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Mechanism of Forming the Smooth Sheared Surface in the Shearing Processes*

(2nd Report, Proposed Methods for Improvement of the Sheared Surface Quality)

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This report deals with the development of a new precision shearing process based on the cutting mechanism for the formation of a smooth surface.

At first, a shearing method which shears two piled specimens and another method which uses negative clearance for this purpose are tried. And, it is confirmed that the negative clearance method can enlarge remarkably the range in which the cutting mechanism is realized and it is applicable to a practical precision shearing process as a principle of forming the smooth sheared surface.

Finally, "Opposed dies shearing process" is proposed as a new precision shearing process. This process is quite different in its principle from the conventional precision shearing processes, and has many features, among which, suppression of the burr, applicability to brittle materials and the prolongation of the tool life may be the most dominant.

1. Introduction

In the previous report, the mechanism of forming the smooth surface has been fundamentally investigated and characteristics and the realizable range of the mechanism by plastic deformation, the cutting mechanism and the intermediate quasi cutting mechanism were made clear⁽¹⁾.

In this report, features of these mechanisms as a fundamental principle of a precision shearing process are investigated and the development of a new precision shearing process which utilizes the mechanism by cutting is dealt with.

2. Considerations about the fundamental principle of the precision shearing processes

In the shearing condition when the mechanism of forming the smooth surface by plastic deformation takes place, severely shear deformed plane caused by the penetration of the tools in the specimen occurs in the direction which connects the two cutting edges. This shear plane coincides with the

contour section of the blank, so the shear deformation must be done on the same plane throughout a process. Consequently, the amount of the shear deformation which is necessary to cause separation becomes extremely large and the most materials used in the shearing can not sustain this amount and are fractured during working. In order to utilize the mechanism by plastic deformation as a principle of a precision shearing, it is necessary to increase the ductility or plastic deformability of the material so as to sustain this large deformation. Several precision shearing processes which have been developed realize this by increasing positively the hydrostatic pressure in the material near the cutting edges through strengthening the restriction of the specimen by tools^{(1) (3)}.

On the other hand, in the cases when the conventional cutting mechanism takes place, severe shear deformation caused by the penetration of the tools occurs along the shear plane in the stock which starts from the die edge and passes through to the edge plane of the stock. This shear plane moves to a new position in the material according to the punch travel, so the amount of the shear deformation which is required for each material part becomes relatively small and the most materials used in the shearing can sustain this amount of deformation. In addition, since the shear plane in the stock

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has an inclination to the contour section of the blank by the amount of the shear angle, there does not remain any chance for the fractured surface to be formed directly on the blank even in the cases when the fracture initiates on the shear plane. From these facts we can surmise that the cutting mechanism has essentially more desirable conditions as to the application range concerning the mechanical properties of the materials than the mechanism by plastic deformation. Moreover, it is not necessary to apply the above-mentioned hydrostatic pressure in utilizing the cutting mechanism, so the cutting mechanism may be called preferable as to the working load, too. These are the main reasons why the cutting mechanism is adopted as a fundamental principle of a new precision shearing process in this investigation.

In order to adopt the cutting mechanism in a precision shearing, the narrowness of the application range concerning the stock length becomes the most serious difficulty. It is on account of this point that the shaving process is limited to a special use. Quasi cutting mechanism which is mentioned in the previous report⁽⁵⁾ may slightly widen the application range concerning the stock length. But this mechanism is much more important because it indicates the facts that there exist some cases in which the severely shear deformed plane can direct towards the stock side in the other cases than conventional cutting process and the smooth surface can be formed provided that the shear deformed plane directs towards the stock side at the die edge.

In the following, we describe the development of a new precision shearing process intended for the formation of the shear plane directed towards the stock side at the die edge throughout a process utilizing either the cutting mechanism or the quasi cutting mechanism to enlarge the application range concerning the stock length.

Fig. 1 Shearing of two piled specimens

3. Shearing of two piled specimens

3.1 Experimental method

In a shaving process, fracture crack may occur when the stock heaps as a chip on the die face and its removal becomes difficult with progress of the punch. So, if the removal of the stock were promoted, the application range of the shaving would be enlarged. But in the range of the shorter stock like this, it is difficult to apply a force to promote the removal of the stock. So, the author conceived a shearing method which sheared two piled specimens from the following simple consideration. That is, when a certain length of the stock must be removed, the ratio of the stock length to the sheet thickness can be reduced by half and the application range of the stock length in the shaving process (shorter than 10 % of the sheet thickness⁽⁵⁾) can be enlarged two times if the two specimens are piled as a single specimen.

The method is very simple, that is, two specimens of the same size are piled one upon the other and sheared together using conventional shearing tools as are shown in Fig. 1. In this case, two specimens are stuck to each other with tallow which is the same lubricant as applied to the tools to secure its piling. In this method, two specimens are named the upper sheet and the lower sheet, respectively, as shown in the figure and distinguished from each other. Apparatus and experimental conditions are the same as those of the previous report^{(4) (5)}.

3.2 Experimental results

Effects of the stock length on the quality of the sheared surface were examined in the same conditions as those of the previous report excepting that the specimens were piled one upon the other. The

Stock length (ratio to the sheet thickness) $l/t \times 100\%$
Experimental conditions

Material: Hard aluminium AlP3-H, 1.00 mm thick

Clearance: 6 % of sheet thickness

Lubricant: Tallow

Supporting condition: Free support

Fig. 2 Quality of the sheared surface (shearing of two piled specimens)

results obtained are shown in Fig. 2. Surface quality of the lower sheet is remarkably improved as compared with the cases of conventional shearing (shown by a solid line in the figure) and it is possible to finish it smooth throughout the thickness when the stock length is shorter than 60 % of the sheet thickness (% representation always shows the ratio to the thickness of a sheet in this report). But the effect of piling decreases rapidly when the stock length exceeds this range. In these experiments, the surface quality of the upper sheet is scarcely improved in the region of shorter stock and slightly improved in the region of longer stock.

3.3 Considerations of experimental results

Now, we consider the mechanism of the improvement of the sheared surface quality in this shearing method. At first, according to the original conception, it attracts our attention whether the expected effect that the ratio of the stock length to the sheet thickness can decrease by piling, is realized or not. In Fig. 3, the surface quality of the lower sheet is compared with that of the two times thicker specimen (2 mm) in the conventional shearing. The surface quality of the lower sheet

Fig. 3 Comparison with the cases of two times thicker specimens

can be compared with the lower half 1 mm of the 2 mm thick specimen. In the figure, the range of the stock length in which the smooth surface more than 1 mm can be formed in a 2 mm thick specimen is less than 0.55 mm (27.5 %) and this limit is about 0.6 mm (60 %), that is, the limit in which the sheared surface of the lower sheet in the piled shearing can be finished smooth throughout the thickness. Next, we compare them with respect to the mechanisms of forming the smooth surface. In this method, when the stock length is 50 %, the rolling fibers of the specimen in the sheared surface are cut off without distortion and the smooth surface is formed by cutting mechanism, as is shown in Fig. 4 (a). It is shown in the previous report⁽⁵⁾ that in conventional shearing the sheared surface is formed by the mechanism by plastic deformation when the stock length is 50 %, and is formed mainly by cutting mechanism when the stock length is shorter than 30 % [Fig. 4 (c)]. Thus, it is understood that the improvement of the sheared surface quality in the piled shearing can be mainly attributed to the relative decreasing effect of the stock length.

In the above, the reason for the improvement of the surface quality of the lower specimen has been discussed assuming that the upper and lower specimen behave as a single specimen. Now, we consider them only from a view point of the lower specimen. As the normal pressure acts on the BC plane of the lower specimen in Fig. 1 owing to the piling of the upper specimen, the resistance for the removal of the stock increases and the hydrostatic pressure in the stock increases. The increase of the hydrostatic pressure itself is not favourable for the realization of the cutting mechanism, but in this case it is necessary to shear-deform simultaneously along AB plane in the upper specimen to realize the shear deformation along EB plane in Fig. 1.

So, the realization of the shear deformation along the shear plane which passes through to CD edge plane is far easier than the shearing along EB plane in spite of the increase of the resistance for the removal of the stock owing to the addition of the compressive stress. This fact is thought to be contributing to the realization of the cutting mechanism.

Next, we consider the deformation processes comparing with the working load. Figure 5 shows the punch load diagram corresponding to Fig. 2 and represents

Fig. 4 Internal deformation states of the sheared surface

the stages until the separation of the lower specimen is completed. In the figure, for instance in the case of 20 % stock length, an increase of the vertical load P_V can be seen after the stage of about 80 % punch travel. This increasing stage of P_V moves towards the earlier stage with an increasing stock length. This stage corresponds to the deformation process when the shear plane shifts from ED plane which passes through to CD edge plane towards a plane which passes through to BC sheet plane in Fig. 1 and the deformation reaches into the upper specimen. Then, the horizontal load P_H scarcely changes at and after corresponding stage in the cases of shorter stock in Fig. 5. This shows the fact that the deformation is limited only to a part of the upper specimen and does not reach the punch edge. But, when the stock length is 60 %, P_H increases continuously after the corresponding stage. This continuous increase of P_H is attributed to the influence of P_H' component which acts normally on the punch flank and shows the occurrence of the penetration of the punch edge to the upper specimen. So, the mechanism of forming the smooth surface shifts to the quasi cutting mechanism and further to the mechanism by plastic deformation after this stage. In these working conditions,

Experimental conditions

Material: Hard aluminium AlP3-H, 1 mm thick

Shearing contour length: 20.0 mm $\times$ 2

Clearance: 6 % of sheet thickness

Lubricant: Tallow

Supporting condition: Free support

Fig. 5 Punch load diagram (shearing of two piled specimens)

when the penetration of the punch edge already begins in the working stage of the lower specimen, a sufficient effect of the piling of the upper specimen can not be expected. The case of 60 % stock length is the limit to which the lower specimen can be finished smooth throughout the thickness, as was mentioned in Fig. 2. In this case, internal fiber of the smooth surface already begins to distort and a bulge can be seen on the upper plane in Fig. 6.

As mentioned above, surface quality only of the lower specimen is improved in this piled shearing. But, if punch travel may stop immediately after separation of the lower specimen, the upper specimen is distorted only slightly. So, we thought that if was possible to use this upper specimen repeatedly by setting the stopping stage of the punch travel exactly. But, we were pointed out that there had been a shaving process in which a half of a specimen was shaved at first, the next specimen was piled on it and shaved by half of the thickness successively⁽²⁾. So, this piled shearing method was not new.

4. Shearing method which uses negative clearance

4.1 Experimental method

Piled shearing method is not convenient for practice because the upper specimen must be left uncut in each stroke and the piling work itself is troublesome. So, we try another shearing method in which the punch is overlapped on the stock part of the specimen instead of the upper specimen of the piled shearing, that is, a negative clearance is given (Fig. 7). Naturally, the die and other working conditions are the same as those of the former section. In this method, the stock is compressed by the punch and die face at the later stage and its separation is not completed. But, as the distortion of the punch which is similar to the deformation of the upper specimen in the piled shearing

Fig. 6 Deformation of the sheared surface in piled shearing (stock length: 60 %)

does not occur, the deformation of the specimen is well controlled by the punch even in the case of longer stock and the effect of improving the surface quality is remarkable.

4.2 Experimental results

In this method, the magnitude of the negative clearance must be decided at first. Now, the problem of the completion of the separation is left till next section and the process is supposed to be completed at the stage where the stock is left uncut by about 0.01 mm thick, for a while. And the work is judged to be a success when a fracture is not found on the sheared surface until this stage. Figure 8 shows the applicability of this method concerning the magnitude of the clearance and the stock length. Specimens of this experiment are A1P3-H 1 mm thick. From this figure, it is seen that a smooth sheared surface can be formed regardless of the stock length, if the clearance is selected below -20 %. And, in the case of -10 % clearance,

Fig. 7 Shearing method which uses negative clearance

a smooth sheared surface can be obtained when the stock length is less than 30 %, but a relatively shallow groove fracture occurs and a secondary shear takes place when the stock becomes longer. Further, the region of mark × shows the case when an ordinary fracture occurs. Chain line in the figure shows the critical stock length above which the working load or deformation states become identical in each clearance regardless of the stock length.

4.3 Considerations of the experimental results

Here, we discuss about the mechanism of the improvement of the surface quality in this method. In order to understand the forming process of the

Fig. 8 Application range of the negative clearance method

(a) Penetration 41.5 % (b) Penetration 64.0 % (c) Penetration 95.0 %

Fig. 9 Deformation process of the specimen in the negative clearance method
(In the case of clearance -30 % and stock length 30 %)

sheared surface, internal deformation states during working are observed on an example of 30 % stock length and -30 % clearance (Fig. 9). A shear plane which passes through to the edge plane of the stock can be seen and conventional cutting takes place in the earlier stages as expected [Fig. (a)]. In the next stage, the shear plane shifts towards a plane which connects two cutting edges. This plane inclines by θ degree to the shearing contour section because negative clearance is adopted [Fig. (b)]. The magnitude of θ naturally increases with punch travel, so the shear plane also moves in the material with it. When θ increases over 45° , deformation states become similar to that of forging in which material flow is restricted to one direction [Fig. (c)].

Next, we examine what kinds of changes have been brought about on the punch load by these changes of the deformation process. Figures 10 and 11 show the punch load curves in the cases when the clearance is altered by setting the stock length to 30 % and when the stock length is altered by setting the clearance to -10 %, respectively. Among these curves, the load curve corresponding to Fig. 9 is the one shown by a solid line in Fig. 10. But, the features of the changes in the load curves are clearly observed in Fig. 11, so we proceed our consideration about this.

In the figure, the vertical load P_v takes a nearly constant value which is decided by the stock length during earlier cutting stages. But, after the stage

when the shear deformation plane is set on a plane which connects two cutting edges (plane AD in Fig. 7), it decreases at a constant rate which is decided by the magnitude of the negative clearance. Further, in the forging-like stage, the punch load increases rapidly because the thickness of the stock is reduced. These changes of the deformation states can occur when another easier mode of the deformation which can be realized by lighter load appears during working. In the case of this figure, the change from the earlier cutting stage to the shear deformation stage along AD plane happens earlier when the stock is long and the earlier cutting load is large. When the stock length exceeds 50 %, punch penetration proceeds on the AD plane from the first stage and in these cases identical punch load curves are obtained regardless of the stock length. It is interesting to note that the load curves become identical after progress in the stage and the shear plane AD is formed even in the cases when the initial cutting stage appears. This is because the shear plane is decided by the magnitude of the negative clearance and moves continuously to a new undeformed portion of the specimen.

In the above, a severely shear deformed plane can be estimated easily during working, so the progress of the vertical load P_v can be calculated from the following Eq. (1) if we assume that the penetration of the cutting edges takes place using only this shear plane and the shearing resistance k along this plane is given. Equation (1) is derived from the consideration that the component of P_v

and the horizontal force $\mu P_V'$ in the direction of AD are equal to the shearing resistance along this plane. Further, the load in the later stage is calculated from Eq. (2) which is known to correspond to the deformation states of the flat plate forging in Fig. 9 (c).

$$P_V = 2k \left(\frac{s^2 + c^2}{s - \mu c} \right) b \dots \dots \dots (1)$$

$$P_V = 4k \left(1 + \frac{\mu c}{s} \right) bc \dots \dots \dots (2)$$

where s : distance between punch and die face
 c : magnitude of negative clearance (absolute value)
 b : sheet width
 μ : coefficient of friction.

Magnitude of k of the test specimen which is derived from tensile test is 10 kg/mm^2 , but we give a constant value of 13 kg/mm^2 to it as estimated from one of the experimental load because the increase of the shearing resistance owing to the spread of the shear deformed region may naturally be included. Then, the calculated load becomes like the fine line in Fig. 12. Although gradients of the curves are slightly different from those of experimental curves because the calculation is much simplified, the progress of the load curves and the differences between conditions of clearance fairly well coincide with experimental results. So, it is seen that the state of actual deformation has been well estimated.

Based on the above understanding of the deformation process, application conditions of this method are examined in Figs. 10 and 11. Initiation stages of the fracture crack are marked by solid circles in the figure. Fracture cracks do not occur during initial cutting stages but always do in the stage when the shear plane is set on the AD plane and in the cases when the horizontal load increases rapidly. This rapid increase of P_H is also attributed to the influence of P_H' component which acts on the

punch flank quite the same as in the cases of the former section. So, in these cases fracture cracks are suppressed if the direction of the removal of the stock is outward inclined by increasing the amount of overlapping of the punch and die face in Fig. 10 and if the amount of overlapping of the punch is increased relative to the stock length by decreasing the stock length in Fig. 11. These results mean that sheared surfaces are improved if the inclination θ of the shear planes is selected larger to some extent in Fig. 7. It is thought that this is because the hydrostatic pressure is superposed on the shear plane owing to the overlapping of the punch face and the fracture crack is suppressed by it. When the inclination θ becomes much larger, a fracture does not occur directly on the sheared surface of the blank even if a fracture crack initiates along this inclined shear plane. In this shearing method, internal rolling fiber of the sheared surface is scarcely distorted just as in the cases of conventional cutting, because the shear deformation plane is always inclined towards the stock and the punch edge does not penetrate into the specimen (Fig. 9).

Although the problem of the completion of separation remains, this shearing method has a remarkable effect for the suppression of the fracture crack and has wider applicabilities.

5. Opposed dies shearing process

5.1 Working principle and method

In the former section, it has been confirmed that a smooth sheared surface could be formed by cutting or quasi cutting mechanism using a negative clearance even in the cases of longer stock. But the problem of the completion of separation of the blank is not solved. In this section, we try to complete this separation and simultaneously to solve the problem of suppression of the burr which is one of the most troublesome problems in the several conventional precision shearing processes. For this purpose, a new precision shearing process named "Opposed dies shearing" is proposed.

Tools used in this process, are a conventional die, a protruding die which opposes the former and a knockout tool, for example in the case of blanking. This process is characterized by the use of such an opposing tool with a protrusion. Arrangement of the tools and the order of the tool action are schematically shown in Fig. 13. When the die descends, at first a shear deformed plane is formed in the plane of material that connects the die edge A and the outer edge of the protruded die B and cutting proceeds from the die edge side solely by means of the cutting mechanism [Fig. (b)]. In this case, penetration of the protruding die into the

Fig. 12 Estimation of the punch load

specimen scarcely occurs if the width of a plane portion at the top of the protruding die is selected to have more than a certain value, so a smooth surface is formed by the same mechanism as the foregoing negative clearance method. Then, operation proceeds to the aforementioned sheet forging-like stage and penetration of the protruding die begins. After this stage, the working load increases rapidly and an undesirable bulge of the blank occurs under certain conditions. So, the cutting by the die must be stopped before this stage [Fig. (c)] and then knockout proceeds and separates the blank [Fig. (d)]. In this separating stage, the stock is pinched between the two dies and is subjected to a hydrostatic pressure high enough to preclude any possibility of initiating a fracture. Further in this case, burring is suppressed by the penetration of the protruding die and if the working direction of

Fig. 13 Illustration of the opposed shearing process

knockout is taken in the direction indicated by arrow mark, burring is suppressed regardless of the existence of this penetration.

This process can be applied not only to the blanking but also to the punching when a set of punch and protruding opposed punch is used. In this case, it is necessary to use additional means such as a prepunched hole to make it possible to remove the stock.

5.2 An example of experimental result

An example of the blank which was blanked by this process is shown in Fig. 14. Specimen is a strip of 1 mm thick, hard-tempered commercially pure aluminium and the diameter of the blank is 18 mm. Top width of the protruding die is 40 % of the sheet thickness. When the same specimen is blanked by the conventional blanking tools, a fractured portion of about 70 % of the thickness is formed, but in this process a smooth surface is formed throughout the thickness as is shown in the figure.

When this process is applied, appropriate selection of the following working conditions becomes necessary, but examinations of these conditions will be made in another report.

(1) Shape of the protruding tool (especially, width of the protruding top).

(2) Initiation stage of knockout.

(3) Means for the removal of the stock.

5.3 Features of the opposed dies shearing process

It may be obvious even from the fundamental considerations that this process has the following features in addition to the attainment of the smooth sheared surface without fracture and burr.

(1) It is possible to work with less load than conventional shearing method because of the use of the cutting mechanism.

(2) It is possible to prolong the tool life because of (1) and the fact that tool wear does not cause the initiation of the burr in this process.

(3) It is applicable to brittle materials.

(4) There is less likelihood of the roll-over of the sheared edge taking place because of the ease of tool penetration.

Fig. 14 Typical blanked component by the opposed dies shearing process

In the above, as to the applicability to brittle materials, it has been confirmed that this process can be applied successfully to phenolic resin laminates and epoxy resin laminates. This process has features which are essentially different from those of conventional precision shearing processes as enumerated above, so it is expected to be utilized as a new precision shearing process.

6. Conclusions

Development of a new precision shearing process which utilizes positively the cutting or quasi cutting mechanism of forming the smooth surface has been attempted with the following results.

At first, it was confirmed that the realizable range of cutting mechanism could be enlarged by shearing two piled specimens and the application range as to the stock length could also be enlarged. To make this piling effect more effective, a shearing method which used negative clearance was thought of. By this method, application range as to the stock length was enlarged remarkably and it

was considered to be practically useful as a process of forming the smooth surface portion. Next, utilizing this principle of forming the smooth surface and adding a means of suppressing the burr, an opposed dies shearing process was proposed as a new precision shearing process.

This process is quite different in its working principle from the conventional precision shearing processes and has new features which can overcome difficulties of conventional processes. Among these features, the most prominent are suppression of the burr, applicability to brittle materials and the prolongation of the tool life.

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Author	Page	Column	Line	For	Read
S. OGINO	360	left	10	<i>m-pol</i>	<i>m-ple</i>
H. ŌSAKI et al.	479	right	19 from the bottom	(1690-5)	(1960-5)