

Technology to Enhance Deep-drawability by Strain Dispersion Using Stress Relaxation Phenomenon

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ABSTRACT

When the introduction of strain is temporarily stopped during tensile testing of a metal, a stress relaxation phenomenon is known to occur whereby the stress diminishes with the passage of time. This phenomenon has been explained as the change of elastic strain into plastic strain.

The present report suggests the application of the stress relaxation phenomenon to stamping for the purpose of strain dispersion. A new step motion that pauses the die during forming was devised and succeeded in modifying the deep-draw forming limit.

Verification was conducted by tensile testing in addition to actual stamping tests. As a result, it was concluded that the mechanism that modifies the deep-draw forming limit arises from the use of step motion for the dispersion of strain, and this was also confirmed to be dependent on the stop time and the temperature.

1. Introduction

Since the 1990s, every automobile manufacturer has been actively advancing the application of high tensile-strength steel in order to achieve a balance of weight reduction and safety in their vehicles. Japan's steel manufacturers have been in the vanguard of high tensile-strength steel development. Their technology development has advanced to produce materials of greater strength and greater formability, and the application of those materials has reached as high as 60% or more on a body-in-white weight basis⁽¹⁾.

In general, increasing the strength of steel material involves a tradeoff in terms of reduced elongation. Consequently, high tensile-strength steel is essentially less formable than mild steel sheet, and stamped parts could not readily be obtained from materials with a tensile strength exceeding 780 MPa.

Materials technology addressed this with the development of materials such as low yield-point steel, which has low deformation resistance and superior elongation. This material is based on dual phase steel (DP steel) with a two-phase structure of ferrite for superior formability and martensite to assure strength. Another such material is transformation induced plasticity steel (TRIP steel) using stress-induced martensitic transformation,

which yields high strength after forming while preventing strain concentrations. More recently, it has been found that the formability of high tensile-strength steel can be increased effectively by enhancing hole expandability. Advances are being made in developing materials with local ductility enhanced for superior hole expandability by having the internal structure of the material combine structures that have smaller differences in hardness between them.

Meanwhile, measures have also been taken to enhance formability by means of stamping technology. Such approaches include increasing the lubricity between the material and the die and devising multi-stepped processing to avoid the concentration of processing strain. The appearance of servo press machinery in recent years now also allows press motions of unprecedented complexity. Tamai et al.⁽²⁾ used complex motions of the servo press in order to return the slide during forming and repour lubricating oil in between the blank material and the die. This succeeded in increasing lubricity during the latter part of forming, thus reducing friction with the die, reducing the amount of strain introduced to the material, and so increasing formability. However, repeating the action of returning the slide several times during forming tends to increase the total time taken in stamping, and there is concern that the diminished productivity could

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cause costs to rise.

Metal materials are known to experience a stress relaxation phenomenon whereby stress is reduced under a certain load at room temperature. Stress relaxation testing to evaluate the reduction in stress has also been standardized⁽³⁾. Initially, much of the research into this phenomenon was used in metal physics analysis, and most of it was related to pure metals, but there have also been recent reports on study of the phenomenon in structural steel⁽⁴⁾. Changes in stress when the crosshead was paused during tensile testing at room temperature were observed, and the results confirm that a significant reduction in stress occurs in an extremely short time. The mechanism of stress relaxation has been explained⁽⁵⁾ using Maxwell's model of viscoelasticity (Fig. 1). Due to viscous displacement of moving dislocation, a portion of the elastic strain that occurs during the initial deformation in the material is said to be substituted by the plastic strain that occurs with room temperature creep, and this is how stress relaxation is thought to occur. Viscous displacement of the dislocation is also accompanied by internal friction, and the moving speed is greater where there is less internal friction. This internal friction is of unrelaxed and relaxed types. The internal friction resulting from elastic strain changing into plastic strain, as can be explained by the Maxwell model, is the relaxed type. The magnitude of the internal friction is referred to as the Bordoni peak, and it is known to display temperature dependence⁽⁶⁾.

Given these circumstances, the present research sought to realize a previously unprecedented high level of deep-drawability using high-strength steel. To that end, a study was made of technology for extending the material forming limit by means of a servo press for complex press motions, in expectation that it would be feasible to control the process of plastic strain introduction through use of the stress relaxation phenomenon.

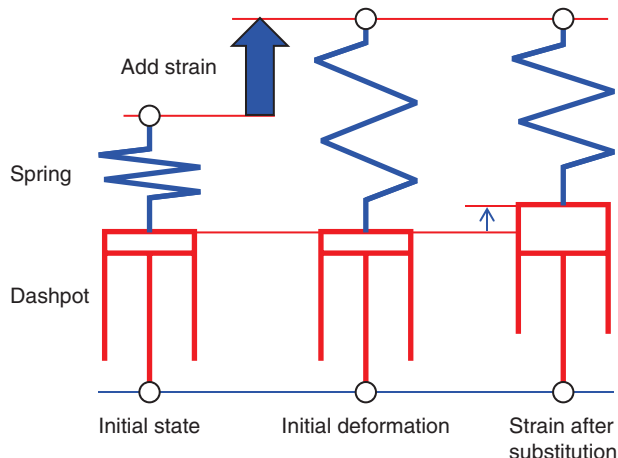


Fig. 1 Maxwell's model

2. Principles of the Method for High-level Deep-draw Processing by Strain Dispersion

The process by which stamping defects such as rupturing or necking occur in ordinary stamping is as follows. First, elastic deformation on a microscopic scale takes place during the initial processing because of heterogeneity in the material. When stress continues to concentrate in the deformed portions, these portions locally exceed the elasticity limit of the material so that plastic deformation occurs. Eventually, the constriction known as necking occurs, which is a deformation on a macroscopic scale. When processing is continued, stress concentrates progressively as a result of macroscopic deformation at this necking location and ultimately reaches the point of rupture.

The authors therefore devised a method to delay the occurrence of macroscopic deformation caused by microscopic elastic deformation that occurs in the material during initial processing, and so to make use of the deformability of the material to enhance its deep-drawability. The principle of this method is to introduce to the stamping process the substitution of plastic strain for elastic strain caused by the stress relaxation phenomenon. The microscopic areas of weakness in the material that would undergo the initial elastic deformation are strengthened by the introduction of plastic strain, and transferring the deformation to other areas causes dispersion of the strain throughout the entire material. In other words, the microscopic areas of elastic deformation that are initially areas of weakness in the material have plastic strain introduced to them by the stress relaxation phenomenon that has been brought about in advance. The dislocation density of these areas is thus increased and their yield strength is enhanced. That plastic deformation is transferred to other areas with lower yield strength in order to disperse the strain, and delaying the macroscopic local deformation thus enhances the stampability.

The principle of this processing method will be explained with stress-time curves from tensile testing of the material (Fig. 2). In the case of tensile testing conducted in the ordinary manner at a constant speed, elastic strain is first introduced (1). As tension continues to be applied, the elastic strain in areas of stress concentration partially turns into plastic strain (2). When this happens, the presence of heterogeneities in the material structure causes the concentrated introduction of plastic strain in some portions and of elastic strain in microscopic areas of weakness. Further strain is subsequently concentrated in the areas of weakness in the material, macroscopic constriction occurs as a result, and the concentration of stress advances further (3). The constriction ultimately advances to the point of rupture (4).

A forming method that works through strain dispersion, by contrast, follows a course like the following. From (1) to (2) is the same as in ordinary tensile testing. At (2), the movement of the die is temporarily stopped when plastic

strain is being introduced in some portions and elastic strain is being introduced into the microscopic areas of weakness. This causes a portion of the elastic strain to be substituted by plastic strain due to the stress relaxation phenomenon so that the microscopic areas of weakness are made stronger by work hardening (A) as a result. This phenomenon corresponds to the part of Fig. 1 from initial deformation to the strain after substitution. Next, when strain is reapplied (B), the dislocation density increases in areas where elastic strain has been substituted by plastic strain, thus increasing the strength more in these areas than in others. Consequently, no advance is made in introducing further plastic strain in these areas, and the introduction of elastic strain and in some parts plastic strain begins in other areas where the strength is relatively low (new areas of weakness) (C).

The authors therefore formulated the hypothesis that the repetition of this strain substitution would enable the dispersion of strain. Then, by suppressing local deformation, stress concentrations would be relaxed so that the occurrence of ruptures would be delayed.

It was reasoned that the application of this hypothesis to stamping and temporarily stopping processing could be anticipated to cause strain dispersion to occur, with the result that the forming limit would be extended.

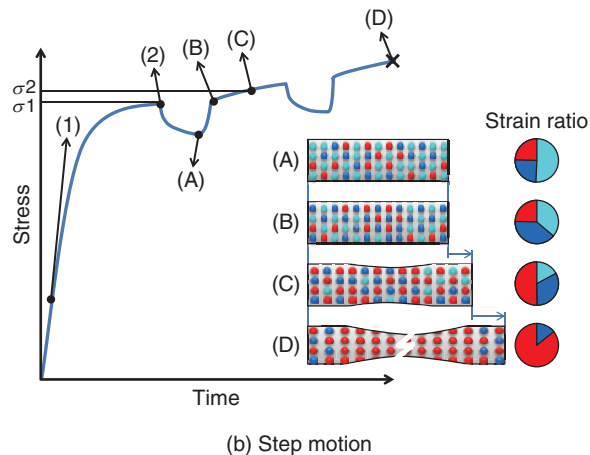
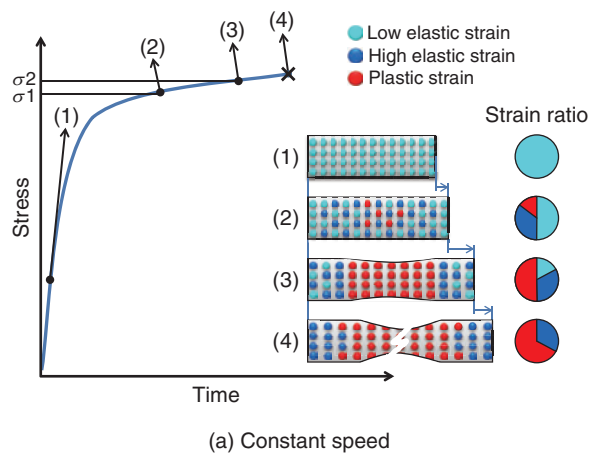


Fig. 2 Concept of forming

Table 1 Test conditions

Item	Data
Blank holding force	100 [kN]
Strokes per minute	1
Blank material	JAC440W 1.4t
	JAC590Y 1.4t

3. Test Method

In order to confirm the effectiveness of strain dispersion, a die with the deep-draw shape was actually used to carry out stamping tests.

3.1. Test Conditions

The test conditions are shown in Table 1.

In ordinary stamping (crank motion), as shown in Fig. 3, the slide position traces a sine wave over time. For the present research, the movement of the die was temporarily stopped during forming in order to promote substitution of elastic strain by plastic strain through the stress relaxation phenomenon. The relationship between time and the slide position is as shown in Fig. 4. Making advantageous use of servo press strengths, the press continued to apply a load even when the die movement was temporarily stopped, and it still performed position control. This stamping method is

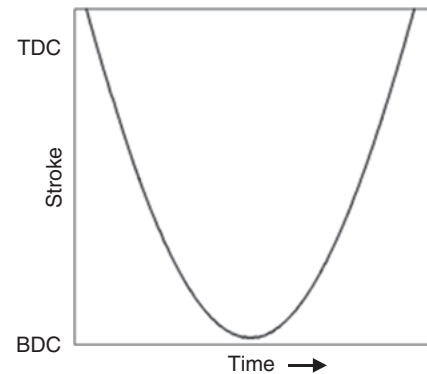


Fig. 3 Motion profile of crank motion

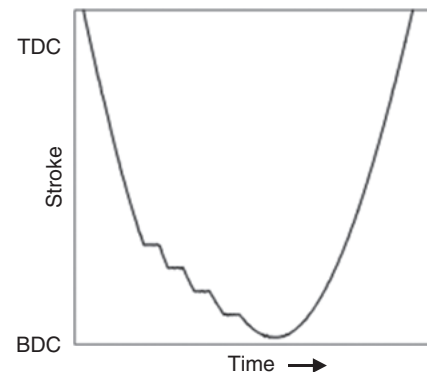


Fig. 4 Motion profile of step motion

referred to in the following as step motion.

The basic stamping stop time was set as 1.0 second. The strain substitution progresses with time, however, so differences in the effects due to stop time were also verified.

There is also the matter of the number of stop iterations. Although the effect can be expected even after one iteration, multiple stop iterations were made (at 5-mm intervals from the start of processing at 10 mm to bottom dead center) in order to make the effect clearer.

The forming depth evaluation method was to increase the forming depth in 5-mm increments. The limit depth where rupture or necking did not occur was identified as the forming limit depth.

Two test materials were used to check the effects of different strengthening mechanisms. JAC440W⁽⁷⁾ was used as a solid solution-strengthened steel, and the DP steel JAC590Y⁽⁷⁾ was used as a structure-strengthened steel.

3.2. Testing Device

Evaluation of deep-draw performance was conducted using the die shown in Fig. 5. The round columns at the bottom of the punch have strain gages attached. Three gages were used to measure the forming load.

Figure 6 shows the blank shape. The sheet is 1.4 mm thick.

The press machine used was an Aida Engineering, Ltd., NC1 2500(D) 2500 kN. This press machine has the advantage that its slide motion can be freely controlled by means of a numerical control (NC) servo mechanism.

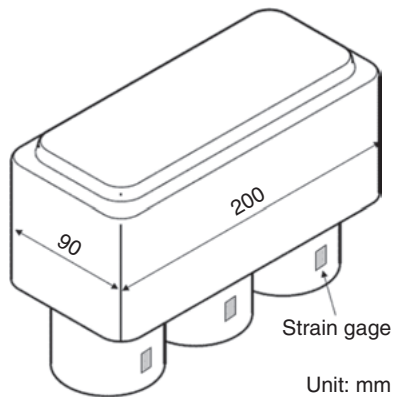


Fig. 5 Punch

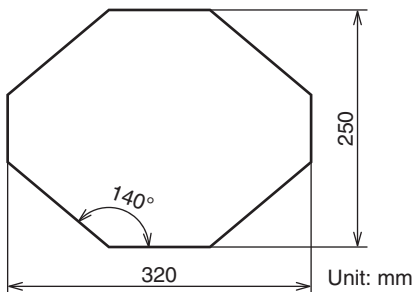


Fig. 6 Blank shape

4. Results and Discussion

4.1. Effects from Application of Step Motion

The result of forming with crank motion using JAC440W are shown in Fig. 7(a), and the result of forming with step motion in Fig. 7(b). With crank motion, forming could proceed to a depth of 60 mm, but a rupture was observed to occur in a corner area at 65 mm. Given the above, the forming limit with crank motion was judged to be 60 mm. When forming was carried out similarly with step motion, forming was able to proceed to a forming depth of 70 mm without any rupture occurring. Given the above results, the application of step motion was found to have the effect of extending the forming limit by approximately 10 mm.

Figure 8 shows forming load with respect to slide position (stroke length) when crank motion and step motion are used. It is apparent from the figure that both crank motion and step motion have generally the same forming load at every slide position. Figure 9, however, shows the changes in forming load with respect to time when using step motion, and it was found from examination of this graph that the forming load relaxes while the press is stopped temporarily during the course of forming. Then, when the stamping die starts moving again, the load recovers to generally the same value it had before stopping, after which the load describes generally the same curve as with crank motion processing.

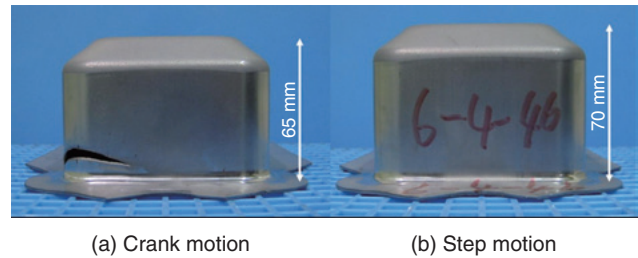


Fig. 7 Results of forming test

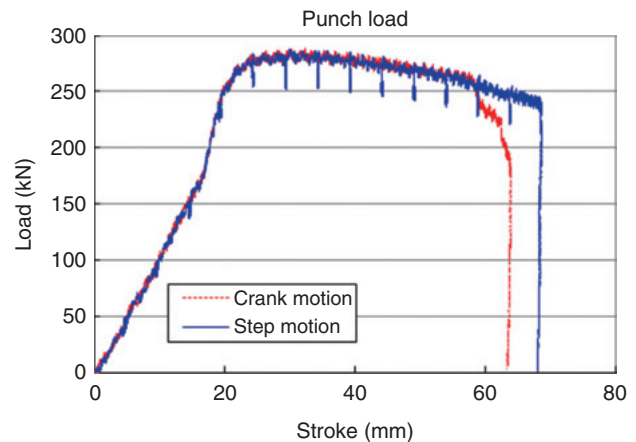


Fig. 8 Forming load in crank motion and step motion

The results of forming tests conducted using JAC590Y show a forming limit of 50 mm with crank motion. With step motion, however, forming was able to proceed to 70 mm. Testing confirmed that formability was enhanced with step motion even in the case of materials with different strengthening mechanisms.

4.2. Influence of Step Motion Stop Time

As discussed above, the strain substitution that occurs with the stress relaxation phenomenon progresses with time. The present results from tests of step motion application show that the load relaxes over time, as well, and it is conceivable that this influences the stop time effect of formability enhancement. In the interest of productivity, it is desirable to shorten stop time to the maximum extent, so verification tests were conducted to determine the shortest necessary stop time that would yield a stampability enhancement effect. Varying stop times of 0, 0.1, 0.3, 0.5, and 1.0 seconds were used, as shown in Fig. 10. The stop time of 0 seconds represents crank motion. Rupture was found to occur with crank motion, but ruptures ceased to occur while necking as a result of localized sheet thinning did occur with stop times of 0.1 and 0.3 seconds. When the stop time was extended to 0.5 seconds and longer, the necking also ceased to occur and forming was able to produce quality parts. It was determined from the above

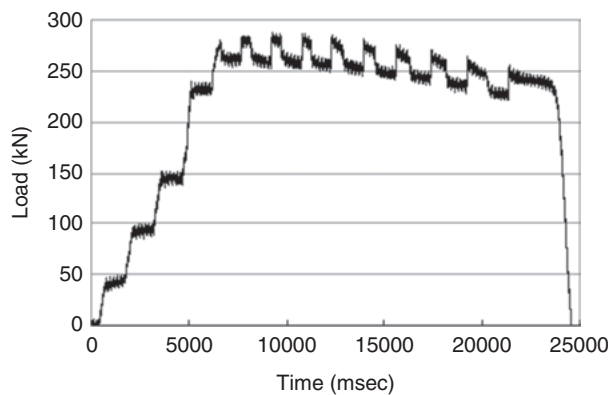


Fig. 9 Forming load in step motion (Time-Load)

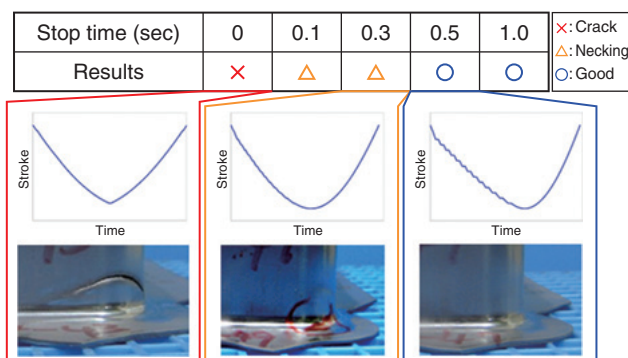


Fig. 10 Influence of stop time

results that the effect of step motion is dependent on stop time, and, with the stamped part shape used here, a die stop time of 0.5 seconds or longer produced stamping products of favorable quality.

4.3. Examination of the Stampability Enhancement Mechanism

Tensile testing with JIS13B test pieces⁽⁸⁾ was carried out in order to verify the influence of step motion on deformation behavior in the material. The test method was to employ two patterns of constant tension speed and step motion in order to confirm the effect of stopping in step motion. In step motion, processing was stopped for 10 seconds for every $\Delta l=1$ or $\Delta l=2$.

Figure 11 shows the stress-strain curves for the two patterns that were tested. As is apparent from the figure, the application of step motion in tensile testing caused the total elongation to increase. The corresponding stresses for the same amounts of strain have the same values here with both constant speed and step motion, and no difference was found between the two.

The sheet thickness distribution in the tensile test pieces was therefore checked in order to verify the influence on rupture of the material. Tensile testing was performed with the two patterns. Test pieces that had the load on them were released when the elongation reached $\Delta l=11$ mm with respect to the distance between reference points (50 mm) were used. The thickness distribution in these test pieces was measured in the longitudinal direction and the results were compared.

As shown in Fig. 12, the pieces tested at a constant speed showed an extreme reduction in thickness only near the middle of the test pieces (maximum rate of reduction in sheet thickness 11.3%). On the other hand, pieces processed using step motion do not show as extreme a reduction in thickness, and even in those parts where the greatest thinning occurred, the rate of reduction in sheet thickness was 9.5%. This thinning occurred in a relatively average manner. A further comparison was then

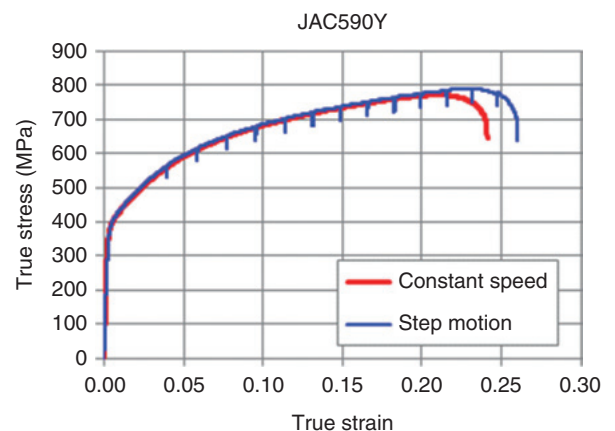


Fig. 11 Strain-stress curve

conducted according to the difference that results when the minimum thinning rate is subtracted from the maximum thinning rate within a range of ± 25 mm from the test piece center. This showed that the application of step motion rather than constant speed in testing suppressed localized deformation to approximately one-third, and confirmed that strain dispersion does have the effect of suppressing local deformation. It can be considered that this change in the type of deformation enabled use of the material's intrinsic deformability to good advantage and increased the total elongation of the material.

4.4. Examination of the Stop Time Dependence of Step Motion

Tensile testing applying step motion was carried out with stop times of 1, 5, and 10 seconds and the thickness distribution was checked in order to verify the time dependence of the deep-drawability enhancement effect found through the stamping tests. First, as shown in Fig. 13, testing with a stop time of 1 second resulted in

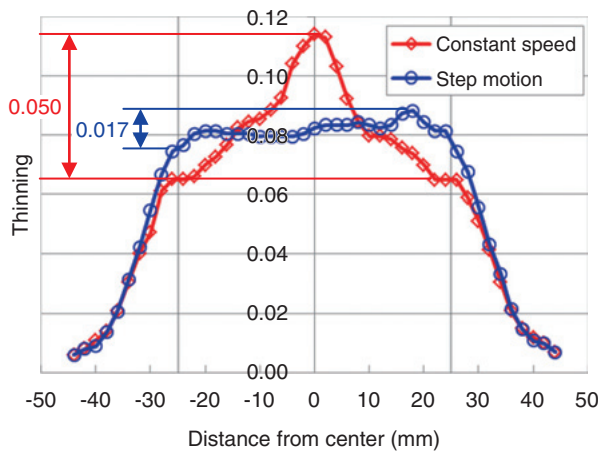


Fig. 12 Comparison of thickness distribution in constant speed and step motion ($\epsilon=22\%$)

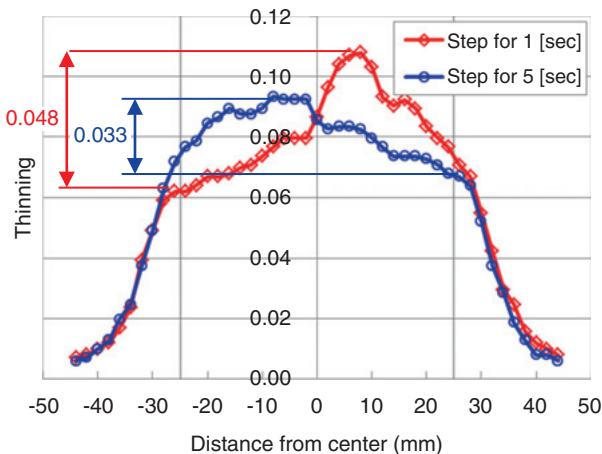


Fig. 13 Comparison of thickness distribution in 1 second stop and 5 second stop ($\epsilon=22\%$)

localized thinning similar to that found when testing with constant speed. The maximum rate of reduction in sheet thickness was 10.8%. Next, when tested with a stop time of 5 seconds, the rate of reduction in sheet thickness was suppressed to 9.2%, and there was a tendency toward suppression of the localized reduction in sheet thickness in comparison with the testing with a stop time of 1 second. Here again, a comparison was conducted according to the difference that results when the minimum thinning rate is subtracted from the maximum thinning rate within a range of ± 25 mm from the test piece center. This showed that local deformation with a stop time of 1 second was generally the same as in testing at a constant speed. With a stop time of 5 seconds, however, the thinning was suppressed to approximately two-thirds. These results confirm that the effect from application of step motion in tensile tests is dependent on the stop time much as it is in stamping tests.

A formability enhancement effect was confirmed in stamping tests with stop times of 0.5 seconds or more, but no such effect was apparent in tensile testing even at 1.0 second. Figure 14 shows the results from comparison of the two in terms of changes in stress when stopped. In the stamping tests, the relaxation of load occurred in an extremely short time by comparison with the tensile testing. With a stop time of 1.0 second, the load relaxation rate was approximately doubled or more.

This difference between the two can be considered to result from the influence of temperature differences or strain speed differences that arise because, while stamping is a high-speed process, tensile testing is conducted at extremely low speed so as to avoid processing heat generation. The influence of strain speed appears unlikely to be a direct factor in this case because the stress relaxation phenomenon is manifested after a temporary stop. Consequently, the influence of temperature was examined as follows.

The magnitude of internal friction with respect to temperature is expressed by F_e in the schematic view

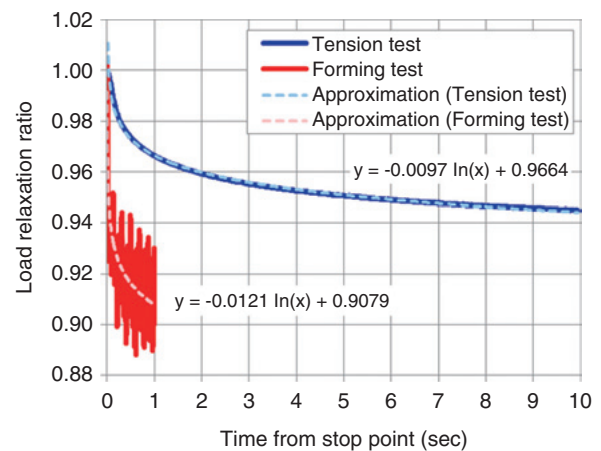


Fig. 14 Time per load relaxation behavior

of Bordoni peaks shown in Fig. 15⁽⁵⁾. It is dependent on temperature and it has two peaks. In order to examine the temperature dependency of the stamping and tensile testing described here, the temperatures of the respective materials used in these tensile tests and in deep-draw stamping were checked against each other, and significant differences in internal frictional force were found to exist, as shown in the figure. It may be inferred specifically that these differences in internal frictional force are closely involved in the stress relaxation time.

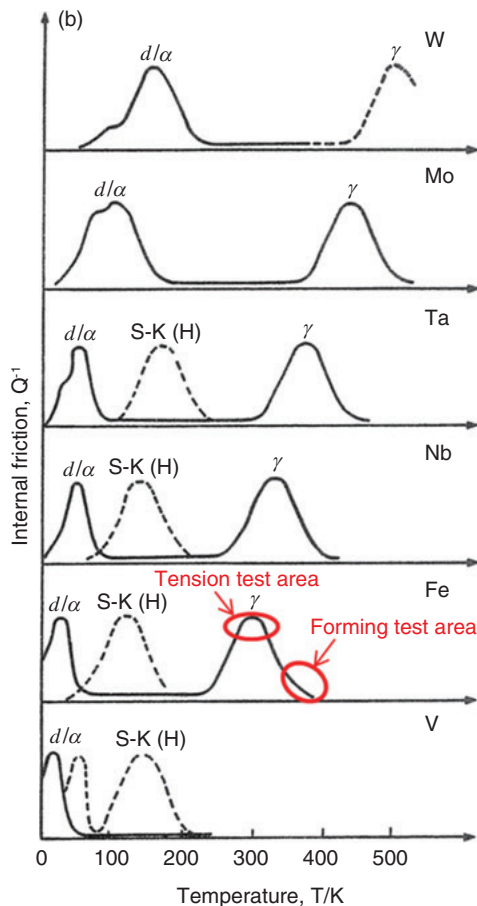


Fig. 15 Image of Bordoni peaks

5. Conclusion

An examination was made of the enhancement of stampability by means of strain dispersion that makes use of the stress relaxation phenomenon. The following conclusions were reached as a result:

- (1) The introduction of step motion in stamping so as to generate stress relaxation by temporarily stopping the die during processing caused a 40% increase in the forming limit depth.
- (2) The suppression of local deformation was confirmed to take place in tensile testing conducted to recreate a step motion, in contrast with tensile testing at constant speed.

- (3) Tensile tests and stamping tests confirmed that step motion has the effect of extending the forming limit and that this effect is dependent on the temporary stop time.

Given the above, the dispersion of strain using the stress relaxation phenomenon, which was presented as a hypothesis, was found to be effective in enhancing formability.

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