VIBRATION-INDUCED INTERNAL STRESS RELIEF

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In recent years, considerable number of papers have been published on the subject of vibration-induced stress relief in weldments, castings, as a substitute for heat treatment [1, 2, 3].

In thermal stress relief, the energy required for stress reduction is transferred in the form of heat. This procedure is quite expensive especially, in the case of very large structures (big weldments). Obviously, economic reasons call for a process such that can replace, at least partially, the expensive heat-treatment operation.

In the non-thermal process, the energy required to reduce residual stresses is given in the form of vibrations in the low-frequency range.

The pre-estimated cost and time saving to be achieved by this method is 90% as compared to thermal stress relief, a ratio far too significant to be ignored.

The equipment used for the experiments (made by the Stress Relief Engineering Co.; Costa Mesa, California, USA) consists of three main parts;

1. control cabinet, with a built-in automation
2. vibrator, clamped to the
3. vibrating table

1. The control cabinet (Formula 62, Model "C") has two different operational modes. In the nonautomatic mode, the frequency can be continuously regulated in the range 0 to 100 cps. In the automatic operation it follows the frequency adjusted by the manufacturer, in 3 × 5-min cycles. The upper limit of the capacity of the equipment is 150 t.

2. Vibration is introduced into the workpiece by a variable speed vibrator which is a 1 HP, DC motor with off-balance weights, clamped to the workpiece directly — when this letter is large enough.

3. Workpieces too light to be attached directly to the vibrator are attached to a vibrating table, which is then attached to the vibrator.

The efficiency of stress relief can be determined by two methods:

a) X-ray diffraction measurement of the residual stresses,

b) measurement of the deformation of the workpiece.

Experimental

First, the possibility of regulation within the frequency range of the equipment had to be examined. From the oscillating pattern of the vibrating table, the vibration was seen to be unstable. The amplitude spectrum of the resonant frequency for the vibration unit (vibrator + vibrating table) is shown in Fig. 1. The frequency interval is 40 to 300 cps measured with a 5 cps band width. The effect of the upper harmonic vibration is seen to be important, its amplitude being about 40 to 80% that of the basic frequency. The maximum f_L is not the multiple of the basic frequency, but probably the interference maximum of a difference frequency. The basic frequency of the table can be regulated from 0 to 100 cps. In automatic operation the basic frequencies of the three cycles are 17, 38 and 25 cps, in this order.

The experiments completed include:

1. Stress relief by heat treatment according to Fig. 2,
2. Stress relief by vibration;
2.1. at the resonant frequency (47 cps),
2.2. in the lower range of frequency band (30 cps),

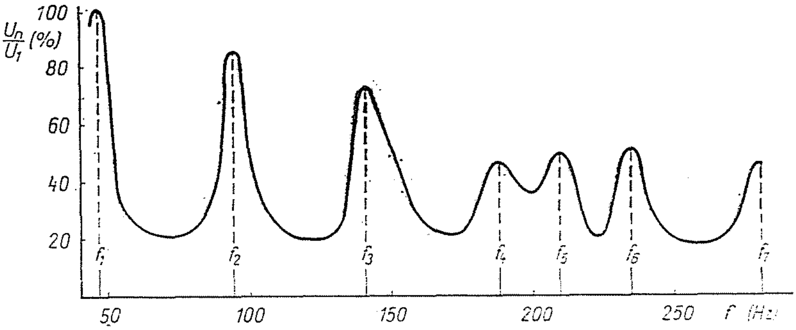

Fig. 1. The upper harmonic amplitudes measured by the resonant frequency

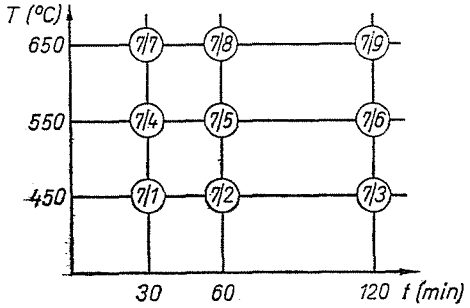

Fig. 2. Map of the heat treatment

2.3. in the upper range of frequency band (80 cps),
2.4. in automatic operation, 10, 20, 30, 40 and 50 minutes at all frequencies.
3. Controlling the results of experiments;
3.1. stress measurements by X-ray diffraction,
3.2. hardness test,
3.3. impact bending test,
3.4. micro-tensile test.

Experimental results

The specimen was made of low-carbon unalloyed steel, 25×150×500 mm in size. Parallel to the longitudinal axis of symmetry, a normal weld was made on the surface of the specimen with an automatic shieldedarc-welding machine. The internal stresses of this specimen, due to the heat introduced by welding and the shrinkage during solidification, approach the yield point of the material.

The internal stress distribution was determined normal to the axis of the weld, by X-ray diffraction, supposing the internal stress value and the change of the lattice parameter to be related by [4, 5, 6]:

$$R = \frac{a - a_0}{a_0} E$$

where R — internal stress,
a — lattice parameter before stress relief,
a_0 — lattice parameter without internal stresses,
E — Young's modulus.

The curve of the internal stress distribution versus distance from the weld is shown in Fig. 3 for the untreated (welded) specimen. Similar curves are shown in Figs 4 and 5 for specimens vibrated during a whole automatic cycle, and heat treated at 650 °C for 1 hour. The actual stress relief was tested by well-known simple material-testing methods, too.

The results of the hardness test are seen in Fig. 6. The average value of the standard deviation was ± 2 HV.

The impact-bending test was carried out on a standard 10 mkp Charpy machine. To make sure that the specimen would break, the biggest notch allowed by the standard (5 mm) was chosen. The specimens were cut out parallel to the weld axis, from that place where the curve of the stress distribution showed the maximum. The results are summarized in Table 1.

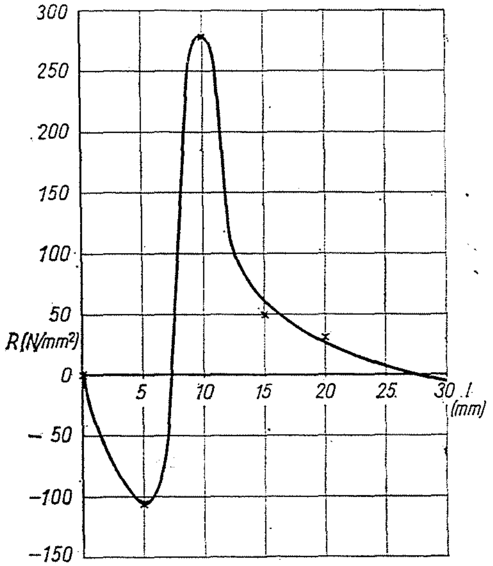

Fig. 3. Stress distribution before stress relief

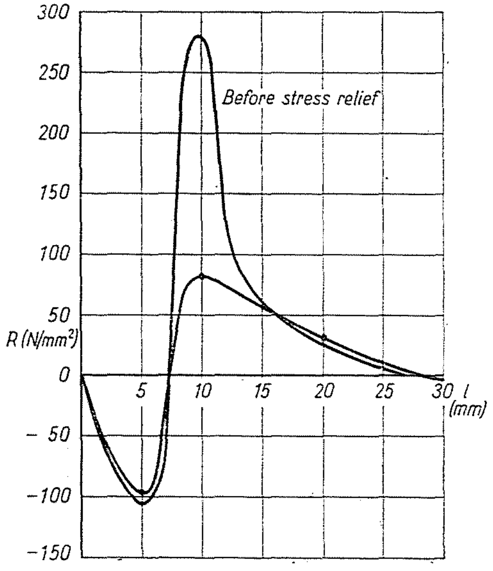

Fig. 4. Stress distribution after vibration within one automatic cycle

Micro-tensile tests were also carried out, on specimens cut out in a similar manner as above. The change in the ultimate tensile strength is shown in Table 2.

As to the results, the stress measurements by X-ray diffraction seem to be the best for indicating the effect, although the values of the hardness tests

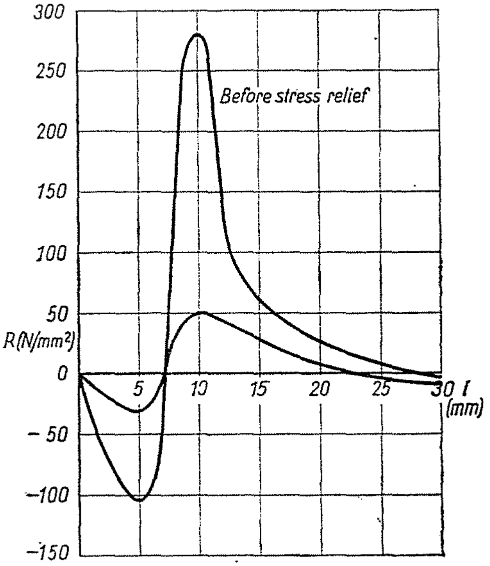

Fig. 5. Stress distribution after heat treatment 650°C/1 hour

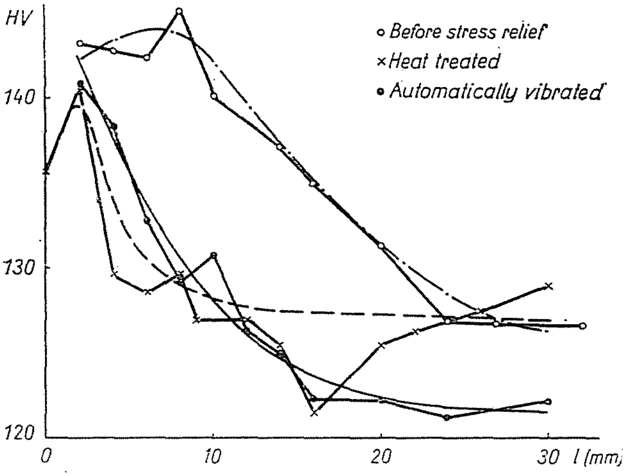

Fig. 6. Change of hardness normal to the weld axis

and impact-bending tests also point to some degree of stress relieving. It should be noted that the effect can only be indicated by mechanical material-testing methods, on the basis of many measurements, because of the important standard deviation in such tests, besides, it is generally useless because of being destructive.

Table 1

Results of the impact-bending test

State	Average of the Charpy value (mkp/mm^2)
Before stress relief	0.118
Vibrated within one automatic cycle	0.121
Heat-treated 650°C/1 hour	0.128

Table 2

Results of the microtensile test

State	Average of the ultimate-tensile strength (N/mm^2)
Before stress relief	380
Vibrated within one automatic cycle	382
Heat treated 650°C/1 hour	347

Structural interpretation of results

It is not surprising that vibration causes stress relief, when considering that material contains a lattice-fault concentration excess due to previous plastic deformation. Plastic deformation is due to the anisotropic temperature increase, or decrease, and to phase transformations accompanying welding. The term "internal stress relief" includes a decrease of lattice-fault concentration, depending on whether the process is viewed macroscopically or microscopically.

An ideal crystal that contains no dislocation may contain no internal stresses either. The internal stresses in one-component and one-phased systems can only be due to the presence of dislocations. In a multi-component, and multi-phased system, such as welding steel, the situation is far more complicated. Here the formation and survival of internal stresses is helped by the formation of transformation products, e.g. ferrite and cementite which have different specific volumes.

Continuity among phases formed with large difference in specific volume is facilitated by plastic deformation. Due to this deformation, regions loaded by internal stresses are left in the material. In these parts the average length of dislocation per unit volume exceeds the value characteristic of the annealed state, thus, if a decrease of internal stresses is achieved either by heat treatment or by other means, in effect it is the total sum of dislocations that is reduced.

It is understood that the structure of dislocations is different in the internally loaded regions from that in the annealed regions. In Figs 8a and 8b, part of a fictitious dislocation structure is illustrated on the slip plane of a crystallite

a) in the annealed state;

b) in the internally stress-loaded state.

A fundamental difference between the two states is that in the annealed state dislocations between the two nodes are straight lines as against the stress-loaded state where their shape is concave, depending on the stress acting on the plane in question.

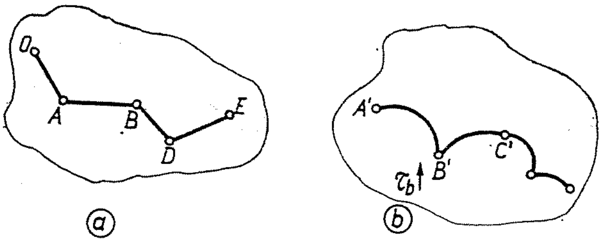

Fig. 7. Dislocation on the slip plane of a crystal in stress-free, and in stress-loaded state

In the first case the straight lines are formed by the line potential of disclocations, with a magnitude of $k \cdot G \cdot b^2$, where k is unity for screw dislocations, and equals 1.5 for line dislocations. For the case of internal stress loads, shear stress τ exerts a force $\tau \cdot b$ for a unit length of dislocation, which, in effect will result in bending (concavity). It is certain that for zero shear stress the dislocation lines are straight, for any shear stress the dislocation lines are no longer straight. (Naturally, one can find exceptions. For instance, if an edge dislocation segment connects two nodes, such as if a slip plane is loaded by a shear stress to the Burgers vector of the dislocation, then the dislocation will be a straight line. This also follows from the scalar product given for the stresses acting on the dislocation. In this case the scalar product equals zero, thus there is no stress on the dislocation.)

Let us consider the two cases presented in Figs 7a and b. Due to the periodic vibrating force, a dislocation segment of the annealaed material of Fig. 7a starts a periodic vibration. The segment of the dislocation fixed in the two nodes can be considered as an elastically strained string. The actual stress equals $k \cdot G \cdot b^2$. The segment may exceed in curvature the half circle for a frequency depending on the distance AB, i.e. for the frequency of the dislocation-line resonance.

Let us suppose that in point C there is a gate hindering dislocation motion, e.g. a dislocation crossing the slip plane, or a precipitation, or a peak stress of some other origin. If the vibrating dislocation was helped by the alternating stresses, to pass this obstacle, then usually it does not return to its original position, from dislocation line AB, lines AC and CB are formed instead, as shown in Fig. 8. This naturally means that the length of the dislocation has permanently changed, thus the dislocation concentration has also increased in that region. Such unit steps may occur anywhere within the crystal, wherever the micro-environment suits it. Presuming the above model to be correct, an annealed crystal is expected to harden upon vibration. This was observed for periodic loading of annealed metals, e.g. in alternate stress tests.

Fig. 8. The effect of vibration on a dislocation fixed in two nodes, in the stress-free state

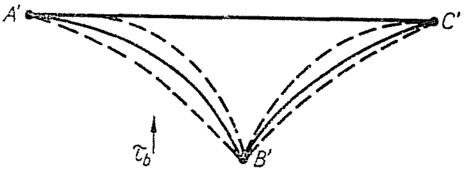

Fig. 9. The effect of vibration on a dislocation in a stress-loaded crystal

What happens in parts loaded with internal stresses? In Fig. 9, an assumed vector τ_b is drawn. Among other things, as a consequence of vibration, the shear stress becomes superimposed on the internal stress $\tau = \tau_0 \sin \omega t$. Thus dislocation lines $A'B'$ and $B'C'$ will no longer vibrate symmetrically to lines defined by given points, but will further bend out in the direction of the internal stress, since in the given case the two stresses should be added.

For point B', the line potential of the two dislocations should be added together, and in case it is sufficiently large to break away the dislocation, then a new segment $A'C'$ will be formed, from segments $A'B'$ and $B'C'$, with a shorter length than the original segment. In fact, that gives the opportunity to decrease the internal stress.

The presented model is expected to clear the phenomenom described by many workers in connection with stress-fatigue phenomenona, i.e. that alternating stresses will increase the strength of annealed metals, and decrease the strength of any metal with a correspondingly higher dislocation concentration.

It is still left to be explained why the same result cannot be achieved as by heat treatment. In the authors' opinion, this should not be expected. When stress relief is achieved by heat treatment, the motion of dislocations is far more extensive: beside motions within the slip plane, climb movements are also allowed. Movements of such nature of line dislocations necessitate the unidirectional motion of interstitials and lattice vacancies. No such motion is likely to occur upon vibration, as the concentration of point defects is not increased by vibration. This is the reason why heat treatment may eliminate a much larger portion of internal stresses than may vibration.

Vibration, however, may also help dislocations to leave the slip plane to a certain extent. Let one of the dislocation segments be, e.g. a screw dislocation, then under given circumstances that dislocation part may leave its slip plane, or in any case the slip plane shown in the picture (Fig. 9).

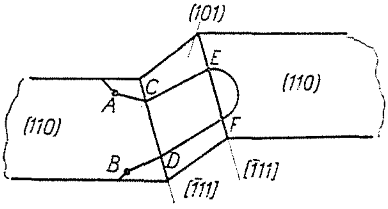

Fig. 10. A possible dislocation line, formed by internal stresses

(In the strict meaning of the word a screw dislocation has no slip plane.) In Fig. 10 it is shown how in steels a dislocation transfers from a plane (110) to another slip plane (101) trough points C and D. Bending from this slip plane is shown at points E and F. Points C, D, E, F are in the intersection lines of (110) and (101). Let us assume that the shape of dislocation shown in Fig. 10 is the consequence of internal stresses. If, upon vibration, dislocation segment EF attains the straight line EF, then, since this dislocation in the given state is of the screw type, it leaves the upper slip plane (110) by cross slip and transfers to the (101) plane. This, of course, results in a decrease of the total length of dislocations. Whether the dislocation will remain on the plane (101) depends on the prevailing microstresses. However, in any case, this is likely to occur sooner or later during vibration.

The model presented here was of help in explaining why in crystals with internal stresses the maximal stresses will decrease due to vibrations. Also it was considered to be unlikely that vibration could achieve the same magnitude of relief as heat treatment. Namely, during vibrational treatment less point defects are formed than in heat treatment to enable line dislocations, slip in the normal direction to the slip plane. This type of motion is quite negligible during vibration.

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Summary

The objective of the present inevstigation was to determine how the internal stresses in welded structures can be reduced by low-frequency vibrations, and to examine how closely the heat treatment-induced state can be approached.

An interpretation of the phenomenon is offered. The efficiency of stress relief has been demonstrated by X-ray diffraction measurements and by methods of mechanical testing.

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