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Basic Studies of Plastic Working with Vibration

(2nd Report, Basis of Vibro-Indentation Hardness Testing)*

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The vibro-indentation with a spherical indenter on low and medium carbon steels was performed in ultrasonic (20 kHz) and in low frequency (50 Hz) ranges in order to establish the foundation for the vibro-Brinell hardness testing that was suggested in our first report. Experimental results show that Meyer's law is still valid in case of the vibro-indentation, provided that Meyer coefficient and index are taken to be the functions of the load amplitude and frequency. It is also shown that the vibro-indentation law and the vibro-Brinell hardness can be reduced to Meyer's law and Brinell hardness respectively, under the "load superposition hypothesis".

1. Introduction

In the previous report⁽¹⁾ "ultrasonic vibro-Brinell hardness HUB" was defined to establish a simple testing method for estimating the resistance to the plastic deformation of materials under the ultrasonic vibrating load. After studying the experimental results about carbon steels (S15C, S35C, S45C) under the frequency of 20 kHz, we found that the indentation diameter increases with an increasing amplitude of the load and that the apparent value of HUB diminishes. Then we made an experimental study of "vibro-indentation law" comparing with Meyer's static one. Further we made similar tests in low frequency range of 50 Hz and compared the results with the previous ones, which are useful for the vibro-plastic working in low frequency range. This has been tried very often lately in U.S.A. and U.S.S.R.⁽²⁾⁻⁽⁵⁾ With these experimental results, we also investigate whether the vibro-indentation law and the vibro-Brinell hardness can be reduced to the static ones under the load superposition hypothesis.⁽¹⁾

2. Ultrasonic Vibro-Indentation Law

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2.1 Method of Analysis

In the static indentation for spherical indenters, the relation between load and size of indentation is expressed empirically by Meyer's law⁽⁶⁾ which states that for a ball of fixed diameter, if P is the load and d the chordal diameter of the remaining indentation,

$$P = k \cdot d^n \quad (1)$$

where k and n are constants for the material under examination. Eq.(1) shows that the relation between P and d plotted on logarithmic ordinates becomes a straight line of which the slope is numerically equal to the Meyer index n , while the value of P at which d is equal to one is numerically equal to k . In the case of vibro indentation, the pulsating load

$$P = P_m + P_a \sin \omega t \quad (2)$$

can be estimated conventionally

Fig. 1

$$P = P_m + \alpha P_a \quad (3)$$

as in the case of vibro-indentation hardness. Keeping the amplitude P_a constant and varying the mean load P_m , the vibro-indentation for the spherical indenter is performed and the relation between P and d on the logarithmic ordinates is investigated. Since the dynamic relation must be reduced to Meyer's law as P_a approaches zero, a similar relation may be expected in the dynamic case but now k and n seem to be functions of P_a . In order to confirm these remarks experiments were performed on three kinds of steels and the results were analyzed by the method described above.

2.2 Experimental Method

The apparatus used is the same as one used in the hardness testing described in the previous paper (20 kHz, 500W, steel ball indenter of 5 ϕ) so that the pulsating load is superposed on the static indentation load. The test specimens are also the same in materials (S15C S35C, S55C; annealed) and in size (18 ϕ x 15) as in the hardness testings. The testing faces are polished. The loading diagram is shown in Fig.1 in which the amplitude is kept constant while the mean load is varied in several steps from be-

low to above the Brinell testing load (750kg for $D = 5$ mm). Chordal diameters along two perpendicular directions to indentation are measured at each step of P_m with a microscope attached to the Micro-Vickers hardness tester. The quantity d is the average value of the chordal diameter in the two directions. Varying the amplitude of the load the same experiments

are repeated. When the ratio P_a/P_m approaches unity the indentation process becomes unstable, so that the amplitude P_a is taken up to 200 kg which is smaller than in the previous report. Keeping the unlubricated condition for the hardness testing, test surfaces and the indenter are cleaned out with benzine before experiments. The experimental results are plotted on a logarithmic graph paper, then,

(1) linearity of the graph

(2) effect of P_a on the n value

(3) effect of P_a on the k value

are investigated.

2.3 Experimental Results and Considerations

2.3.1 Static Indentation and Meyer's Law

In order to prepare a standard for vibro-indentation, static indentation was performed previously and the validity of Meyer's law (Eq.1) for the testing materials was checked. The experimental results in d/D range of 0.26 - 0.76 are shown in Fig.2. As usually said, the relation between load and size of indentation shows a broken line on the logarithmic graph paper. The slope of the graph (n value) varies about 8 % at the bending point that exists about $P = 600 - 700$ kg and $d = 2.0 - 2.5$ mm. The three kinds of steels show the same tendency in their slope (n value), but are different in their ordinate value at $d = 1$ mm (k value).

2.3.2 Apparent Law of Ultrasonic Vibro-Indentation

Performing the vibro-indentation in the way described above and plotting the results on the logarithmic graph paper under the condition of $\alpha = 0$ in Eq.(2) or $P = P_m$, an apparent law of vibro-indentation

Fig. 2

Fig. 3

tation is obtained. A typical example is shown in Fig.3. It is evident that the relation is expressed by a broken line as in the static one. As the amplitude P_a increases the graph moves almost parallel and its slope is apt to increase a little in low P_m range. The linearity of each line seems to be of the same degree as in the static case. Therefore it is concluded that the apparent law of vibro-indentation can be expressed in the form of Meyer's law. The above remarks are also true for smaller values of P_a and for other materials tested (S35C, S55C). The index n and the coefficient k are measured for each line element of a broken line. Then average values (n and k) are calculated. For simplicity, the apparent law is expressed as

$$P_m = k(P_a) \cdot d^{n(P_a)} \quad (4)$$

where the functions $k(P_a)$ and $n(P_a)$ are indicated in Fig.4. It is seen that the value of n increases a little and k decreases as P_a increases. Experimental equations for them are

$$n(P_a) = 2.18 + 0.000467 P_a \quad (5)$$

$$k(P_a) = \begin{cases} 117 - 0.0583 P_a & \text{(S55C)} \\ 109 - 0.0966 P_a & \text{(S35C)} \\ 83.5 - 0.0783 P_a & \text{(S15C)} \end{cases} \quad (6) \quad (7) \quad (8)$$

Referring to the book of Tabor⁽⁶⁾, $n = 3.0$ for the static indentation, $n = 2.0$ for ideally plastic one. The value of n obtained above exists within these limits. The value of k decreases as P_a increases.

2.3.3 The Effect of α on the Vibro-Indentation Law

To clarify the effect of α in Eq.(3) on the indentation law, three cases ($\alpha = 0, 0.5, 1.0$) are compared with each other in Fig.5 for S15C, $P_a = 200$ kg as an example. The linearity of the graph is held for the various α values. The test data for $\alpha = 0.5$ ("o") agree well with a full line for the static indentation except data located at the left-hand end which seems to

belong to the instability region. These facts were confirmed for all testing materials provided P_a is smaller than 200 kg. In the previous report, the value of α to convert the ultrasonic vibro-Brinell hardness to the static one is 0.5. It is worth noting that the same conversion rate is again held for a more basic relation of P to d .

Fig. 5

Fig. 4

Fig. 6

3. Vibro-Indentation Law in Low Frequency Range

3.1 Experimental Apparatus

The vibro-indentation in low frequency range (50 Hz) is performed with a Haigh type fatigue testing machine shown in Fig. 6. The pulsating load up to 1000 kg is imposed on the steel ball indenter ($D=5\text{mm}$). Measurement of the load is performed with a combination of wire strain gauge type load cell, dynamic strainmeter and electromagnetic oscillograph. Thus, in low frequency range, the measuring apparatus for mechanical vibration is used and all the loading processes shown in Fig.1 can be recorded on the paper from which both the load amplitude P_a and the mean load P_m are measured. Therefore the assumption made in the ultrasonic range, that the load measured with a loop-tester is regarded as P_m , is unnecessary in the low frequency range. As described above the maximum load (P_m+P_a) is restricted under 1000 kg in this apparatus, so that the mean load P_m is taken up to 800 kg and the amplitude P_a up to 200 kg.

3.2 Apparent Indentation Law in the Low Frequency Range

Taking α as a parameter, the experimental results are plotted on the logarithmic graph paper. Then the linearity, the effect of the load amplitude on the index n and the coefficient k are investigated as in the ultrasonic case. Putting $\alpha = 0$ for the low carbon steel Fig.7 is obtained. Though the range of P_m is narrower and the number of the plotted data is smaller than the ultrasonic case, they lie almost on a straight line. Similar results were obtained about the middle and the high carbon steels.

Fig. 7

Therefore the apparent law of vibro indentation in the low frequency range is also expressed by Eq.4. Then the value of α to convert the vibro-indentation law of low frequency range to the static one is investigated and $\alpha = 1.0$ is obtained as Fig.8. This means that the load superposition hypothesis is satisfied more completely in the low frequency range. As the range of P_m is narrower than the ultrasonic case, the graph consists of a straight line from which values of n and k are decided. Though the n value for $\alpha = 0$ increases rapidly with an increasing P_a , this tendency is relieved by putting $\alpha = 1.0$ and it comes to fall within the range for static n described above (Fig.9). On the other hand k decreases rapidly with an increasing P_a (Fig.10).

Fig. 8

Fig. 9

The ultrasonic case is illustrated for comparison. The experimental formulae for $n(P_a)$ and $k(P_a)$ are expressed as follows.

$$n(P_a) = 2.17 + 0.00072 P_a + 0.0000363 P_a^2 \quad (9)$$

$$K(P_a) = \begin{cases} 117 - 0.494 P_a & (S55C) \quad (10) \\ 109 - 0.450 P_a & (S35C) \quad (11) \\ 83.5 - 0.351 P_a & (S15C) \quad (12) \end{cases}$$

4. Vibro-Brinell Hardness Testing in Low Frequency Range

4.1 Vibro-Brinell Hardness

Using the same apparatus described above, vibro-Brinell Hardness testing in the low frequency range was performed. The experimental condition is chosen as the previous report; $P_a/P_m = 0.5$ and unlubricated indentation. Loading program is that the static indentation up to the Brinell testing load (750 kg) is performed and the pulsating load of a constant amplitude is superposed on the static one for 30 seconds, then unloaded in the reverse order. The measuring

Fig. 10

Fig. 11

method of diameters of the indentation and the definition of the "vibro-Brinell hardness HB_{vib} " is the same as in the previous section.

$$HB_{vib} = \frac{2(P_m + \alpha P_a)}{\pi D^2 (1 - \sqrt{1 - (d/D)^2})} \quad (13)$$

where D is the diameter of a spherical indenter (5 mm) and d is a chordal diameter of indentation under no-load condition.

4.2 Frequency Effect on the Vibro-Softening Phenomenon

Under the condition of $\alpha = 0$, the relation between HB_{vib} and P_a is shown in Fig. 11. The apparent vibro-Brinell hardness decreases linearly with an increasing P_a . Referring to the experimental results of the previous section we put $\alpha = 1.0$, so that Fig. 12 is obtained. It seems to be independent of P_a . From the facts described above, we may conclude as follows. Most of the "vibro-softening phenomenon", that is reported in the paper about vibro-plastic working in low frequency range, seems to be an apparent effect due to the lack of response of the load measuring apparatus,

Fig. 12

Fig. 13

so that the plastic resistance of the material to the peak value of the pulsating load is the same as in the static case. Taking dimensionless quantity HB_{vib}/HB on the ordinate and P_a/P_m on the abscissa, the three kinds of steels are compared in Fig.13. It is clear that they show the similar tendency described above. Ultrasonic case (20 kHz) is also shown in the figure for comparison. Though the graphs for $\alpha = 0$ show softening tendency in both frequency ranges, the degree of it is different. Graphs for $\alpha = 1.0$ no longer show the same tendency for each other, so that the graph for 20 kHz shows the tendency of hardening with an increasing P_a . As the deformation caused by the compressive pulsating load of about 50 Hz is of the same degree as that caused by the static load equal to the peak value of the pulsating load, the material testing under pulsating load seems to be unnecessary in such a low frequency range. But in the ultrasonic range the flow stress is no longer estimated statically, so that the converting modulus α must be determined dynamically. Both for the hardness and the indentation law in the ultrasonic range, the converting modulus equals to 0.5, which means the larger flow stress

or the vibro hardening against the traditional notion⁽⁷⁾. The cause seems to be reduced to the change in mechanical property, strain rate effect on the flow stress and etc. However no particular change is recognized in micro-Vickers hardness of the carbon steels as follows, so that the main cause seems to be strain rate effect.

4.3 Indentation Profile

As described above the vibro-Brinell hardness is the ratio of the pulsating load to the surface area of the indentation which is calculated from the chordal diameter d with the assumption of spherical indentation. In order to check the validity of the assumption on the indentation is measured with the combination of a lever type dial gauge and a measuring table, so that the deviation from the sphere is investigated. Indentation profile varies with superposition of the pulsating load on the Brinell load as shown in Fig.14. It is clear that the depth and the diameter of the indentation increase with an increasing load amplitude while the pattern of the profile ("sinking-in", "piling-up", etc.) shows no change. Referring to Fig.15 the relation

$$\left(\frac{D}{2} - h\right)^2 + \left(\frac{d_1}{2}\right)^2 = \left(\frac{D}{2}\right)^2$$

must hold for the spherical indentations ($\Delta R = 0$). The measured data ($h, d_1/2$) are plotted in Fig. 16 and compared with this spherical relation (full line). Furthermore the amplitude dependence of

Fig. 14

Fig. 15

Fig. 16

Fig. 17

the deviation $\Delta R/R$ is investigated with Fig.17. It shows that the deviation is within 1 % and independent of the load amplitude. From these results, the assumption of the spherical indentation seems to be valid for the practical use. The relation between diameter d measured with the microscope and d_1 , d_2 from the profile measurement is shown in Fig.18. In the figure, d is nearly equal to d_2 . As the pattern of the profile seems to be a "piling-up" type as shown in Fig.15, the difference between d_1 and d_2 is small, so that it is concluded from the previous results about d_1 and h as follows: In the case of annealed carbon steels, the spherical indentation formed by the Brinell load only grows larger and an apparent growth due to change in type of the indentation profile doesn't occur. Therefore the vibro-Brinell hardness may be calculated by substitution of d measured microscopically into Eq.13 on the assumption of spherical indentation, as in the ultrasonic case.

4.4 Loading Time Effect

Though it is ideal that the pulsating load continues until the indentation completes, we chose loading time of 30 seconds for the practical use. The effect of loading time on the deformation of the indentation is shown in Fig.19. The deformation d/D increases rapidly during the first 1 minute, then comes to slow gradually.

Fig. 18

Fig. 19

Comparing the deformation at 30 seconds and one at 2 minutes in the figure, d/D differs about 3 % but the effect on the value of HBvib is negligible considering the accuracy of the pulsating load.

4.5 Frequency Effect on α

As described above, frequency dependence of the indentation hardness and of the indentation law with a spherical indenter may be indicated with the equivalent load P or the modulus α defined in Eq.3. It may be supposed that the strain rate for various loading speeds increases in order of static, 50 Hz and 20kHz*. As the flow stress (yield point) generally depends on the strain rate, the indentation load increases also in the same order, so that α decreases in the order described above. Considering the fact microscopically, it seems to be reduced to the inertial resistance of dislocation against dynamic loading as mentioned in the previous report. Therefore large acceleration due to the ultrasonic vibrating stress results in $\alpha < 1$. Referring to the experimental results described above and the tensile test with vibrating load in low frequency range performed by the authors, the inertia effect is negligible up to about 50 Hz, so that $\alpha \approx 1$. The α value for 50 Hz - 20kHz that belongs to audiofrequency seems to decrease gradually from 1.0 to 0.5, provided there is no peak for inner friction in this range.

5. Conclusions

From all the facts described above, we may conclude as follows:

- (1) In the indentation of a spherical indenter receiving a pulsating load, the experimental relation similar to Meyer's law holds between mean load and chordal diameter of the indentation, provided Meyer index and the coefficient of the law become functions of load amplitude. Furthermore, type of the function depends on frequency.
- (2) Estimating method of the pulsating load gives rise to apparent phenomena in the hardness and the indentation law. Among these, the apparent phenomena for the mean load are practically most important, which

* Referring to the analysis performed by Ishlinsky(6), the plastic strain distribution for a spherical indenter deforming an ideally plastic metal becomes rather complicated, but assuming its strain rate to be proportional to the indentation rate of the indenter, the maximum indentation rate for the vibro indentation is greater than for the static one. Moreover, the displacement amplitude during the vibro-indentation measured microscopically shows a peak to peak value of about several tens microns both for 50 Hz and 20 kHz. Consequently the indentation rate is in proportion to the frequency, so that the indentation rate for 20 kHz is greater than the rate for 50 Hz.

may be converted to a static case by putting $\gamma = 1.0$ for 50 Hz and $\gamma = 0.5$ for 20 kHz.

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