The measurement and relief of internal stresses in welded joints

By B P SABBERWAL*

Introduction

The stresses present in the absence of any external load are called internal stresses. They may also be considered as stresses that remain in a structure as a result of elastic and plastic deformation. Such stresses are generated in a material during forming and welding operations.

The most convenient way of illustrating the generation of internal stresses and the parameters which affect its magnitude is to consider a structure of parallel bars whose ends on both sides are not free to move (restrained) (Fig. 1). Internal stresses are produced by heating the centre bar. Its expansion is prevented by the constraint and the unheated bars. The unheated bars will be under tension and the centre bar under compression (Fig. 1a). Since the yield point of the material falls with the increasing temperature, the heated parts will suffer plastic deformation (Fig. 1b).

When the cooling starts, the contraction in the middle of the centre bar will begin as there the rate of cooling is the fastest. The process may be complicated by the fact that in a part of the centre bar, which is away from the heated portion, the temperature may still be rising, but this has little effect on the final result. As the contraction proceeds in the centre bar, the tension in the surrounding ones is reduced and these will be under compression against further contraction in the centre. Now the centre bar will be stressed in tension to values nearing or reaching the yield point of the material and the surrounding bars will remain in compression (Fig. 1c). These stresses are balanced within the structure and exist without any external sign or influence at room temperature. Therefore such stresses may be termed as internal stresses.

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A similar explanation was given by Wilson and Hao (1) about the generation of internal stresses. They plotted the stress temperature relationship to show the generation of internal stresses. In an actual structure, usually there is greater plastic deformation and the degree of the restraint is much higher as compared to that of the above mentioned structure.

This model is a realistic representation of generation of internal stresses. Internal stresses may also be generated due to volumetric changes during structural transformation and surface effects due to machining and allied processes.

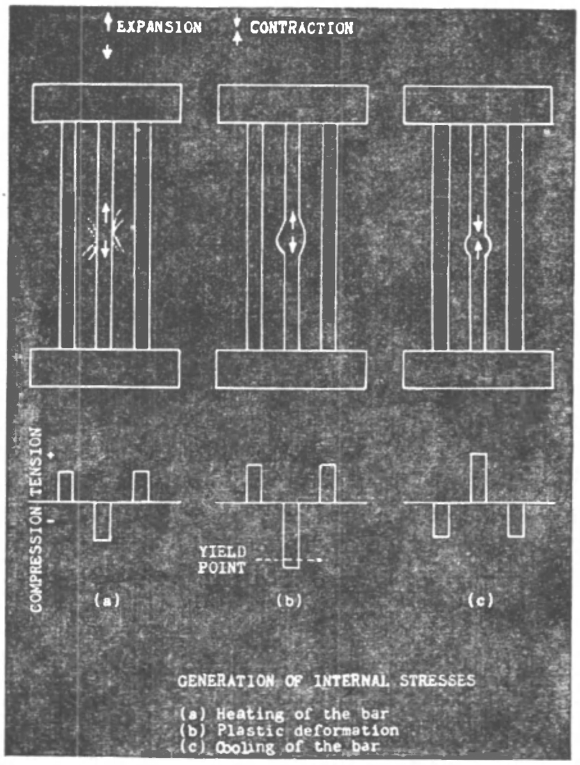

Fig. 1.

The commonly known detrimental mechanical effects are the dimensional instability after manufacture, brittle fracture in service and warping of castings or welded structures during manufacture. Opinions are still conflicting about the effect of internal stresses on the mechanical strength properties of the materials. Some investigators consider that the experimental evidence so far available appears to indicate that the internal stresses have little effect unless defects such as notches are present. Others, however, consider that their presence is deleterious in any event.

The detrimental effects caused by the presence of internal stresses necessitate their relief or reduction to within a safe limit. On the other hand, internal stresses can also be of great value if properly controlled. For example, the proper utilisation of internal stresses is the inducement of compressive surface stresses for the improvement of the fatigue life of a structure. This may be achieved by peening. Therefore in order to control these stresses, it is essential first to find their magnitude and direction in any structure. Also such measuement would then be the basis for predicting the necessity or otherwise of stress relief.

This paper describes various techniques of measuring internal stresses with specific examples of their usage in production components. Various methods of stress relief have also been discussed.

2. Measurement of Internal Stresses

A method of measurement of such stresses should fulfil the following conditions (2) :—

(i) It should be possible to measure the stresses close to the yield point.

(ii) The method should enable local stresses to be determined as closely as possible. For this, the area of measurement within which the mean stresses are measured should be very small.

(iii) The method should permit the intensity and the direction of principal stresses to be determined.

Based on the above considerations, it is possible to classify the measuring techniques into three groups :

(i) Measurement of strain by destructive methods in which the component or structure is completely destroyed while measuring internal stresses.

(ii) Semi-destructive methods, which involve minor damage to the component. In this case, it is however possible to repair this damage afterwards, e.g. by plugging holes which had to be drilled for stress measuring purpose.

(iii) Non-destructive testing.

2.1 Destructive Method

Generally, speaking, it is true that, the internal stresses are always in equilibrium in any material. If a portion of the material is removed by any mechanical or chemical process, this would upset the equilibrium, resulting in partial relief of stress in that material. The complete relief of internal stresses may be obtained by further material removal or sub-division.

Based on the above principle, Sach's found a technique called "Sach's boring method". In this method, the component under consideration is machined in stages and residual strain readings are taken. From these, the internal stresses (reaction and residual stresses) are calculated. Sach's boring method has been modified from time to time (3) so as to utilise this technique for larger welded components.

Based on this principle of dimensional instability by machining, the effect of reaction and residual stresses in weld cracking was investigated for a welded component. Fig. 2 shows the weld preparation for two discs. The discs were welded by the submerged arc process.

12 pairs of longitudinal and circumferential strain gauges were equally spaced around the circumference

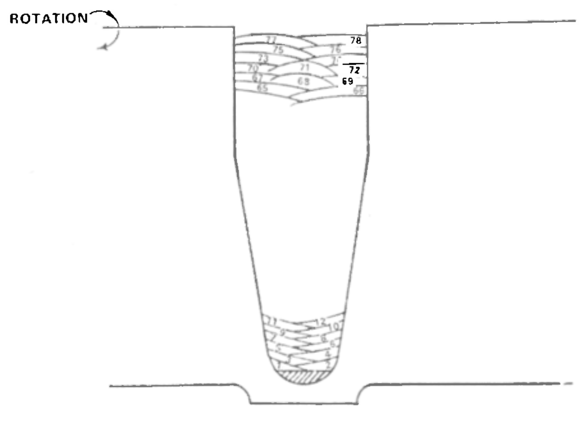

Fig. 2. Weld preparation.

of the weld (Fig. 3). These gauges were mounted using Araldite strain gauge cement. Equal number of dummy gauges were mounted on a metal strip for comparative measurements, and while taking measurements this metal strip was kept as close to the active gauges as possible.

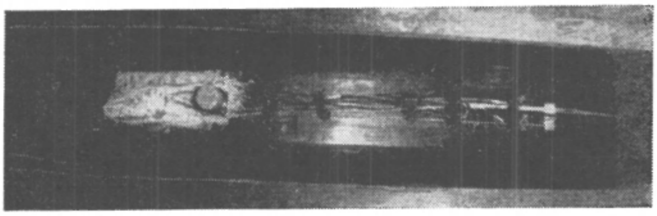

Fig. 3.

The strain gauges were connected in the form of a Wheatstone bridge (Fig. 4). The bridge was supplied with 2.139 V from the Solatron data logger unit which was used to measure the voltage variation across the bridge.

As it was impractical to make positive connections between the gauges and instrumentation it was decided to use plug and socket connections. Subsequent to the wiring connections being made, the sockets were held in position by support wires and completely encased in silicon rubber. Removal caps were then fitted to ensure complete protection from water and swarf. The complete installation was tested by spraying water for half an hour.

The size of the welded discs made it impractical to use a machining technique in which the rotor remained stationary while the cutting tool revolved. Therefore the welded discs were mounted on a vertical turning and boring machine and the strain gauge leads were disconnected while machining. The effect of reaction stresses was measured by machining away the discs on either side of the weld (Fig.3). Subsequently the remaining ring was cut radially at two positions to measure the effect of residual stresses.

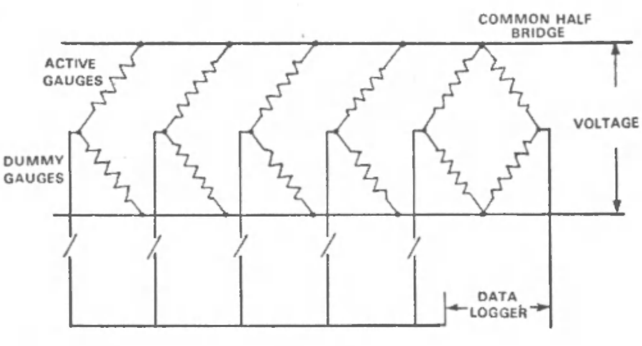

Fig. 4. Diagrammatic strain gauge connections.

To avoid the regeneration of internal stresses due to machining, light cuts were taken while machining and coolant was used to prevent excessive heating. The metal temperature did not rise more than 5°C at any time and the temperature difference between the active and dummy gauges was never more than 0.25°C.

The magnitude of longitudinal (F_L) and circumferential (F_θ) stress was calculated by the following relationships :

$$F_L = \frac{E\,(e_L + \nu e_\theta)}{1 - \nu^2}$$

$$F_\theta = \frac{E\,(e_\theta + \nu e_L)}{1 - \nu^2}$$

where e_L and e_θ are longitudinal and circumferential strains
E is Young's modulus
and ν is Poisson's ratio.

Results

The calculated values of longitudinal and circumferential stresses are shown in Figs. 5-10. The maximum values of reaction stresses were 5.5 and 3.2 tonf/in² (tensile) in the longitudinal and circumferential directions (Figs. 5 and 6) while the maximum residual stresses were 2.6 tonf/in² (compressive) and 2.3 tonf/in² (tensile) in the longitudinal and circumferential directions (Figs. 7 and 8). The maximum internal stresses (reaction + residual) were 5.5 and 5 tonf/in² (tensile)

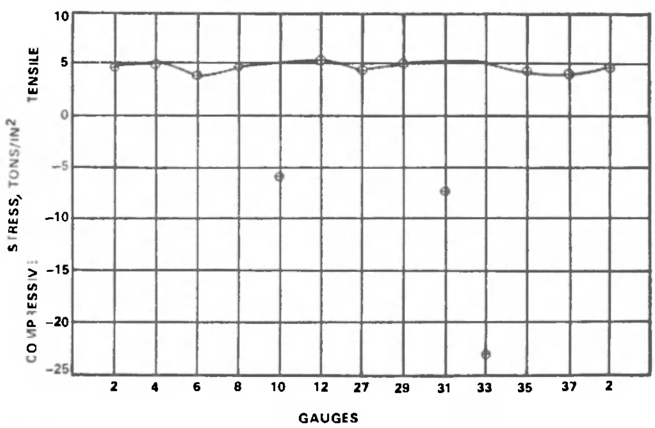

Fig. 5. Longitudinal reaction stresses in the welded discs.

in the circumferential and longitudinal directions (Figs. 9 and 10).

Although all the points shown in Figs. 5—10 represent stresses at the position of each strain gauge, only the maximum stress values have been joined to show a trend in the results. The deviation of certain points from the general trend is due to non-uniform distribution of internal stresses.

Above is a practical example of measuring internal stresses by the destructive method.

In finished components it may not be possible to use the destructive method. This may be replaced by semi-destructive or non-destructive techniques.

Semi-Destructive Method

The following techniques may be classified as semi-destructive :—

(i) Brittle Lacquer Method

(ii) Stress measurement around a hole by ultrasonics.

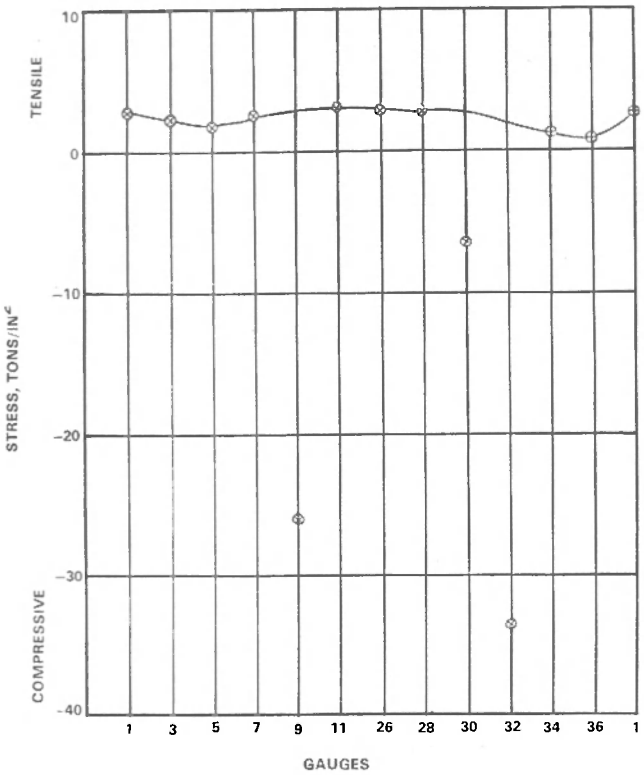

Fig. 6. Circumferential reaction stresses in the welded discs.

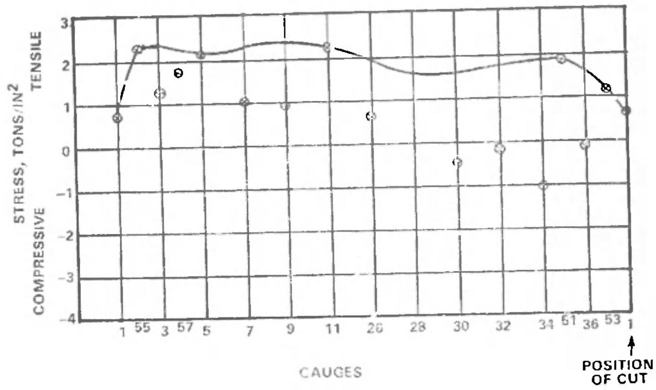

Fig. 7. Circumferential residual stresses in the welded discs.

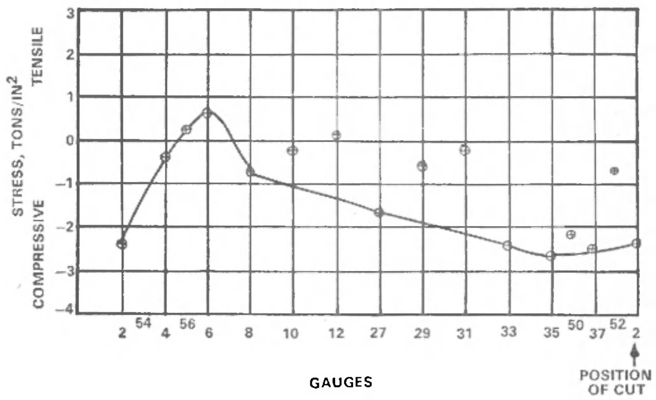

Fig. 8. Longitudinal residual stresses in the welded discs.

Brittle Lacquer Method

The surface of the material containing internal stresses is coated with a brittle lacquer known as "stress coat". The stress coat will crack if the internal stresses in the material are removed. The crack pattern thus obtained will indicate the direction of principal stresses in the material. If the internal stresses in the material are very high, a pattern will be formed immediately on cracking. In the case of low stresses it sometimes becomes necessary to chill the lacquer slightly to bring out the pattern. The brittle lacquer pattern was first used by Gadd (4).

Durelli and Taso (5) produced approximate quantitative expression to account for the stress produced by a coat of known sensitivity and these were later modified by Tokaroik and Polzin (6). The latter have also described in detail the effect of stress coat with a dye etchant sensitizer. It is shown that the effect induced by the drilling can result in serious error in the case of aluminium. Tokaroik and Polzin also

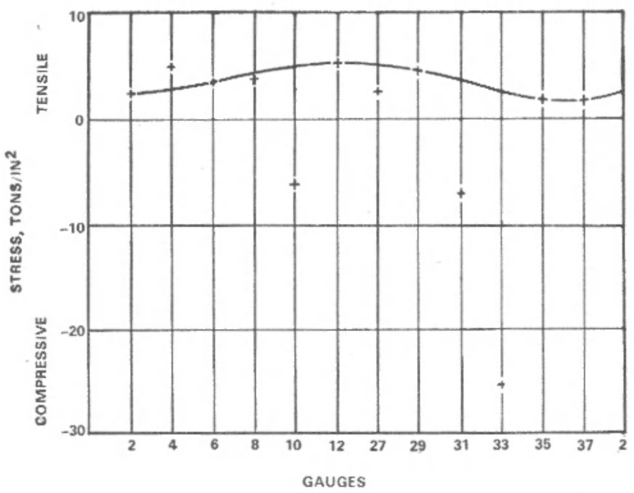

Fig. 9. Internal stresses in the welded discs in the longitudinal direction.

reported scatter of results of as much as 15,000 lbs/in in mild steel.

This method gives only an indication of the presence of internal stresses without giving their magnitude. This technique has therefore the advantages in speed and cost which may suit industrial applications where only the degree of internal stress concentration is of importance. The magnitude and direction of internal stresses may be measured accurately by other methods after establishing their presence by brittle lacquer.

Stress Measurement Around A Hole by Ultrasonics

Ultrasonic waves are reflected back if there is any flaw present in the material. The size of the flaw can be measured on the calibrated oscilloscope. This fact may be utilized for measuring the internal stresses in any material. The pulse type generators generally used for flaw detection may be used for measuring internal stresses. Short pulses of ultrasonic energy are transmitted to a material at one end and the wave is reflected back from the other.end, provided there is no flaw in it. Two echoes will appear on the cathode ray tube ; one due to transmission and the other reception with a time base. If there is a flaw in the material (Hole, crack) energy transmitted will be reflected back from the flaw and a third echo will appear on the cathode ray tube. If a hole 1/16″ dia. and 1/16″ deep is drilled in a specimen containing internal stresses, the shape of the hole distorts. Such distortion will not occur in a stress free material. If ultrasonic energy is applied by means of a pulse type generator, the echo received from the distorted hole will be different from that of the undistorted hole. By comparing these echoes, it is possible to measure the magnitude of internal stresses on a calibrated oscilloscope. This method of stress measurement may yield very accurate results and is a very near approach to non-destructive methods. The damage done to the material is very small and is easy to repair.

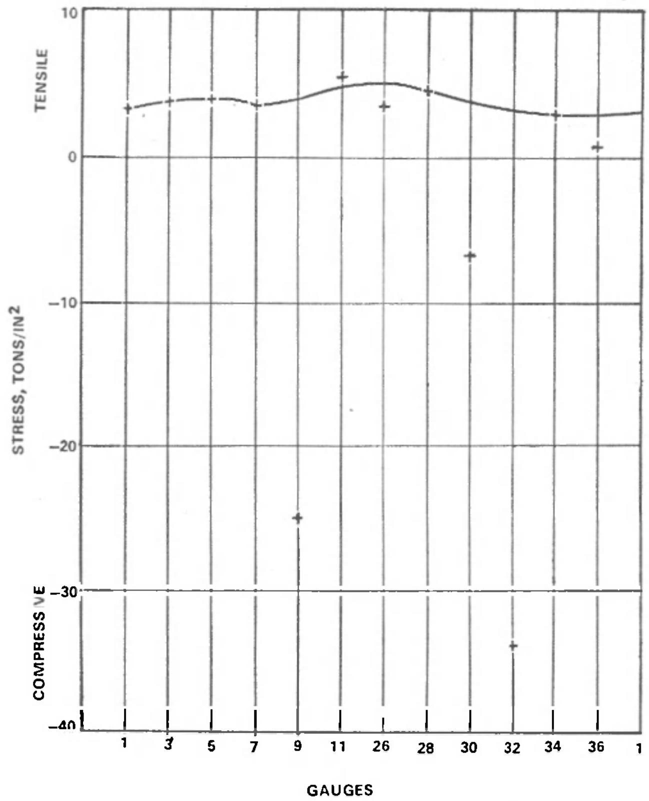

Fig. 10. Internal stresses in the welded discs in the circumferential direction.

Non-Destructive Methods

The advantage of non-destructive method over other techniques of measurement is that it does not damage the structure and some of the non-destructive methods may be used in cases where the applicability of other methods is not possible.

The non-destructive methods may be classified into two groups :—

(i) X-ray diffraction technique.

(ii) Ultrasonic method.

Use of X-ray Technique

The measurement of strain by means of an X-ray technique is based on the fact that the interatomic spacing of the atoms within an object changes when the object is subjected to stresses. A change in the interatomic spacing due to the applied or internal stresses enables the elastic strain to be measured. When mono-chromatic X-rays impinge upon atoms in a metallic crystal, the rays are scattered by the electrons of the atomic structure. The superposition of the rays results in a diffraction which form a pattern that can be recorded on a photographic film. Bragg's law relates the interatomic spacing to the wave length of the incident beam by a factor which can be determined by measuring the diameter of the diffraction rings before and after straining. Thus the internal stresses may be calculated. Unlike the mechanical methods, localised stresses or a sharply changing stress gradient can be determined by X-ray techniques.

The disadvantages of this method is that good accuracy is only obtained with specimens that yield sharp diffraction lines. Quenched steel or cold worked steels give diffused lines that produce a very large error.

Ultrasonic Method

In this technique, the internal stresses are measured by comparing the velocity of sound in a material containing internal stresses and a similar material that has relatively no stresses. The velocity will be different because of the spacing of the atoms and might either be increased or decreased. Acousto-elastcity is the name given to this effect of stress on the velocity of sound in the material (7). The change of velocity due to stresses in a material is very small. It has been reported that the magnitude of velocity changes due to an internal stress of 10,000 p.s.i. is less than 1%. The instrument for measuring velocity changes can read with an error of less than 0.05% (8).

This technique has many practical advantages. It is quick and also can be used in the field. The magnitude of internal stresses present in structures may be found out even after assembly.

After strain measurement, the real problem is to avoid failure in service due to internal stresses. Various methods are used for stress relieving. Some of these techniques and new investigations are described below :

(i) Thermal treatment.

(ii) Mechanical stressing

(iii) Vibrations.

(iv) Ultrasonic energy.

Thermal Treatment

Depending upon the method of application of heat, this technique can be further subdivided into three parts.

(i) Furnace stress relieving.

(ii) Induction heating.

(iii) Low temperature stress relieving.

Furnace Stress Relieving

The basis for this method is that the yield point of the material is lowered at high temperature. Therefore, all the internal stresses in the material above the yield point are converted into plastic deformations. Consequently, it results in the reduction of the internal stresses to the yield point of the material at elevated temperature. According to B.S.S. and American Standard specifications the component should be heated at approximately 70°C below the transformation temperature, i.e. to between 600 and 650°C (British practice) and 1100°F (600°C) and 1250°F (675°C) (American practice). The component should be held at this temperature for a period in hours equal to the maximum thickness in inches. The rate of heating above 300°C should not exceed 200°C per hour divided by the maximum thickness in inches and the rate of cooling down to 300°C should not exceed 250°C per hour divided by the maximum thickness in inches. By American standards, the rate of heating per hour is 400°F (205°C) and the rate of cooling is 500°F (260°C) divided by the maximum thickness in inches. Below 300°C cooling in still air is allowed in British practice whereas in American practice, it is 600°F (315°C).

Though it is possible to reduce the internal stresses by the above mentioned method, it is very difficult to achieve complete relief of internal stresses. The scale formation on the surface of a component necessitates machining which may reintroduce internal stresses. The cooling of the component during stress relieving may produce temperature gradient in it, resulting in the regeneration of internal stresses. These factors make it difficult to use this method for relieving internal stresses in precision components where dimensional stability is of great importance.

Induction Heating

Many fabricated vessels are too large compared with the capacity of existing furnaces. In these cases, the relieving of internal stresses is some times achieved by the "induction heating method" (9). The induction coil is wound round the component and is connected to a power source. Insulation over the winding reduces the loss of heat. This system can be controlled to a considerable extent by the regulation of current through the coil. However, there is a tendency to form hot spots directly under the coil which results in the development of thermal stresses. Even though, through proper insulation, it may be possible to avoid heat losses due to radiation, it is very difficult to achieve a uniform rate of cooling throughout the structure.

Hot spots found under the coil during induction heating may be avoided by using radiant heat (10) for stress relieving. This technique also suffers the disadvantage of non-uniform heating and cooling.

Low Temperature Stress Relieving

During the process of welding, the constraint offered by the adjacent plate causes internal tensile stresses in the weld metal. These stresses can be locally severe. Heat is applied to the plate on either side of the weld so that the weld metal is at a lower temperature than the surrounding hot region. Although elastically constrained by the even larger unheated plate, the slight expansion of the hot areas may be sufficient to superimpose further tensile stresses on the weld, resulting in plastic deformation in the weld.

In practice, this process involves heating of two bands adjacent and parallel to the weld to a temperature of 175°C while keeping the zone of weld cool (11). The heating is accomplished by running oxy-acetylene blow pipes and the cooling is done by water spray on the plate behind the advancing burners. The temperature attained by the heated metal is dependent upon both the "power" of the blow-pipes and their speed and in practice is varied by means of the latter.

This technique of stress relieving has only a limited use. It reduces stresses in the weld zone but at the same time it may generate stresses in other parts of the structure due to the heating of a limited zone. Also it is very difficult to believe that this method may act as a substitute for relieving internal stresses throughout the structure which is normally done by stress relieving furnaces.

Stress Relieving By Vibrations

Vibrations at a resonant or harmonic frequency for a particular structure are used for relieving stresses in castings and fabricated structures. An equipment working on this principle was developed by M/s. Enke Machine Tool Company (12). The available equipment consists of a bed 6′×6′ supported on four rubber supports. The vibrator unit is mounted under the bed. It comprises a $\frac{3}{4}$ H.P. motor to provide the drive for a rotating disc. To this rotating disc, certain weights are attached to produce unbalance and hence the generation of vibrations. The vibrations may be applied in any required direction. Two vibrators can be used to produce bivectorial vibrations, i.e. vibrations in two directions at right angles to each other. The structure which is to be stress relieved is clamped at one end of the table while the other end is free. Gauge marks are made on the component to be stress relieved. The material is vibrated and the distance between the gauge marks changes. After some time when there is no further change in the distance between the gauge marks, the vibrations are stopped.

Similarly, Satch and Minehisa (13) performed some experiments on the welded joints. The specimen used by them was a standard H-type constraint. The specimen was clamped at one end and the vibrations were applied at the other end. The frequency used was 1300 cycles/min. and the amplitude was changed from 2mm to 15mm. It was found that the value of stress relief increased with the amplitude of vibrations.

The reliability of the above mentioned processes for practical application is questionable. Forced vibrations are introduced in the system by keeping one end fixed and applying the vibrations on the other end. This produces cumulative displacement of molecules while the displacement between adjacent molecules is very small. This is being concluded because of the fact that no appreciable rise in temperature of the specimen takes place as compared to ultrasonic vibrations (described later) when applied to a specimen subjected to free vibrations.

The high amplitude of vibrations results in the distortion of the specimen. This distortion may produce some relief of the internal stresses but if the amplitude of vibrations is very high, it may result in the regeneration of internal stresses.

The technique of "stress relieving by vibrations" (12) is also doubtful because the measured stresses are found only on the surface. It has not yet been shown as to how the stress system below the surface is affected. Therefore in the author's opinion this method of stress relieving seems to be inefficient.

Stress Relieving By Ultrasonics

The use of ultrasonics in the processing of weldments has established a positive effect in the direction of lowering internal stresses and improvement in some of the strength characteristics of such weldments (14). Ol'shanskii and Mordvinsteva (15) have reported using ultrasonics to obtain significant relief of the internal stresses which were produced in two plates of austenitic stainless steel 3mm thick. It was found that ultrasonic treatment is a method conducive to lowering the magnitude of internal stresses. The stress relief obtained by this method was about 60% of the internal stresses present in a non-vibrated welded plate. These investigators also reported that ultrasonic vibrations of the welded joint in low carbon steel resulted in an increase of the impact strength by as much as 80%.

These tests were only of experimental nature and were performed on a relatively thin material. The amount of energy utilized and the way it was applied to the weld was not described by the investigators in their publication. No information has been provided about the type of ultrasonic generator used.

The technique of stress relieving by ultrasonics is based on the principle that the yield point of the material is lowered by the application of ultrasonic energy. Therefore stresses above the yield point are converted to plastic deformation and hence internal stresses are relieved.

Vibrations are applied after the plate is welded and cooled to room temperature. The amount of stress relief varies with amplitude of vibrations. (16)

It was found that this process of stress relieving does not cause any damage to the component and can easily be used on finished components. So far this process has been used on laboratory scale and with certain modifications, it can be adopted on production components.

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