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Heat Treatment by Ultrasonic Heating

(2nd Report: Selection of Heating Position and Tempering)*

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The principle of heat treatment by ultrasonic heating lies in using the calorification originated from internal friction in metals caused by ultrasonic vibration with large amplitude. Therefore, this heat treatment is a selective one according to the vibration mode. When a new heating method is put practical application, its practicability and generality are extraordinarily important. In this report, arbitrary selection of the length and the heated position of materials was aimed at. With various additional masses attached to the test pieces, the relationships between the length of the test pieces, the position to which additional masses were attached, resonant frequency, the weight of additional masses, and the heated position were identified. As a result, it became clear that the selection of the length and the heated position of materials is possible. And further, the tempering by ultrasonic heating was tried successfully as a link in the chain of ultrasonic heat treatment.

1. Introduction

Ultrasonic heating uses the stress of vibrations when ultrasonic vibration is applied to materials and positive use is made of heat generated by the internal frictions in the materials themselves for heat treatment. When materials resonate at around 20 kHz, a vibration mode as shown in Fig. 1 appears. At that time, calorification is proportional to the stress of vibration, in other words, calorification becomes maximum at the point of maximum stress of vibration. Moreover, internal frictions become larger once calorification takes place, and this calorification concentrates on the maximum stress of vibration, which can even exceed 950°C in approximately 10-mm length around the point. This phenomenon is very similar to the heat which is generated by electric resistance in materials when a large electric current is applied to steel materials⁽¹⁾. Therefore, this ultrasonic heating is a partial one following the vibration mode and does not require any heat intake from the outside. Although the calorification by internal friction had been an obstacle in the ultrasonic fatigue tests⁽²⁾⁽³⁾ and dynamic application of ultrasonic waves, it was purposely utilized in this research. Since the heat source of ultrasonic heating is the stress of vibrations and internal frictions that

result in calorification, the effect of the stress of vibration in the austenite region and the after effect of vibration are expected. In the previous report⁽⁴⁾, the heat treatment method by ultrasonic heating was advocated and its principle and actual procedure were introduced. Previous report also included comparison between various properties of quenched materials by ultrasonic heating and those of conventional quenched materials.

When a new heating method is put to practical application, its practicability and generality are extraordinarily important. As for the materials used, since the heat source is the stress of vibrations, ultrasonic heating can possibly be applied not only to iron or steel but also to solids such as non-ferrous metals and high polymers. However, since materials must be resonated in the ultrasonic region, there is a limit in size and shape. Because this heating method is a partial one following the vibration mode, the length and the position of the maximum stress of vibration of smooth specimens (that is, the heated position) are determined once the resonant frequency is fixed. This fact greatly narrows the practicability and generality of this method.

Taking the above mentioned factor into consideration, arbitrary selection of the length and the heated position of materials was aimed at in this study by using the same vibration system. With various additional masses attached to the test pieces, the relationship between the length of the test pieces, the position to which additional masses were attached, resonant frequency and the weight of additional masses, and the heated position were investigated in detail in this research. As a result, it became clear

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that the selection of the length and the heated position of materials is possible. In the previous report⁽⁴⁾ quenching by ultrasonic heating was done as an ultrasonic heat treatment. Thus, in this study, tempering by ultrasonic heating was tried and a series of consecutive heat treatments in a short time, including quenching and tempering, were made. In this study, more emphasis was laid on experiments than on theoretical calculations because, importance was attached to the practicability of the ultrasonic heating. The results obtained in this research will also provide the basic data to extend the applicable range of the ultrasonic fatigue test method, which is under development, as a highspeed and short-time fatigue test method.

Fig. 1 Vibration mode of smooth specimen

2. Apparatus and Test Pieces

The ultrasonic vibrator used consisted of an oscillator (for 9 ~ 55 KHz), a wide range amplifier (for 10 ~ 100 KHz, 2 KW), a transducer (the ferrite type, for 20 KHz) and a horn (for 19 KHz). The measuring apparatus, which was used when necessary, included: frequency counter, voltmeters for input and output, synchroscopes, microscopes for displacement amplitude, automatic pyrometers (the non-contact type), optical pyrometers, thermocouples, and thermocouples. Round bars with 5-mm diameter were used as test pieces and their chemical composition is shown in Table 1. However, in the case of Figs. 10 and 11, rolled screws of low carbon steel were used as test pieces. In this study the length of test pieces was

Table 1 Chemical composition

S45C (wt %)				
C	Si	Mn	P	S
0.48	0.26	0.76	0.017	0.022

treated as a variable. Each test piece had a 15 mm long screw (JIS M5 thread, pitch was 0.8 mm) at one end to connect to the horn, and a 10 mm long screw (M5, Pitch was also 0.8 mm) at the other end to place the additional masses upon. 5 mm thick round plates with holes in the center, which could contain M5 screws, were used as additional masses. Taking the machinability and fitness into account, brass was chosen as the material for the additional masses. The weight of additional masses was raised by increasing the outer diameter.

3. Method

The length L , and the weight of the additional masses M , were changed in Types A to D indicated in Fig. 2. The relationship between resonant frequency and the heated position, namely the position of the maximum stress of vibration, X , was examined. The test piece Type A had an additional mass on its free end, Type B had equal additional masses on both ends, Type C had an additional mass on its horn side, and Type D had an additional mass in the middle. Unlike the other three Types, Type D was a screw to move the additional mass along the test piece. The additional mass was locked by a steel nut. Thus, the additional mass M , represented the sum of the weights of the additional mass itself, the nut, and a part of the test piece covered by the nut. (In other words, 1.0 gf of the nut and 1.3 gf of the screw part were added to the mass.).

Fig. 2 Test pieces

4. Selection of Heated Position by Mass Adding Method

4.1 The Distribution of Temperatures in the Test Pieces under Ultrasonic Heating

Fig. 3 shows a longitudinal distribution of temperatures in a smooth material taking the temperature at the center of maximum glow part as the parameter. In the case of the temperature at 850°C, the part exceeding the transformation point of A3 was approximately 10 mm long and when the test piece was quenched, only that

Fig. 3 Distribution of temperatures (smoothed specimen)

Fig. 4 Distribution of temperatures (specimen with additional mass)

part was hardened. In this case, the results revealed that the resonant frequency was reduced by approximately 320 Hz when the temperature reached 850°C. Fig. 4 shows the temperature distribution when the mass was added (Type A, $L = 90$ mm, $M = 6.3$ gf). The figure shows that the mass moves the position of the maximum temperature to the free end side.

4.2 Effect of the Volume of Mass on Resonant Frequency

The mass added to the test pieces is taken as a concentrated mass in this research. First, the effect of the volume of masses will be explained. Fig. 5 shows the changes in resonant frequency due to the masses with the same weight but with different volumes. Brass (6.3 gf [$\phi 12$ mm], 10.3 gf [$\phi 16$ mm]) and aluminum (6.3 gf [$\phi 20$ mm], 10.3 gf [$\phi 26$ mm]) were used as additional masses. When these masses had the same weight, the resonant frequency changes corresponding to the length L , were completely the same as shown in the figure. It had been expected that the difference in their volumes and material,

Fig. 5 Effect of the volume of mass on resonant frequency (Type A)

would change their acoustic velocity so that their resonant frequency would be changed. However, coincidence of these two materials' data shown in Fig. 5 is interesting for future studies. In other words, the weight of the additional masses, not their size, will have to be taken into consideration in the laboratory test and practical applications from now on.

4.3 The Effect of the Additional Mass upon the Resonant Frequency and Heated Position

Using specimens with the additional masses shown in Fig. 2, L and M were changed to measure the resonant frequency and the distance X between the free end and the most heated position (namely the position of the maximum stress of vibration). Figs. 6 and 7 show changes in resonant frequency and X of Type A in which an additional mass was on its free end. Fig. 6 shows that the larger the M is, the smaller the resonant frequency f_r at each length L . Fig. 7 shows that the larger the M is, the smaller the X . This means that the heavier the weight of the additional masses is, the closer the most heated position gets to the free end side. On the contrary, in the case of Type C in which the additional mass was placed on the horn side, the most heated position shifted to the horn side with an increasing weight of the additional mass. (The figure for Type C is omitted here.) The degree of the shift in Type C was smaller than in Type A. Putting together the findings with Types A and C, the most heated position moved in the direction of the position where the masses were added and the amount of movement depended upon the weight of masses. This result is important in treating the ultrasonic wave. Figs. 8 and 9 show the findings with Type B having the same weight of masses added to both ends. Fig. 9 shows that the most heated position moved to the free end side as additional masses became heavier. Figs. 10 and 11 show the results with Type D. In this case, the screw was used to set the additional mass in the middle of the test piece. Both figures show that

Fig. 6 Resonant frequency of Type A

Fig. 7 Heated position of Type A

Fig. 8 Resonant frequency of Type B

Fig. 9 Heated position of Type B

Fig. 10 Resonant frequency of Type D

Fig. 11 Heated position of Type D

the closer the additional mass was set to the center of the test piece, the smaller the changes in resonant frequency and also the amount of movement of the most heated position became. Also in the case of Type D, the most heated position moved to the additional mass side as if it had been attracted to the mass. Figs 6-11 are useful for practical vibration designs utilizing the ultrasonic heating.

The amount of movement of the most heated position in Type B is smaller than in Type A. However, since the test piece in Type B was symmetric, the data on Type B are useful for basic researches and the application. Therefore, further research was made on Type B when the most heated position (the position of the maximum stress of vibration) was just in the center of the test piece which was equivalent to the case when $X/L = 0.5$ shown in Fig. 9. Table 2 gives X , M , and f_r when the most heated part is in the middle point of L . As Table 2 shows, f_r was stable and fixed at 19.1 KHz level. The vibration mode of the test pieces under this condition was equivalent to that shown in Fig. 1. In the case of smooth specimens, when the test piece was 130 mm long, f_r took a value of 19.1 KHz and the most heated position came at the center of the specimen. Thus, if the length of the smooth specimen (130 mm) was reduced gradually, the decrease in the weight of the test piece ΔM due to shortening of L , is expressed by the following equation:

$$\Delta M = \rho(130 - L)$$

ρ represents the linear density of the test piece (0.153 gf/mm). Then $\Delta M/2$ was added to each end of the specimen which was shortened to less than 130 mm, as a concentrated mass. The weight of the mass on one end ($\Delta M/2$) was expressed as M , $M = (1/2)\rho(130 - L)$. This equation is shown in Fig. 12. On the other hand, the values of M for various values of L shown in Table 2 are plotted in Fig. 12. As this figure clearly indicates, the plotted points fall on a straight line, $M = (1/2)\rho(130 - L)$. This means that when a half of the weight equivalent to the weight caused by the reduction in the length of the material is added to both ends of the shortened test pieces as a concentrated mass, the condition becomes the same as the standard specimen and that the equation $X/L = 0.5$ holds. This result may be useful when the central part of a shorter specimen is heated or the maximum displacement amplitude is to be obtained at both ends. Fig. 13 shows the glow condition of the test pieces with masses and Fig. 14 shows the shift of the glowed positions.

Table 2 Type B

L mm	X mm	M gf	f_r KHz
110	55	1.9	19.0
100	50	2.1	19.1
90	45	3.1	19.1
80	40	3.8	19.1
70	35	5.0	19.1
60	30	5.6	19.3

Fig. 12 Type B

4.4 The Effect of the Additional Mass on the Distribution of Displacement Amplitudes

Figs. 15-17 show a distribution of the displacement amplitudes in Type A when the mass is added to the free end. The amplitude was measured with a microscope and expressed in terms of relative displacement. The point of the displacement amplitude expressing zero in the figure is the center of the most heated position. Fig. 15 shows a distribution of displacement amplitudes when $L = 70$ mm. It is evident that the weight of the additional mass shifts the zero point of the displacement amplitude to the mass side. As shown in Figs. 15-17 the distribution of displacement amplitudes on the mass side changed more rapidly than on the horn side, as the additional mass became heavier. That is to say, the distribution of stresses of vibration can be considered to change rapidly with the node (where the displacement amplitude is zero).

4.5 Resonant Frequency of Test Pieces with Additional Masses Obtained by the Calculation

Regarding the test piece with additional mass as a bar with a step, calculation of the resonant frequency was tried on Type A. When the distance between the horn side end and the step is L , the length of the step part (the mass part) as l_1 , and sectional areas of the two parts are S and S_1 respectively. Then, the natural angular equation is as follows:

$$\tan \beta L = -\frac{S_1}{S} \tan \beta l_1 \quad (1)$$

given $\beta = \omega/C = 2\pi f/C$ (C : acoustic velocity, f : resonant frequency) (5)(6). Since the test piece penetrated the additional mass, the quality of the material was regarded as homogeneous. Fig. 18 shows the relationship between L and the resonant frequency obtained by calculation and experiment ("Cal" stands for calculation and "Exp", for experiment). Length L was obtained by substituting the resonant frequency into equation (1). The diameters shown in the figure represent the outer diameters of the additional masses, and the weight in parentheses is the sum of the weights of the additional mass, the nut, and the part of the test piece.

Fig. 13 Glow condition by ultrasonic heating

Fig. 14 Movement of the glowed position of Type A

Therefore, $\phi 0(1.3 \text{ gf})$ means a smooth specimen. As shown in Fig. 18, a considerable difference was observed between the values obtained by calculation and experiment. This difference is partly due to the change in the shape of the nut and screw part which was not taken into consideration, as the test piece of Type A was regarded simply as a bar with a step. However, the major cause for the difference is that the resonant frequency obtained by calculation was only of the test piece whereas the value obtained by experiment represents not only that of the test piece but also that of the whole vibration system including the horn. Therefore, in practice, changes in the resonant frequency are kept small, as in Fig. 18, by the effect of the horn part even if L was changed to some extent. So, as mentioned in 4.3, there is a wide range for selection in the length of the test pieces and the weight of the masses, even with the same vibration system. However, as in the case of (1) in Fig. 15, for instance, when the resonant frequency is high, the maximum amplitude is not obtained on the horn end, and thus, the stress of vibration is added to the horn end. Therefore, the quality and shape of the horn must be considered, when used continuously, in order to prevent the fatigue of the horn. Similar consideration is also needed even when resonant frequency is low, like in (9) of Fig. 17 since the stress of vibration is added to the horn end.

Thus, in the actual application it is desirable to select the resonant frequency

Fig. 15 Distribution of displacement amplitudes of Type A ($L = 70 \text{ mm}$) Fig. 16 Distribution of displacement amplitudes of Type A ($L = 90 \text{ mm}$)

Fig. 17 Distribution of displacement amplitudes of Type A ($L = 110$ mm)

Fig. 18 Resonant frequency and length of test pieces by calculation and experiment (Type A)

close to the natural frequency of the horn (for this vibration system, 18.5~19.5 KHz seems adequate). Regarding the additional mass, its position (ranging from Type A to D) and weight should be determined according to the length of the test piece. However, during the experiment, enough ultrasonic wave was generated to glow the specimen even in the extreme cases and also no abnormality was observed in the end side of the horn.

4.6 Utilization of Secondary Vibration

Utilization of secondary vibration is possible for long materials. When a test piece (approximately 250 mm long), whose length is double that of the smooth specimen with a fundamental vibration of around 19 KHz, is vibrated by ultrasonic wave, it

resonates also at 19 KHz. Maximum displacement amplitude is obtained at three positions, namely both ends and the center part. On the other hand, the stress amplitude becomes maximum at points a quarter wave length away (about 63 mm) from both ends. When the specimen is heated under such a condition, either of the two points of maximum stress glows (both points never glow together at the same time; probability for one part to glow is one-half). If a specific point is to be glowed, it can be easily achieved by cooling another point with a little water. These facts have been confirmed by experiments, and there are no problems on the ultrasonic output, vibration mode, and glow.

5. Tempering by Ultrasonic Heating

The previous report mainly dealt with quenching by ultrasonic heating. However, in this report, tempering was tried as a part of the heat treatment by ultrasonic heating, and its feasibility was studied. Round bars of S45C with 135 mm length and 5 mm diameter (shown in Table 1) were used as test pieces. Quenched specimens, one by ultrasonic heating and the other by conventional heating, were tempered by electric furnace, and hardness of each cross section was measured for various tempering temperatures, as shown in Fig. 19. It can be seen from this figure that the hardness of materials quenched by ultrasonic heating is by no means inferior to that of ones quenched by conventional heating. Based upon this result, materials quenched by ultrasonic heating were tempered by two methods of heating and the hardness of the cross sections was measured, and the results are shown in Fig. 20. The materials were tempered by ultrasonic heating with holding times of 1, 3 and 5 minutes respectively. In the case of tempering by electric furnace, the holding time was set at 10 and 30 minutes. As Fig. 20 shows, the hardness of materials tempered by ultrasonic heating even in the 1 minute holding time, is almost the same as that tempered by the other method. Fig. 21 shows the result of the tension test of such materials, indicating that there was no difference in tensile strength between various holding times. When the structure of materials was further inspected by a scanning electron-microscope, no difference was recognized in each tempering temperature. These results lend to conclusion that ultrasonic heating is effective as a short time tempering method. In addition, this method has the advantage that it can be readily conducted in the consecutive heat treatment such as quenching and tempering.

6. Discussion

(1) Water can be used to select the position of heating as well as adding of the mass. When the smooth specimen is cooled by water, except for its central

Moreover, this fact implies the possibility that the ultrasonic fatigue tests can be applied to machine elements and machine materials.

7. Conclusions

- (1) The mass adding method in Types A to D in the ultrasonic heating made it possible to select the length of test pieces and the heated position.
- (2) Figs. 6~11 define the relationship among the resonant frequency, the length of the test pieces, the weight of the additional masses, and the heated positions.
- (3) In practice the weight, not the size, of the additional masses should be taken into account.
- (4) In a specimen shorter than the standard smooth specimen, when a half of the weight equivalent to the weight caused by the reduction in the length of the material is added to both ends of the shortened specimen as a concentrated mass, the condition of vibration becomes the same as the standard specimen.
- (5) Utilization of the secondary vibration makes ultrasonic heating of longer materials possible.
- (6) Short time tempering without a furnace is made possible by ultrasonic heating. This will realize a consecutive treatment with serial heating processes.

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