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Basic Studies of Plastic Working with Vibration*

(1st Report, Ultrasonic Vibro-Indentation Hardness of Carbon Steels)

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In this report, "ultrasonic vibro-Brinell hardness H_{UB} " is defined in order to estimate the resistance to the plastic deformation of materials under the ultrasonic pulsating loads. The ultrasonic vibro-indentation hardness testing (20 kHz, 500 W, the ratio of the load amplitude and the mean indentation load: $P_a/P_m=0.5$) of annealed carbon steels (0.15 % and 0.55 % carbon included respectively) with a spherical indenter, made of hardened steel, was performed. Experimental results show that this testing method is useful as a simulative test of the plastic working under the ultrasonic pulsating compressive load, and that for the same material the differences of the estimating methods of the vibro-indentation load give different results, as "vibro-softening" or "vibro-hardening".

1. Introduction

Recently the application of the ultrasonic power to the plastic working has developed rapidly and a lot of basic and applied researches have been done in the United States⁽¹⁾, Soviet Russia⁽¹⁰⁾ and some other countries. As far as we investigated, the effects of the ultrasonic vibration on the plastic working are summarized as follows.

(1) The resistance to the plastic deformation of a material is reduced according to the intensity of the ultrasonic vibration loaded. (so called "vibro softening.")

(2) The coefficient of friction at the contact surface between tool and work reduces, which corresponds to the apparent good lubrication.

(3) The physical and mechanical properties of the material may change after the ultrasonic radiation (so called "after effect").

(4) Those effects described above result in an increased formability and working speed, and a reduction of the plastic working force. The improvement on the dimensional accuracy of the work is also attained by the reduction of springback^{(1)~(4)}.

From the viewpoint of the material testing for the vibroplastic working, it is necessary to develop a practical testing method for measuring the formability of the material under vibration. We have noticed the usefulness and convenience of the hard-

ness test. In this report we will propose a new testing method named "vibro-indentation hardness test" for this purpose and examine experimentally the possibility of the method. On the other hand, since there have been many discussions about the mechanism of the vibro softening, we will further examine it under superposition of the oscillating load.

2. Ultrasonic vibro-indentation hardness

Taking into account the fact that the Brinell hardness test gave the basic concept of the indentation hardness, we adopt the same method and define the "ultrasonic vibro-Brinell hardness" as

$$H_{UB} = \frac{2P}{\pi D^2 \{1 - \sqrt{1 - (d/D)^2}\}} \quad \dots\dots\dots (1)$$

where P is the indentation load under vibration (Fig. 1) and d is the chordal diameter of the indentation, and D is the diameter of the spherical indenter. We think there are three types of the vibro indentation that analogize the actual vibro formings or at least are related to them. They

Fig. 1

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are illustrated in Fig. 1 and we take this time a case (a) in which the directions of indentation and vibration are the same. Hence if P_m is a fixed normal load (or the mean load) and P_a is the amplitude of the vibrating load and ω is the angular velocity of vibration,

$$P = P_m + P_a \sin \omega t$$

or

$$P/P_m = 1 + (P_a/P_m) \sin \omega t$$

Loading diagram is shown in Fig. 2. Since the angular velocity is kept constant, the effect of vibration on the hardness value may be evaluated by the amplitude P_a and the equivalent load modulus α as

$$P = P_m + \alpha P_a \quad \dots\dots\dots (2)$$

or

$$P/P_m = 1 + \alpha (P_a/P_m)$$

If the after effect is assumed to be negligible, α will take a value between zero and unity, which corresponds to $P = P_m$ and $P = P_m + P_a$ respectively. While the shape and size of the indentation formed depend on the intensity of the vibration P_a (or

P_a/P_m), either the numerator or the denominator in Eq. (1) is a function of P_a (or P_a/P_m). These relations will be investigated by the following experiments.

3. Apparatus and test piece

Experimental apparatus

Referring to Eq. (1), the instruments for measuring P_m , P_a and d are necessary in addition to ones for the ultrasonic vibro indentation described above. Figure 3 shows the testing machine and the instruments which will be mentioned in every chapter of the report. The detail of the apparatus and their vibration mode in no-load condition ($P=0$) are shown in Fig. 4. The static indentation force is loaded by a universal testing machine (Shimazu, REH-50) and measured with an elastic loop tester shown in Fig. 4-⑨. The ultrasonic vibration is generated with the combination of a wide range oscillator (Choonpa-Kogyo, USV-500V) and a ferrite transducer shown in Fig. 4-①. The amplitude of the longitudinal vibration generated with the transducer is magnified with the couplers in several steps, and finally the peak to peak value of 60×10^{-3} mm is obtained under the condition of $P_m=0$. A hard steel ball indenter ($D=5$ mm) is in contact with the edge of the conical hole drilled on the end surface of the coupler (Fig. 5). The test piece which (18×17 mm) is placed on the brass cylinder (60×87.6 mm) with high resonant frequency restricts the vibration of the indenter under the condition of $P_m \neq 0$, and a vibrating load arises

Fig. 2

Fig. 3

Fig. 4

at the indenter. Due to the inertia of the anvil and the loop-tester itself, the pointer of the loop-tester doesn't respond to the ultrasonic oscillating load at all. Therefore the static load measured with the loop-tester is regarded as the mean indentation load. The vibrating system is supported at the nodal point by a flange through which the static force P_m is loaded. Since the resonant frequency of the system changes slightly with the indentation, it is necessary to adjust the oscillating frequency of the oscillator so as to make the system resonate during the indentation. The distribution of the displacement amplitude measured with a

Fig. 5

Fig. 6

microscope is shown in Fig. 5. It is seen that the brass cylinder acts effectively as a non-resonant anvil. The amplitude of the oscillating load P_a is measured by the combination of a piezo-electric pickup (VPZ, $18^\circ \times 1$, 111 kHz) and an oscilloscope (Iwasaki-Tsushinki, SS 5003). The calibration of the measured value is performed with the calibrated load-cell in a low frequency range (50 Hz) using the equipment shown in Fig. 7. The chordal diameter of the indentation d is measured with a microscope attached to the Micro-Vickers hardness tester (Akashi MVK). The quantity d_m is the average value of d measured along two perpendicular directions. Furthermore the vertical contour of the indentation is measured with the combination of a measuring table with a micrometer and a dialgauge.

Test piece

Among many kinds of structural materials we choose a low carbon steel and a medium carbon steel for their broad utility (Table 1). The test piece is lathed to cylindrical shape ($18^\circ \times 17$ mm), vacuum annealed in 2 hours at 850°C , and gradually cooled in the vacuum furnace, then the testing surfaces are ground. When an especially precise finish is required for the measurement of the contour of the indentation, the test surface is polished furthermore.

Testing method

Before testing, the testing surface and the indenter are cleaned out with benzine to keep the unlubricated condition. As it is seen in Fig. 2 the

Fig. 7

Table 1

Chemical Composition	C $\times 100$	Si $\times 100$	Mn $\times 100$	P $\times 1000$	S $\times 1000$	Cu $\times 100$	Ni $\times 100$	Cr $\times 100$
S15C (standard)	13~18	15~35	30~60	<30	<35	<30	<20	<20
Test piece	15	18	40	11	22	22	7	10
S55C (standard)	52~58	15~35	60~90	<30	<35	<30	<20	<20
Test piece	55	21	69	12	19	16	6	13

loading process consists of two steps; loading statically up to P_m , then increasing the ultrasonic vibration up to P_a . After holding P_m and P_a constant for 120 seconds the dynamic load is removed, then the static load is unloaded. We take the condition of $P_m=750$ kg and $P_a/P_m=0\sim0.5$ this time. All of these conditions are kept constant manually.

4. Experimental results and considerations

4.1 Vibro-softening

As stated in the introduction the central problem of this study is to reproduce the vibrosoftening in the hardness test and clarify its mechanism from the view point of the strength of materials. Hence it is necessary to clarify the condition under which the vibrosoftening was observed. As far as we investigated the vibro-softening was always observed as the reduction of the static or quasi-static load required to deform the materials. In other words the dynamic load was not considered in the observation of the vibro-softening, which

Fig. 8

Fig. 9

corresponds to putting $\alpha=0$ in our case. Therefore the numerator of Eq. (1) becomes $P=P_m$ constant and the effect of the vibration will appear only in the denominator. Since the denominator is a function of the chordal diameter d the effect will appear in the quantity d . The experimental relation between the chordal diameter and the load amplitude is shown in Fig. 8. Both of the quantities are normalized with the diameter of the indenter D and the static indentation load P_m respectively in the figure. It is evident from the figure that the chordal diameter increases with an increasing load amplitude P_a . As the result the vibro-Brinell hardness H_{UB}/H_B decreases with an increasing P_a/P_m (Fig. 9), which we regard as the "vibrosoftening" described above. It is also evident that the two kinds of steel show a similar tendency in Fig. 9. Now we investigate the change of the relation caused by taking the dynamic load P_a into account. If we put $\alpha=1$ or $P=P_m+P_a$ in Eq. (1), the effect due to the oscillating load will be compensated between the numerator and the denominator of Eq. (1). Referring to the experimental results about the actual load in the low cycle tension test⁽⁶⁾, the value of $H_{UB\alpha=1}/H_B$ must approximately equal to unity. However the results show that $H_{UB\alpha=1}/H_B$ increases with P_a/P_m as illustrated in Fig. 9. In other words the size of the indentation formed with the ultrasonic oscillating load is smaller than the one formed statically with its peak load P_m+P_a . Therefore we conclude that the "vibro-softening" described above is nothing but an "apparent" phenomenon due to the estimating method of the load P . We define the "true vibro-softening" as a decreasing of H_{UB}/H_B with an increasing P_a/P_m even for $\alpha=1$ (Fig. 10-A). If we get the case (B) for $\alpha=1$, it means that the true resistance for the plastic deformation does not change in both static and dynamic inden-

Fig. 10

tation. Under the condition of $\alpha=1$, the causes for the case (C) can be reduced to

(1) Hardening of the material itself due to the ultrasonic vibration (so called "after effect"), and

(2) The strain rate effect on the plastic deformation.

In order to confirm the principal cause, the presence of the after effect was investigated with the micro-Vickers hardness tester. The hardness distribution along the vertical contour of the indentation is illustrated in Fig. 11. Figure 12 shows the relation between the hardness at the bottom of the indentation and the intensity of the vibration P_a/P_m . Though the hardness values illustrated in the figure are the average of three or four measurements, the test results are still scattered, which may be attributed to the difference in the original state of the specimen. In order to avoid these errors we calculate the difference of H_{MV} at the bottom of the indentation and at the undeformed portion of the same specimen, and illustrate them against P_a/P_m in the same figure. Although the experimental values are slightly scattered yet, the dependence of ΔH_{MV} on P_a/P_m seems to be negligible as a whole. Since the extent of the after

Fig. 11

Fig. 12

effect seems to be dependent on the intensity of the ultrasonic vibration loaded, we conclude that the after effect is negligible in our case. Therefore the cause (2) mentioned above seems to be the principal cause of getting Fig. 10 (C).

Load superposition hypothesis

Japanese scientists, F. Fujimori and M. Yamamoto confirmed from their experiments on the absolute measurement of the acoustic stress^{(7) (8)} that the stress superposition hypothesis proposed by Nevill and Brotzen⁽⁵⁾ should be modified in case of the ultrasonic vibroplasticity. They introduced a parameter named "reduction coefficient ϕ " as the ratio of the stress reduction due to vibration to the acoustic stress⁽⁴⁾. Although the stress condition is more complicated in the indentation of the spherical indenter than that in the vibro-tension or compression test, there seems to be a close relation between the reduction coefficient ϕ and the equivalent load modulus α proposed above. In order to distinguish the hypothesis on the load from the one on the stress we call the former the "load superposition hypothesis". According to this hypothesis, the vibro-softening in the hardness test is expressed as "a decreasing of the value $H_{UBa=0}/H_B$ with an increasing P_a/P_m ". It is also concluded that the reduction rate of $H_{UBa=0}/H_B$ with P_a/P_m is independent of the material used. As illustrated above this is true within our experiment.

4.2 Dependence of the Brinell hardness values on the indentation load

Now let us consider about the other possible factors causing the apparent vibro-softening. It is well known that the Brinell hardness value varies

Fig. 13

with the magnitude of the testing load when the diameter of the indenter is kept constant. In the vibro-Brinell hardness testing the actual indentation load varies with the load amplitude P_a . Therefore this may be a possible cause of the amplitude dependence of H_{UB}/H_B . For this reason it is necessary to estimate the effect of the magnitude of the load statically. The experimental results are shown in Fig. 13. For the variation of load which corresponds to $P_a/P_m = 0 \sim 0.5$ the H_B values vary about 4% for the low carbon steel and 2% for the medium carbon steel. On the other hand, the variation of H_{UB}/H_B amounts to about 20%, and the load amplitude dependence shown in Fig. 9 still holds.

4.3 Shape of the indentation

The shape of the indentation formed by the spherical indenter is usually classified into two typical types known as "piling-up" and "sinking-in". According to Tabor⁽⁹⁾, the former type occurs with highly work-hardened metals and the latter type with annealed ones. Although it is not easy to distinguish strictly these two types of indentation, it is interesting to observe the indentation formed by the vibrational load. It may be possible to change one type of the indentation to the other by the superposition of the ultrasonic vibration. If such a change occurs, the optically measured diameter of the indentation may lead to a noticeable error. The shape of the indentation is measured

with the apparatus described in the previous section. The contour of the indentation is illustrated in Fig. 14 and Fig. 15 in which the ordinate scales are magnified 10 times as large as the one for the

Fig. 16

Fig. 17

Fig. 14

Fig. 15

Fig. 18

abscissa. As shown in the figures each size of the indentation increases with an increasing P_a/P_m , and the change in the type described above is not observed within the limits of this experiment. In order to show this result more clearly, the relations between each size of the indentation and P_a/P_m are shown in Fig. 16 and Fig. 17. By the way, the Brinell hardness calculated from the depth of the indentation t using the formula,

$$H_{UB}(t) = \frac{P}{\pi D t} \dots \dots \dots (3)$$

$$P = P_m + \alpha P_a$$

depends on P_a/P_m as shown in Fig. 18 which is similar to the previous result (Fig. 9) calculated from the diameter d_m . Thus the effect of vibration on the shape and size of the indentation is also explained by the superposition hypothesis.

5. Conclusion

We conclude from the experiment described above that

(1) This testing method is useful as the analogical testing for various plastic workings under the repeated compressive load.

(2) The ultrasonic vibro-Brinell hardness defined in this report is useful to estimate the vibro-softening quantitatively as the rate of reduction of the value H_{UB} with the intensity of the vibration.

(3) The vibro-softening is mostly attributed to the load measuring system. Hence the vibrosoftening seems to be only an apparent phenomenon.

(4) In the ultrasonic range of 20 KHz, the indentation phenomenon can not be explained by the simple superposition hypothesis. The dynamic effects of the loading can be estimated statically with the equivalent load modulus α , which gives $H_{UB} = H_B$, and usually its value is between 0 and 1. We got $\alpha = 0.5$ for the carbon steels at the frequency of 20 kHz. Taking $\alpha = 0$, the results show the vibro-softening, and $\alpha = 1$ corresponds to the vibro-hardening. It was confirmed experimentally that both of them are only an apparent phenomenon.

(5) In case of the vibro-indentation, the after effect on the mechanical properties of the material is scarcely observed unless a remarkable generation of heat happens.

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Appendix

Frequency dependence of the calibrated value of P_a

In this experiments, the output voltage of the piezo-electric pickup is measured with an oscilloscope of high impedance type. In such a case, the measured value depends on the frequency of the oscillating load. Hence there is a fear of a noticeable error being caused by the frequency difference between the calibration (50 Hz) and the operation (20 kHz), it must be investigated. A piezo electric element subjected to the load P_a produces an electric charge of

$$Q = kdSP_a$$

where d is the thickness, S is the area and k is the coefficient of the electro-mechanical coupling of the element. Since the piezo electric pickup used in the experiment consists of two elements in parallel, the charge produced by P_a is

$$Q = Q_1 + Q_2 = (k_1 + k_2)dSP_a \dots \dots \dots (4)$$

The pickup and the amplifier of the oscilloscope make an electric circuit shown in Fig. 19, where C is the electrostatic capacity of the pickup ($C = C_1 + C_2$), C' is that of the connecting cable and the input vacuum tube of the amplifier, and R is the input resistance of the amplifier. When the electric charge proportional to P_a is produced at the pickup, the output voltage V of the circuit is represented as

$$V = \frac{Q}{C + C' + (j\omega R)^{-1}} = \frac{j\omega R Q}{j\omega R(C + C') + 1} \dots \dots (5)$$

which varies with the angular velocity ω of the loading. Substituting Eq. (4) into Eq. (5), we have the ratio of the input and the output of the system

$$\begin{aligned} \frac{V}{P_a} &= \frac{j\omega R(k_1 + k_2)dS}{1 + j\omega R(C + C')} \\ &= \frac{(k_1 + k_2)dS\omega R}{1 + \omega^2 R^2(C + C')^2} \{ \omega R(C + C') + j \} \end{aligned}$$

Fig. 19

$$\left| \frac{V}{P_a} \right| = \frac{(k_1 + k_2) d S \omega R}{1 + \omega^2 R^2 (C + C')^2} \{ \omega^2 R^2 (C + C')^2 + 1 \}^{1/2} \\ = \frac{(k_1 + k_2) d S \omega R}{\{ 1 + \omega^2 R^2 (C + C')^2 \}^{1/2}} \dots \dots \dots (6)$$

If the relation $\omega R(C + C') > 10$ holds, we have approximately,

$$\left| \frac{V}{P_a} \right| = \frac{(k_1 + k_2) d S \omega R}{\{ \omega^2 R^2 (C + C')^2 \}^{1/2}} = \frac{(k_1 + k_2) d S}{C + C'}$$

which is independent of the angular velocity ω . The error due to this approximation is less than 1%. In our case,

$$R = 10 M \Omega = 10^7 \Omega [m^2 kg \sec^{-3} A^{-2}]$$

$$C = C_1 + C_2 = (3\ 800 + 3\ 930) PF$$

$$= 7.73 \times 10^{-9} F [m^{-2} kg^{-1} sec^4 A^2]$$

and we have

$$\omega R(C + C')|_{20\ kHz} > \omega R(C$$

$$+ C')|_{50\ Hz} > \omega R C|_{50\ Hz} = 24.3$$

Therefore the approximation described above holds with good accuracy. In other words the calibrating method described above is valid for our purpose.

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Discussion

Y. YAMADA and M. YAMAMOTO (Tokyo University):

(1) The equivalent load modulus α in this paper is defined under the condition of $P_m = \text{constant}$, while the reduction coefficient ϕ proposed by the one of the debaters is defined under the condition of a constant strain rate or a constant strain. There seems to be some difference between these definitions. How about the authors' opinion?

(2) There will be many arguments whether the effect of the ultrasonic superposition should be assessed from the view point $\alpha = 0$ or $\alpha = 1$. In this report, the authors discussed from the viewpoint of $\alpha = 0$. Show the reason for taking $\alpha = 0$ and give the author's opinion about the physical meaning of the experimental result, for $H_{UB}/H_B = 1$ or $\alpha = 0.5$.

(3) Show the base for assuming that the dynamic load P_a can be measured exactly by the method shown in Fig. 5 and Fig. 7. It is doubtful that the load amplitude picked up at the bottom of the specimen represents the actual indentation load at the indenter in case of the ultrasonic indentation (Fig. 5). Is it confirmed by the method of calibration shown in Fig. 7?

T. JIMMA (Tokyo Institute of Technology):

(4) Illustrate the wave shape of the oscillating stress on the screen of the oscilloscope.

(5) Although Fig. 4(b) illustrates the stationary wave of the displacement, it is necessary

to make clear the stationary waves in the test piece, the piezo-electric pickup and the nonresonant anvil, to represent exactly the actual oscillating force on the indenter by the output of the pickup. If there are something investigated about this problem, display the results, although it may offer no problem for the reason that the contact surface between the pickup and the anvil almost stands still and the height of the test piece is small.

H. KUDO (Yokohama National University):

(6) When calibrating the load cell, the present authors used an oscillating load of a low frequency as the standard input. The discussor doubts if the actual high frequency load operating at the indenter was transmitted to the piezo-electric pick-up without modification.

(7) The present authors state in their conclusions (1) that the vibro-indentation testing method is useful as a simulative material testing method for various metal forming processes with superimposed ultrasonic vibration. It is expected, however, that in those processes the forming limit is raised owing to low friction reduced by vibration. It might be also possible that in vibro-drawing the traction transmitting portion of workpiece yields or fractures depending upon the operating mean stress rather than the peak stress thus resulting again in a raised forming limit. Can these possible features be simulated in the present vibro-indentation test?

Authors' closure

(1) In this report the authors considered that the condition of constant strain or constant strain rate was not necessary to define the quantity ϕ . However if it is necessary to take the condition into account, the relation between α and ϕ will be no longer valid.

(2) (i) As described in Chapter 4, we intend to compare our results with the other's, in which the vibro-softening was usually observed by ignoring the oscillating load. This is the reason why we took $\alpha=0$.

(ii) It is shown in Chapter 4 that the cause of getting $\alpha=0.5$ can be reduced to the strain rate effect on the plastic deformation. The physical meaning of the effect may be reduced microscopically to the inertia force of dislocation against the large acceleration of the ultrasonic vibration.

(3) Please refer to the closure (5).

(4) Although the oscilloscope was only used for measuring the amplitude of the load and a photographic recording of the waves was not performed, the waves showed almost always a sinusoidal shape under the condition of $P_a/P_m \leq 0.5$. Under exceptionally light loadings, the value of P_a/P_m approaches unity and a stable indentation is no longer held.

(5) As pointed out, it is necessary to make clear the mode of the stationary wave of the system including the indenter, testpiece, piezo-electric pickup, brass anvil and so forth. However it is impossible to obtain the mode analytically because of its geometrical and dynamical complexity. In neither case the testpiece vibrates longitudinally

in the mode of one end fixed and the other end free and when the internal friction of the testpiece is remarkable, the load translates the specimen no longer accurately. Since the lowest resonant frequency of the specimen is $n=v/\lambda=v/4h=5180/(4 \times 17 \times 10^{-3}) \approx 76$ kHz and it is more than three times the frequency of the forced vibration (20 kHz) (in case of the calibration shown in Fig. 7, $76 \text{ kHz}/50 \text{ Hz}=1520$ times), the first case seems to be impossible. It is also clear from the measured distribution of the displacement shown in Fig. 5(b). On the other hand, the heat generation and its after effect of the test piece scarcely appearing, the second case is impossible too. Therefore it seems to be true that the indentation load at the indenter agrees with the load on the pickup.

(6) Please refer to the closure (5).

(7) We drew the conclusion (1) in the sense that the testing method is enough to reproduce and to measure the vibro-softening which is one of the most noticeable phenomena in the vibro-plastic working. In other words, the testing method has the possibilities of the analogical testing for the vibro-plastic workings. Therefore it is the subject for a future study to relate the results of the vibro-hardness test with the various properties for the vibro-plastic workings. Since the indenter and the testpiece are in contact with each other, the reduction of friction pointed out may be expected in the light indentation. However the causes for increasing the drawing limit and deep drawing limit due to vibration have not been made clear, and the authors can not say anything about the relations between those limits and the hardness.