests. Accordingly, the authors selected square deep drawing test as one of such test methods. **Photo 2** shows test pieces after square deep drawing tests under the same forming conditions. Because the flange width remaining at the corners is large and the stretch forming factor increases in square deep drawing, cracking occurred with NSSC 180 near the corners when the drawing height was 40 mm. This seems to indicate that, in forming work to leave a flange, the possibility of successful forming is lower with NSSC 180 than with SUS304, all other conditions being equal.

2.3.2 Forming conditions to improve formability

To improve drawability, measures such as the following are considered effective[9-12]:

(1) To lower the blank holder force to the limit not to cause wrinkles,
(2) To relax die conditions for stretch forming (larger corner radii),

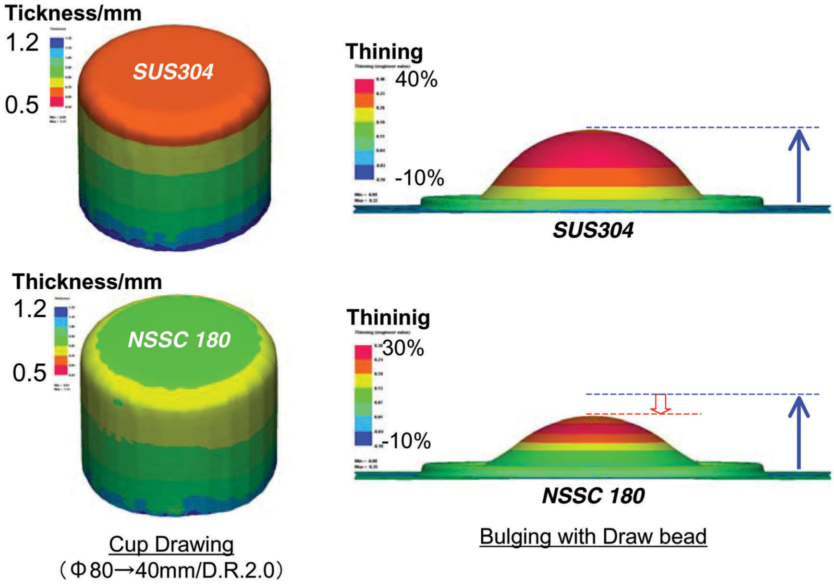


Fig. 2 Comparison of forming properties by FEM simulation

Photo 2 Comparison of square formability

(3) To change lubrication conditions to lower the friction coefficient, and

(4) To minimize the blank size.

All these are intended to make the most of the high r-value by decreasing the friction in material influx and minimizing any decrease in thickness. Any one of these measures, however, involve problems, and careful study is required for their practical application: decreasing blank holder force and relaxing die conditions decrease the stretching in the sidewall of the formed piece and are likely to result in canning or other poor forming; a change in lubrication conditions may require change in manufacturing conditions such as use of lubricant and addition of a degreasing process after forming work, meaning increased costs; and smaller blank size accelerates material influx, and consequently, only a slight change in forming conditions may result in local shortage of material.

2.3.3 Test results

In order to study how formability changes under different forming conditions, the authors conducted a FEM simulation; the results are shown in **Fig. 3**. NSSC 180 cracked at the same position as seen in Photo 2 before SUS304 did under the same forming conditions. Then, another simulation was performed by significantly decreasing the friction coefficient to improve drawability; the result is shown in Fig. 3 (c). The decrease in the friction coefficient proved effective in attaining a punching height of 48 mm with NSSC 180, the same as with SUS304. With respect to the calculated thickness distribution, however, the portion of NSSC 180 where the thickness decrease was largest was the sidewall, different from the case for SUS304. This is probably because, whereas for SUS304 the forming conditions were selected such that the stretching accounted for most of the deformation, and thus, thickness decrease occurred mainly in regions near the corners of the square punch, with NSSC 180, for which the forming conditions were set to allow easy material influx, the bottom material was not forced to flow much, and thinning was small there.

In consideration of the above test results, the authors conducted square drawing tests under different lubrication conditions; **Photo 3** shows the results. So as to decrease the friction coefficient, protective films were applied to both the sheet surfaces[15], and #122 lubricant was applied to the die. With this friction-decreasing measure, NSSC 180 was successfully formed to a height of 48 mm. Comparing the scribed circles on the surfaces in Photos 2 and 3, one can note that the flange has markedly decreased at the corners and straight portions. This seems to indicate that the easier material influx was effective in decreasing local strain concentration, and the principal mode of deformation changed from stretching to drawing. It is therefore possible with NSSC 180, though inferior in ductility, to obtain formed products having shapes as complex as those made of SUS304, provided that the most suitable forming conditions are selected in consideration of the product shape and forming process.

2.4 Stretch flanging properties

2.4.1 Hole-expanding test

Stretch flanging properties were evaluated by means of hole-expanding tests. The initial holes 12 mm in diameter were made by punching with clearance set at 2.5, 5.0 and 10.0 percent of the sheet thickness. To confirm the effects of the punching clearance, the authors observed the morphology of the edge of the initial hole and measured the hardness near the edge. In order to see the effects of difference in the forming conditions, conical head punches with head angles of 30° and 60° and a flat-head punch (corner radius 4 mm), each 40 mm in diameter, were used for hole expansion. The speed of the hole-expanding punch was 6 mm/min, and the blank holder force

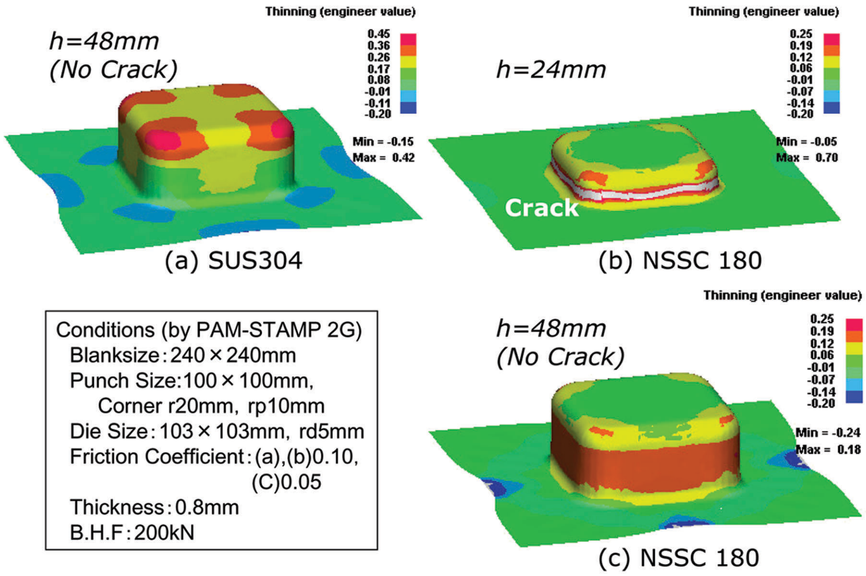
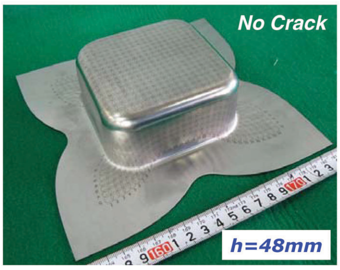


Fig. 3 Effect of friction condition on square formability in NSSC 180

Punch: 100×100mm, Corner r20mm, rp10mm
Die: 103×103mm, rd5mm, BHF: 300kN



Friction: Thin Film with #122wax

Photo 3 Result of low friction condition on square formability

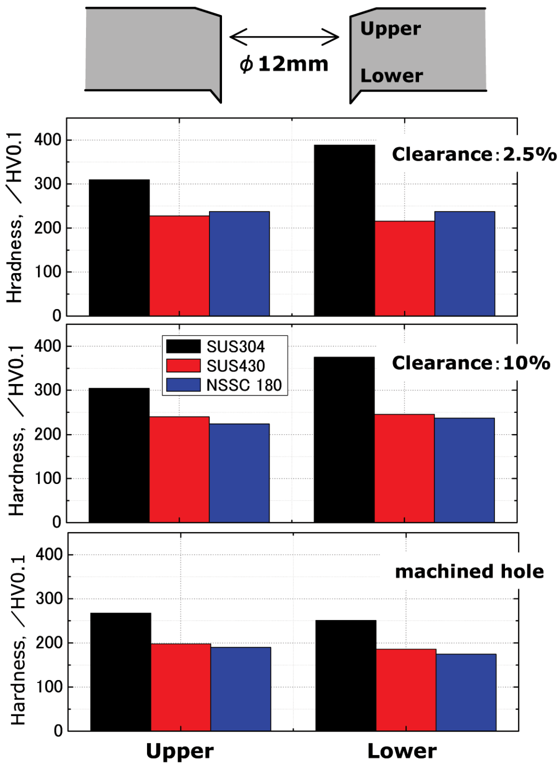


Fig. 4 Comparison of work hardening on punch hole clearance and machined hole

was 10 kN. For lubrication, rust-preventive oil was applied lightly to the punch surface. In addition, for comparative purposes, the same hole-expanding test was conducted using specimens with initial holes drilled by machining.

2.4.2 Morphology evaluation of punched edges of initial holes

Fig. 4 compares the hardness measured near the upper and lower edges of the initial holes punched under different clearance conditions and the same of the holes drilled by machining. The hardness increase (work hardening) was more conspicuous near the edge of a punched hole than a machined hole. Regarding punched holes, where the work hardening was more conspicuous, both NSSC 180 and SUS430 hardened slightly near the hole, and the extent of hardening and its tendency at the upper and lower sides of the two steels were substantially the same. In contrast, significant work hardening due to TRIP was observed with SUS304; in the cases of 2.5- and 10-percent clearance, the work hardening of SUS304 was more noticeable on the lower side, where there were burrs.

Fig. 5 shows the results of hole-expanding tests on three steels using a punch with a head angle of 60°. The three steels were lined in descending order in terms of hole-expanding ratio λ, thus NSSC 180, SUS304, SUS430, which demonstrates the excellent hole expansibility of NSSC 180. Another finding was that the smaller the clearance at the punching of the initial hole, the higher the hole expansibility became regardless of the kind of steel. **Fig. 6** shows the effect of punching clearance on the hole-expanding ratio of NSSC 180; the hole-expanding ratio was highest with a machined initial hole and an expanding punch with a head angle of 60°, but in the case of punched initial holes, it was highest with an expanding punch with a head angle of 30°. Additionally, the effect of punch shape was

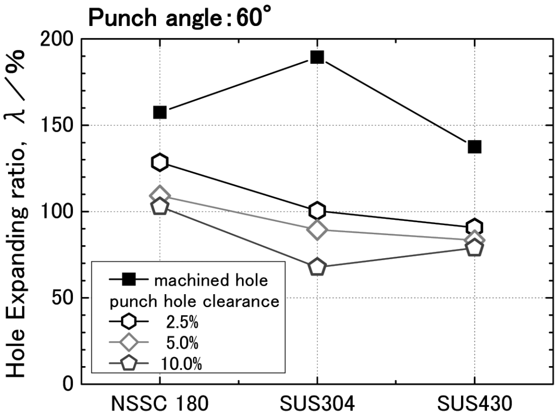


Fig. 5 Results of hole expanding test

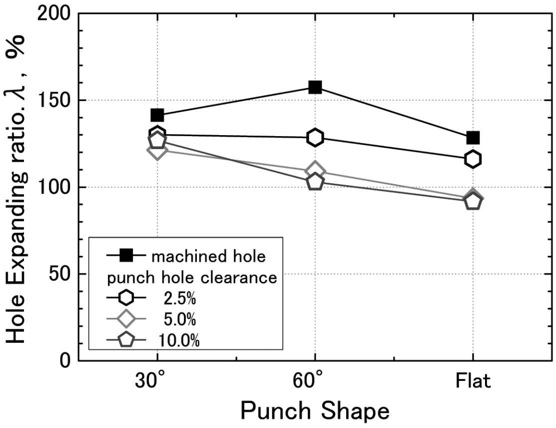


Fig. 6 Effect of punch shape on hole expanding ratio in NSSC 180

insignificant when the punching clearance was 2.5 percent, and the hole-expanding ratio was substantially the same when the clearance was either 5.0 or 10.0 percent.

2.4.3 Morphology of punched edge and hole expansibility

It is widely known that the hole-expanding ratio λ, starting from a punched initial hole varies significantly depending on the fracture morphology (burrs) at the edge of the initial hole, and to decrease the effects of the fracture morphology, a measure to smooth the irregularity of the edge by coining with a conical punch is being studied[16]. **Photo 4** shows edge surfaces of the initial holes of the three steels punched at clearances of 2.5 and 10.0 percent. When the clearance was 2.5 percent, the rate of rough fracture (as seen in the lower part of each frame in Fig. 4) was low and so was the occurrence of burrs, which seems to indicate that, when the clearance is small, the initial hole has a smooth edge, the stress concentration during hole-expanding work is small, and the punch shape has limited influence on the hole-expanding ratio. The fracture morphology of NSSC 180 was smooth especially when the clearance was 2.5 percent, and this good fracture morphology was presumably a favorable factor for the high hole-expanding ratio of NSSC 180. When the clearance was 10.0 percent, on the other hand, there was little difference in the rough portion ratio of the edge surface between the three steels, and voids and other irregularities that lowered the hole-expanding ratio were found on the edge surfaces, indicating that punching clearance affects hole expansibility.

The authors also examined the effects of burrs, which are an-

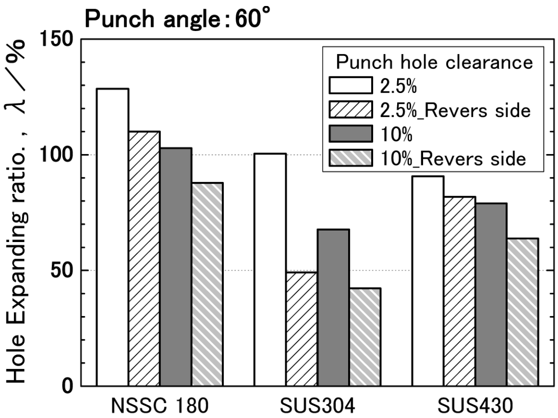


Fig. 7 Effect of punch hole direction on hole expanding ratio

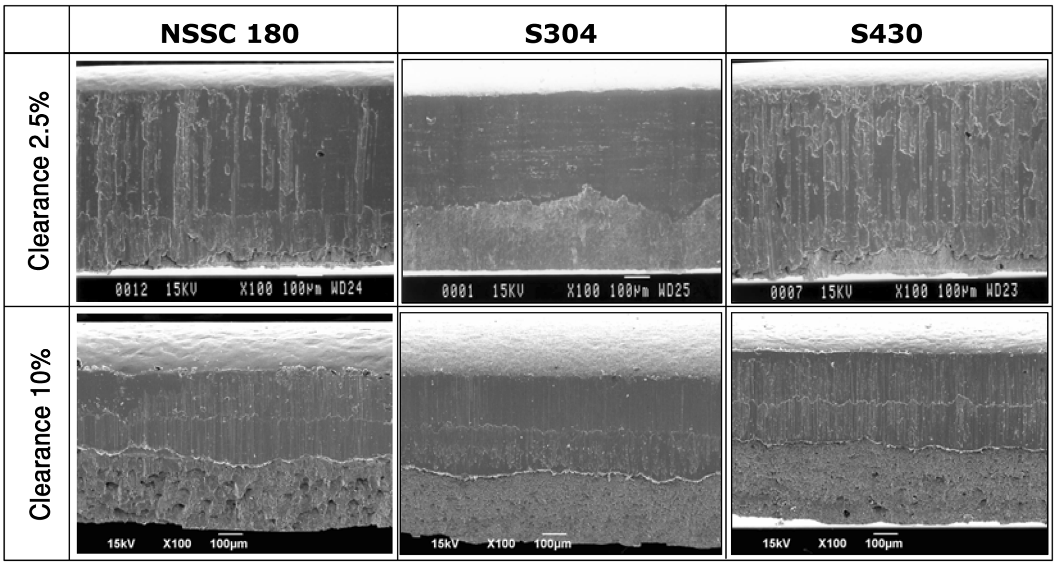


Photo 4 Effect of punch hole clearance on edge morphology by SEM

other important factor influencing hole expansibility. **Fig. 7** shows the effects of punching direction on the hole-expanding ratio of specimens punched at different clearances. The tendency of the effects of the direction of burrs on the hole-expanding ratio λ, is the same with both ferritic and austenitic stainless steel: even when the burrs are turned upward, in which case there are no coining effects, better results were obtained with the 2.5 percent clearance. By contrast, the hole-expanding ratio λ, of SUS304 decreased significantly when the burrs were turned upward and there were no coining effects; this is presumably because the hardening caused by the punching work on the initial hole added effects to those of burrs.

2.4.4 Punch shape and hole expansibility

It is well known that, during hole-expanding work, the stress gradient at the hole edge changes with different head angles of hole-expanding punches, and the hole-expanding ratio becomes highest when the angle is between 30° and 60°[16, 17]. In fact, as seen in Fig. 7, the hole-expanding ratio of NSSC 180 was better with a conical headed punch than with a flat-head one. In addition, whereas the hole-expanding ratio was highest using a punch with a head angle of 60° when the initial holes were machine drilled; when the initial holes were made by punching, the results were better with a 30-degree punch than with a 60-degree punch. **Photo 5** shows SEM photomicrographs of fractures of NSSC 180 specimens after hole-expanding work. Whereas widely opening constrictions were seen with the fracture by the 30-degree punch, the constrictions in the fracture by the flat-head punch were narrower, and there were many cracks originating from burrs.

Fig. 8 shows the hardness distribution of the NSSC 180 and SUS304 specimens before and after hole-expanding work with hole-expanding punches of different head shapes. The range of hardness distribution from the punched hole edge after the expanding work is smaller using the punch with a head angle of 30° than with the flat punch, which presumably demonstrates the greater strain-dispersing effects of a conical head. The higher hole-expanding ratio λ, obtained with the 30-degree punch is attributable, most likely, to the added effects of coining of the burrs and smaller contact angle leading to a larger stress gradient and dispersal of constrictions. Many

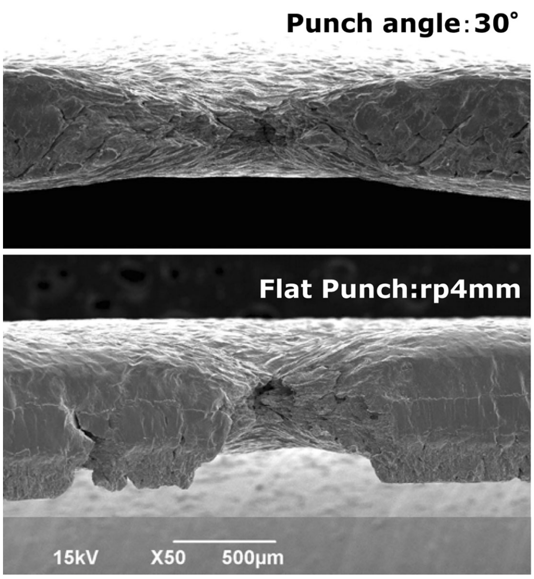


Photo 5 Effect of punch shape on crack morphology at hole expanding test

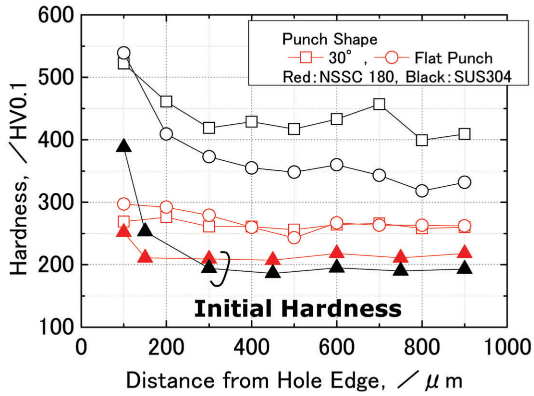


Fig. 8 Effect of punch shape on work hardening at punch hole edge

specimens fractured in a direction approximately 45° to the rolling direction; the r-value shows anisotropy and is low in this direction. Assuming that sufficiently high ductility remains in the region near the edge of a punched initial hole, the above result seems to indicate that the r-value affects the formation of constrictions similar to local elongation[16].

3. Applications of NSSC 180

The application of NSSC 180 has been expanding rapidly thanks to the latest trend toward resource saving and its price stability in spite of the fluctuating prices of rare metals. **Photo 6** shows a specially designed kitchen sink made of the developed steel. Because specially designed sinks require formability into complex shapes coupled with a beautiful sheet surface after forming, austenitic stainless steels – typically such as SUS304—were conventionally used for this application practically exclusively. Commercial use of NSSC 180 for this kind of application has been made possible through close examination of the final product shape, work processes and forming conditions, and their improvement.

4. Summary

The effects of forming conditions and material properties over the formability of high-purity ferritic stainless steel, NSSC 180, were examined and the following findings were obtained:

(1) NSSC 180 has a high r-value, which is effective in improving cup formability, and thanks to this, its limit-drawing ratio is higher than that of JIS SUS304.

Photo 6 Application of NSSC 180 at design sink

(2) Stretching is the major mode of plastic deformation in drawing work to leave a flange, and therefore, under the same forming conditions, NSSC 180 is more likely to crack than SUS304. Thus, to improve the formability of NSSC 180 in this type of forming work, it is necessary to set forming conditions to allow easy material influx.
(3) NSSC 180 is superior to SUS304 in its hole-expanding ratio λ in the case of a punched initial hole.
(4) The above indicates that NSSC 180 applications can be expanded by carefully analyzing forming conditions and changing them to optimize the mode of plastic deformation (less stretching and more drawing).

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