# RESIDUAL STRESSES IN IRON CASTINGS

## C. Balasingh,* M. R. Seshadri** S. Ramaseshan† and M. N. Srinivasan††

## Abstract

*In this paper an attempt has been made to review critically the methods employed for the measurement of residual stresses, the test pieces used, causes of residual stresses in castings, mechanism of residual stress formation and relief of residual stresses. It is concluded that the causes of residual stress formation are fairly well understood, but the mechanism behind the stress relief produced by different methods is not as well understood. It is suggested that a detailed study of the various stress relief methods, independently or in combination, is essential to understand the mechanism.*

Key words: Residual stress, iron castings.

## Introduction

The presence of locked-in residual stresses in castings have been recognised long back. Castings with appreciable residual stresses are found to distort during storage, transportation, machining and service. Many examples of cracks occurring due to high stresses can be found in the literature.[1] The residual stresses limit the external load to which the cast component can be subjected to. This is so because wherever the residual stresses and stresses due to the external load are in the same direction, the load carrying ability of the component is only the difference between its strength (tensile or compressive as the case may be) and the residual stress.

However, the presence of residual stresses is not always bad. From the argument presented above, it is immediately obvious that residual stresses are desirable if they counteract stresses arising from external forces. In many instances residual stresses are purposely introduced to increase the service life of the component. It is a common practice nowadays to

* Materials Science Division, National Aeronautical Laboratory, Bangalore 560 017.

** Professor, Department of Mechanical Engineering, Indian Institute of Science, Bangalore 560 012.

† Head, Materials Science Division, National Aeronautical Laboratory, Bangalore 560 017.

†† Associate Professor, Department of Mechanical Engineering, Indian Institute of Science, Bangalore 560 012.

323

induce surface compressive residual stresses to enhance the fatigue life of components. Portevin and Pomey[2] and Patterson and Dietzel[3] carried out detailed investigations to bring out the beneficial effects of residual stress. They concluded that surface compressive stresses increased the tensile strength, bending strength, impact strength, torsional strength and hardness. Notch effect was also reduced.

In majority of cases, especially when the castings are complex, it is difficult to predict the distribution of residual stresses. In such cases the standard method is to eliminate the residual stresses altogether. There are two ways to achieve this: one is to make castings in the stress-free condition by adjusting different variables. This requires understanding as to how and why stresses arise, and what factors influence the magnitude of the residual stresses. The second alternative is to produce castings with stresses, and then subject them to treatments to relieve the residual stresses.

### METHODS OF RESIDUAL STRESS MEASUREMENT

The methods employed for the measurement of residual stresses may be classified into mechanical, physical and chemical. The choice of a particular method depends on the shape of the specimen, precision required and the location and direction along which stresses are to be measured.

I. The four most important and very widely used methods coming under the category of mechanical methods are:

(i) Parting-out method

(ii) Layer removal method

(iii) The boring and turning method and

(iv) The hole drilling method.

Abundant literature is available on these methods. In the report SAE J 936[4] (and also TR 144[5]) published by the Society of Automative Engineers, the details of different techniques are given clearly. Refinements in the mathematical approach, and improvements in techniques are being reported periodically. In the present article, only a brief mention of the principle and the advantage of each method will be made.

### (i) *Parting-out method*

The parting-out method can be used either as a first step in a detailed stress determination (using other methods) or as a method complete in itself. The method requires removal of a coupon from the parent part in

the region of interest. The coupon can have the shape of flat plate or a straight or curved beam. Strain and/or curvature, produced in the parted out coupon, are measured to compute the stresses.

If the distribution of stress through the thickness of the coupon is known or can be reasonably assumed, the residual stress in the parent part may be determined. If the principal stress directions are known, the procedure becomes simpler. One beam oriented in the direction of principal stress is parted out and analysed. If the directions are not known, two beams may be necessary. However, since cutting in one direction will affect the stresses in the other directions also, appropriate correction factors are to be introduced into the calculations. The minimum size of the beam removed should be 1 in. long. In case of plate it should be 1 in. square.

The method is ideally suited to determine average stresses in large part. The error in measurement can be quite large if steep stress gradients are present.

### (ii) *Layer removal method*

This is a very useful and sensitive method in determining the residual stresses in flat plates or beams in which the stress varies with the thickness, particularly if the stress gradient is sharp. The stress in a layer is determined by removing the layer and measuring the strain and curvature changes it produces on the remainder of the specimen. Strain gauges are used for strain measurement and precision curvature gauges for the curvature measurement.

Plate coupons are used if the principal stress directions are unknown. If the directions are known, beams parted out in the principal directions are used. The thickness of the specimen needed depends on the extent of stress measurement required. In case only surface stresses are desired, thickness of the order of 1/8 in. is sufficient. If the entire stress distribution is needed, the coupon should be much thicker. The determination of surface stresses requires only primary cuts, whereas for the evaluation of entire stress distribution, primary and secondary cuts should be used. The thickness of the layers to be removed depends on various factors such as size of the specimen, precision of the measurement required, and steepness of the stress gradient.

If precise results are to be obtained, the machining technique should be chosen such that the induced machining stresses have the minimum effect. The usual techniques are grinding, etching or electropolishing. The layer

removal method is relatively complex, especially for thick curved beams. Computer programming is necessary if several specimens are to be studied. There are experimental set-ups wherein continuous measurement of strain and curvature, as electropolishing goes on, is possible and a computer coupled to it calculates the stresses.

### (iii) *The boring and turning method*

This method is applicable only to circular cylindrical members. The tangential, radial and longitudinal stress distributions along a radius may be determined by removing layers from the bore or the outer surface and measuring the longitudinal and tangential strain changes. The two basic assumptions made are: (*a*) The stresses are symmetrical about the central axis and constant along its length; (*b*) the removal of a layer produces a constant change in the longitudinal stress at all points in the specimen.

The strains are measured on the side opposite to the one on which the layers are removed and are a measure of the stresses released in the removed layers. If complete stress distribution is desired, or if the stresses at one surface (bore or outer surface) are to be determined with the greatest possible precision then primary and secondary layer removal may be used. For example, suppose the stresses at the surface of a solid shaft are desired. Then the shaft is bored first (primary cuts). This reduces the stiffness so that secondary cuts at the surface produce significant strain changes. Similarly in the case of a thick walled tube, if the stresses at the bore are required with the greatest precision, primary cuts are made at the outer surface and secondary cuts at the bore. Combination of boring and turning is necessary to reduce the error.

The precision of the method is determined by the accuracy of the measurement of dimensional changes and the care taken in the removal of layers. Due to the stiffness of the members, only small strain changes are produced for a given thickness of layer removed. Hence the thickness of the removed layer and the strain should be measured with the greatest precision. The length of the specimen should be more than two times its diameter. If not, end corrections are necessary.

### (iv) *Hole drilling method*

This is a valuable technique because it can be used to survey the stresses at the surface of a large part. In this method, the surface strains in the vicinity of a hole are measured as the hole is drilled. This method can be classified as semi-destructive, since the hole produced may be repaired in

large structures. One of the techniques employed is to coat the surface of the part with brittle lacquer and drill small holes at various points of interest. The crack pattern produced is used to estimate the direction, magnitude and nature of the biaxial residual stresses.

For quantitative work strain gauge rosettes (3, 4 or 6) are to be used, unless primary directions are known. In the latter case, strain gauges located in appropriate directions are sufficient. One of the basic assumptions made is that the residual stresses are constant in the region of the drilled hole. The stress distribution can be determined only for a limited depth, since the surface strain changes become negligible when the material is removed at a depth below the surface of one to two hole diameters.

The precision of the method is low, since the strains produced by drilling are very small. There have been various attempts to improve the sensitivity of the method and also to measure stresses as a function of depth. The hole drilling method is not limited to parts with flat surfaces only. It can also be used in fillets and at other locations where section changes are gradual.

II. Under the category of physical methods we can list:

(i) X-ray diffraction method

(ii) Ultrasonic method and

(iii) Magnetic anisotropy method.

### (i) *X-ray diffraction method*

This is a non-destructive method for the measurement of residual stresses. The principle of the method can be briefly stated as follows. The metallic materials which are crystalline in nature diffract x-rays and from the diffraction pattern interatomic spacings can be determined. Stresses (either applied or residual) cause changes in the interplanar spacings thereby affecting the diffraction pattern. Stresses within the elastic limit cause a shift in the position of the diffraction peak. From this peak shift, strain (and hence stress) can be calculated.

The method can be used either to find out the sum of principal stresses at a point or the stress along any particular direction. The direction and magnitude of the principal stresses can also be determined.

Since the penetrating power of x-rays used for diffraction work is small, one can safely assume biaxial stress field. The diffraction information comes from a layer of few microns thickness. Incidentally, this factor shows

the importance of surface preparation. The accuracy with which stresses can be determined depends on the accuracy with which small changes in interplanar spacings can be measured. For this reason, high angle diffraction lines are used. Lattice faults and uniaxial plastic flow are found to give spurious shifts. The first one can be eliminated by proper experimental procedure.

Either photographic technique or diffractometer can be used. The diffractometer is quite fast and nowadays computer controlled stress diffractometers are being used in industries.

### (ii) *Ultrasonic method*

Just like transparent materials are birefringent to a beam of polarised light, stressed metals are birefringent to an ultrasonic (frequency of the order of 5 MHz) shear wave. A polarised shear wave passing through such a material is resolved into two components, which lie in the planes of the principal stresses. These two wave components travel at different velocities, which are dependent on the magnitude of the principal stresses. These velocity changes are measured, and from that the stresses computed. However, complications arise due to the fact that birefringence is not only caused by stress, but is also produced as a result of anisotropy. There had been many attempts to separate out the two effects and some are successful. In future, this may prove to be a very powerful non-destructive method for residual stress analysis.

### (iii) *Magnetic anisotropy method*

This is applicable only to ferromagnetic materials. The method involves the measurement of the effective permeability over a range of frequency of the applied alternating field. It is still in the development stage.

### III. *Chemical*

Under this category, the main method is " stress corrosion method ". Corrodents which cause cracking of the surface of certain metals when tensile stresses exist may be used to detect residual stresses. Though in principle by controlling the conditions it is possible to get quantitative data, it is highly unreliable in practice. Further, stresses below a particular value cannot be detected since no cracking will occur in that case. Since small changes in composition of the metal or corrodent, temperature and metal anisotropy can have large effect on the stress corrosion behaviour, the method is only qualitative.

SPECIMENS EMPLOYED FOR THE MEASUREMENT OF RESIDUAL STRESSES

Experiments on prototype castings[6–12] for the evaluation of residual stresses and the effect of different variables on their magnitudes will be too expensive. Hence the necessity for designing some simple structures.

The specimens used to investigate residual stresses can be classified into three groups.

I. Specimens designed in such a way that high casting stresses are developed.

II. Blanks or approximate shapes (later machined) or exact sizes are cast, and then subjected to various quenching treatments and

III. Blanks or approximate shapes are cast and machined to final dimensions. Preplanned stresses are then introduced and the effect of various relief treatments investigated.

Majority of the specimens coming under group I are designed on the basis of differential cooling between parts of the casting. The grid castings were developed on this basis. The shape of the specimen used by Russel[13] is as shown in Fig. 1. In the thick member, tensile and bending stresses (the latter due to the weakness of the side members) are developed. A gap is milled in the thick member and the gap width is taken as a measure of stress. The method is not very sensitive.
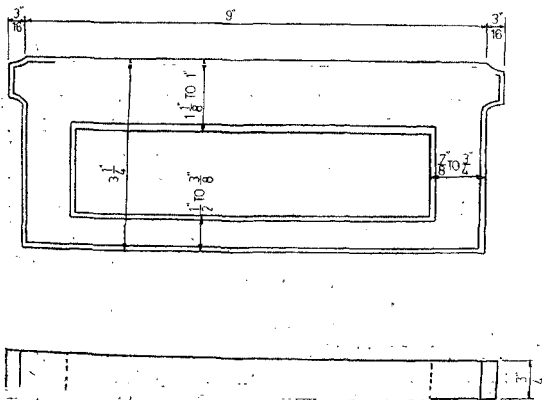


FIG. 1. Specimen used by Russel.

Dodd[14] first tried to use a simple rectangular framework (Fig. 2). It was observed that the connecting members were subjected to high bending stresses, and this in turn offered a partial relief of stress in the centre
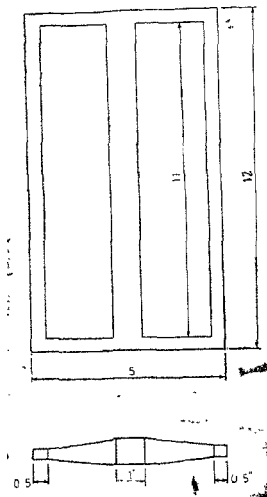


FIG. 2. Simple rectangular grid.

member. Following the discussion of Roth and Seumel,[15] Dodd modified the yokes, as shown in Fig. 3, to give the ends sufficient rigidity. In this case the stress in the centre member approaches a state of uniaxial tension. Parkins and Cowan[16] and Kosowski[17] used specimens of similar shape.

Kasch and Mikelonis[18] used a modified rectangular framework designated G–66–2B (Fig. 4). The design looks a bit complicated, but it seems to ensure unidirectional stress. The grid used by Patterson and Dietzel[19] is analogous to the rectangular framework. Here the thin outer members have a double trapezium-shaped cross-section whereas the centre member has a circular cross-section. The middle member is tapered in the centre. The yokes have a double T-shaped cross-section. Extensions provided from the centre member can be used to clamp the specimen in tensile testing machines. According to the authors the trapezium shape of the thin
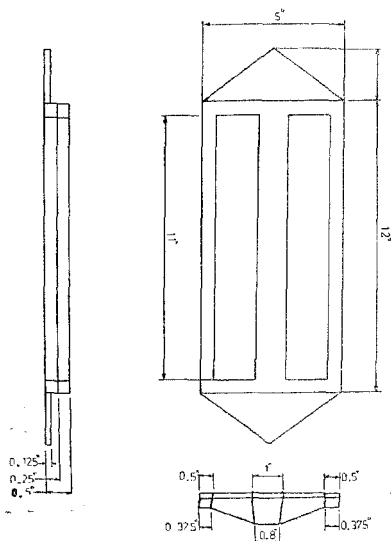
FIG. 3. Modified rectangular grid.

member prevents the rotation of the grid under the action of residual stresses. The shape of the specimen suggested by Portevin and Pomey[2] is similar to the one used by Russel[13] except that the measurements were carried out on thinner members and that distance between two points before and after cutting were measured instead of gap width. Triangular grid castings were used by the Technical Subcommittee[20],[21] (T.S. 32) appointed by the Institute of British Foundrymen. A schematic drawing is shown in Fig. 5. The outer members and yoke, because of their high surface area to volume ratio, solidify fast and become rigid compared to the thick centre member.

In the rectangular as well as the triangular grids, strain gauges are used to find out the stresses. One or two strain gauges are attached to the centre member and then it is sawed through. The strain indicated by the gauge is straightaway used for the calculation of residual stress, if the value of Young's modulus is known. There are some difficulties in fixing
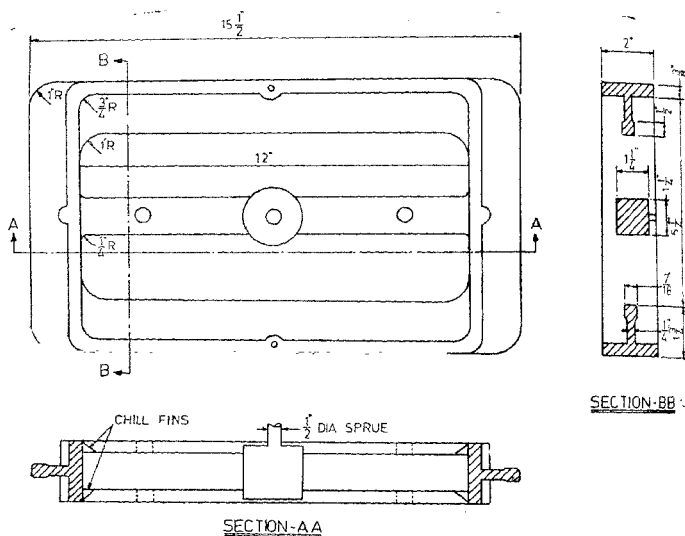
C. BALASINGH *et al.*



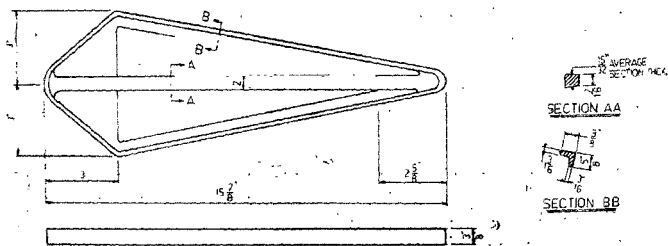Fig. 4. G–66–2B Rectangular framework used by Kasch and Mikelonis.



Fig. 5. Triangular Grid.

the correct value of Young's modulus as will be evident from the discussions later. Kasch and Mikelonis[18] suggest another method which could be adopted by Foundries not in a position to afford the strain gauge equipment. Patterson and Dietzel,[19] in addition to determining the stresses by the strain gauge technique, also used a method called the difference method. However, the validity of the method is questionable.

The drawbacks of the grid castings are: (i) The microstructure of thick and thin members are usually not identical with the result that the value of Young's modulus may not be the same for different parts. (ii) Young's modulus is not a constant for cast iron, but it depends on the strain. Assumption of a mean value for Young's modulus may lead to errors. (iii) There is always the likelihood of some bending of the members, which cannot be taken into account by employing the present methods of calculation of stress.

The second drawback can be overcome by plotting a stress-strain curve and reading off the stress corresponding to the strain observed. There is another procedure which doesn't involve the measurement of strains. The centre member is sawn slowly until fracture occurs. If the area of fracture is $a$, the stress $\sigma$ is calculated using the formula

$$\sigma = P\,\frac{a}{A}$$

where $P$ and $A$ are the tensile strength and the area of cross-section respectively of the centre member.

Usually cylindrical rods were poured along with the grids. From these rods specimens for tensile test and bending test were machined. Average value of $E$ (Young's modulus) can be determined from each test. In addition to these, the value of $E$ can be calculated from the graphite content also. Patterson and Dietzel used these $3\,E$ values for the calculation of stress and tried to arrive at a best fit which will give smooth variation with other variables studied.

Two other types of specimens can also be included in this group. First is the double flanged bars[20] used by T.S. 32 to study the effect of mould hindrance on the magnitude of residual stress. Next is the large $T$ section castings used by Girschovich and Simanovskii[22] to investigate the casting distortion.

The type of specimens coming under group II are usually either cylinders or hollow cylinders.[3] All the specimens were cast to approximate sizes, machined to final dimensions and subjected to an initial thermal stress-relief treatment. Patteison and others used the cylindrical samples to study the effect of various quenching operations on the magnitude of the residual stresses, and also to investigate how the mechanical properties were altered by the residual stresses. The hollow cylinders, after heating to a particular temperature were cooled differently and the effect of these on the magnitude and distribution of residual stresses studied.

Under group III we can list the ring specimens used by Hallett and Wing,[23] Kotsyubinskii *et al.*,[24] and Zeppelzauer and Brezina[25] and the rectangular bars (bent transversely by a stirrup using distance pieces at ends) used by Benson and Allison[26] and Tottle.[27] The ring specimens were machined from hollow cylinders. A slit was made in the ring and a wedge introduced so that known amount of stress can be introduced. In this loaded condition the rings were subjected to various relief treatments. From a measurement of the width of the slit before and after treatment the percentage of stress relief can be easily calculated. Hallet and Wing[23] used the following formula

$$R = \frac{G_2 - G_1 - P}{W - G_1 - P} \times 100$$

where $R$ is the percentage of stress relief ;

   $G_2$—width of the gap after removal from the spacer wedge;

   $G_1$—width of the original gap;

   $W$—width of the spacer wedge;

   $P$—plastic deformation at room temperature $= (G_2 - G_1)$ at RT

if no plastic deformation occurs at room temperature, $P = 0$. Zeppelzauer and Brezina[25] neglect $P$. Both the groups of investigators were studying the effect of different heat treatments on the magnitude of relief of stress in iron castings of different compositions.

Some of the objections raised against this type of specimens are:

(i) The stress distribution across the thickness of the ring varies continuously through the neutral axis.

(ii) The difference in coefficients of thermal expansion of the material of the ring and of the wedge may introduce additional stresses,

(iii) Whereas actual castings are not restrained while heating, the wedge, at least partially, puts a geometrical restraint.

Some investigators feel that it is wise to draw a distinction between the relaxation of externally applied stress and the relaxation of inherent casting stress.

Kotsyubinskii *et al.*[24] used cylindrical specimens also in addition to rings. The specimens were held in rigid holders and known stresses introduced. Stress relaxation over prolonged periods were studied.

Another type of specimen[28,29,30] is shown in Fig. 6. This has been mainly used to study the effect of vibration on the relief of stress. The
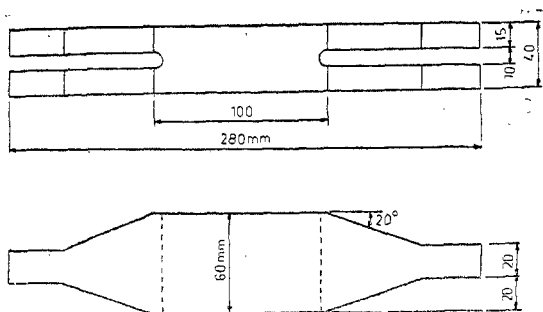


FIG. 6. Cantilever type specimen.

specimen consists of a rigid central portion with 4 projecting cantilever beams. The cantilever beams form the working section of the specimen. The stresses are set up by inserting calibrated pins in the gaps. The pins were fixed to rigid supports. Vibratory stress is applied in the form of concentrated load $\pm P$ in the rigid centre section. The vibratory load can be checked by monitoring the signals from the strain gauges attached to the cantilever arms to an oscilloscope. The gap widths are measured before loading and also after removal of the pin subsequent to vibration treatment. The change in gap width is used to calculate the relief of stress as well as distortion.

The objection raised against the ring specimens can also be raised here. Though this type of specimen has been used to study the effect of vibration

only, there is no reason why it should not be used to study stress relief by other methods, for example thermal stress-relief.

The main advantage of specimens under group III is that one can introduce known stresses and then study how different treatments relieve the stresses. Also data collection is easier.

## CAUSES AND EFFECT OF DIFFERENT VARIABLES ON THE MAGNITUDE OF RESIDUAL STRESSES IN CASTINGS

### A. *Causes*

The residual stresses in castings arise due to inhomogeneous plastic deformations. While cooling to room temperature, in order to enable the parts of the casting to fit together elastic strains corresponding to the residual stresses are introduced. Non-uniform deformations can be expected due to the following reasons.

(i) Variations in cooling in different parts of the casting.

(ii) Hindrance to free contraction by the mould material—often referred to as mould restraint.

(iii) Phase transformations accompanied by volume changes.

Residual stresses can also be set up due to temperature gradients existing from the surface to the centre of casting during cooling. Here stresses are related to the overall rate of cooling of the casting. The stresses arising due to this cause attain appreciable magnitude, only under conditions of rapid cooling (for example, quenching). Compositional and structural heterogeneity can also cause stresses.

The relative contributions of the above three factors to the final residual stress depend on the shape and material of the casting, and other foundry variables. Phase transformations and mould hindrance can cause appreciable amount of stress only if temperature difference exists between parts of the casting while cooling.

### B. *Effect of Different Variables on the Magnitude of Residual Stress*

The factors which influence the magnitude of residual stress can be classified into three categories :

(i) Composition, melt treatment and pouring temperature.

(ii) Mould materials and properties.

(iii) Other foundry variables such as knock-out.

Let us consider one by one.

(i) *Composition, melt treatment and pouring temperature*

In case of cast iron, we can consider the following compositional variables:

(a) Carbon and silicon content;

(b) Phosphorous content;

(c) Sulphur content;

(d) Manganese content.

(a) *Carbon and silicon content*

Not much literature is available regarding the effect of composition and inoculation on the residual stresses in cast iron. Girshovich and Simanovskii[22] measured deflections in *T* section castings of grey cast iron of different compositions. As the total carbon content was raised from 2·5 to 3·5% at a silicon content of 2·1%, the deflection observed changed from negative to a positive value. At a particular carbon content, zero deflection was observed. Similarly at a constant carbon content, an increase in silicon content from 1·7 to 2·7% made the deflection change from negative to positive. At a particular value of silicon content the deflection becomes zero. As the carbon equivalent is increased, the deflection reduces, passes through zero from negative to positive. Further increase in the carbon and silicon contents increase the deflection.

Patterson and Dietzel[19] studied the effect of carbon and silicon contents using rectangular grid castings. They poured six types of cast iron with different carbon and silicon contents. The results were discussed in terms of K factor and the degree of saturation. The degree of saturation Sc is calculated from the relation

$$Sc = \frac{C}{4 \cdot 26 - \frac{Si + P}{3}}.$$

and the K factor given by

$$K = \frac{4}{3} Si \left( 1 - \frac{3}{C + Sc} \right)$$

As the degree of saturation was increased, the residual stresses decreased. For the same degree of saturation higher stress values were observed for castings with higher K factor. Further they observed a linear relationship between the tensile strength (or bending strength) and residual stresses, provided the melt treatments were the same.

### (b) Phosphorous content

In case of inoculated iron, the residual stresses increased with increase in phosphorous content, if the $E$ values were estimated from the bending test. On the other hand, if $E$ values determined from the graphite content were used for the calculation of residual stress, the residual stresses increased slightly up to a P content of $0.49\%$ and thereafter decreased In case of uninoculated iron, the residual stresses increased if $E$ values estimated from graphite content and tensile test were used. Experiments with solid cylinders quenched from high temperatures also showed some increase in residual stress with increase in the phosphorous content.

### (c) Sulphur content

To study the effect of sulphur content on residual stress, irons inoculated with calcium silicide were used by Patterson and Dietzel. The residual stress, calculated with the $E$ values obtained from graphite content, increased as the sulphur content was increased. The authors attribute this to the carbide stabilizing effect of sulphur in cast iron. The residual stress values, calculated with $E$ obtained from bending and tensile tests, decreased slightly with increasing sulphur content, up to $0.1\%$ and thereafter increased.

### (d) Manganese content

The iron used was not inoculated. The variation of residual stress with manganese content shows a maximum and a minimum. The reasons for the minimum and maximum are thought to be as follows. Up to $0.5\%$ Mn the fraction of combined carbon decreases. This causes a decrease in the strength of the material with the result that the rapidly cooling thin members are not in a position to deform plastically the thick member Hence the stresses are lower. Above $0.6\%$ Mn the fraction of combined carbon increases, strength increases and residual stress increases. From $0.8\%$ Mn onwards transformation stresses become effective which in this case reduces the final value of residual stress. This accounts for the maximum value observed.

### Inoculation

Patterson and Dietzel inoculated the irons with ferrosilicon and calcium silicide. Inoculation with calcium silicide resulted in higher stresses. However, with inoculation, the strength of the iron also increased. Therefore, rather than comparing the absolute values of residual stress, it is more enlightening if the ratios of tensile strength to residual stress are compared. This ratio was found to be very high for irons inoculated with calcium silicide compared to uninoculated irons. This means inoculation (calcium silicide) is favourable from the residual stress point of view also. On the other hand, inoculation with ferrosilicon resulted in a lower ratio of tensile strength to residual stress, *i.e.*, the residual stress has increased, but the tensile strength has not increased to that extent.

### Pouring Temperature

Angus and Tonk[1] observe that low pouring temperatures give rise to slag and blow hole defects. These defects can provide stress raisers and initiate cracks. According to them, relatively high pouring temperature will tend to reduce temperature differences due to difference in sections and slow down the overall cooling rate. Patterson and Dietzel also put forward the same argument.

However, the results obtained are just the reverse. Dodd[14] observed a slight increase in residual stress with increase in pouring temperature (Al alloy). T.S. 32 in their work with Al alloy and steel[20] observed an increase in residual stress with increase in pouring temperature. Girschovich *et al.* observed increase in deflection of their *T* section castings (cast iron) with increase in pouring temperature.

### (ii) *Mould materials and properties*

### (a) *Mould strength*

Dodd[14] from his investigations on RR 59 Aluminium alloy in sand moulds came to the conclusion that residual stress was independent of mould hardness. Further he couldn't find any variation in residual stress with mould strength (dry).

T.S. 32 using the triangular grid casting tried to find the variation of residual stress with mould strength in case of Al alloy and steel. They found that the variation of stress with the strength of the mould didn't follow any consistent pattern. However it is worth noting that in their experi-

ments with flanged bars, though they didn't observe any residual stress, after removal from the mould, the casting in the hard rammed mould contracted more than the casting in the medium rammed mould. This immediately suggests that provided sufficient difference in cooling rate, exist, the casting in a mould with high strength can give rise to higher residual stresses.

Parkins and Cowan[16] conducted experiments with cast iron, brass and Y alloy in moulds of different strength. Though in each case wide variation in residual stress with mould strength was observed, no meaningful relationship could be established. Experiments proved that high temperature strength is important and residual stresses increased as the high temperature strength increased.

### (b) Moisture content in the mould

Dodd and T.S. 32 found that residual stresses increased linearly with the water content in the mould. They used Al alloy and steel. Kasch and Mikelonis observed slightly higher value of stresses for casting in the dry mould than those cast in the green sand mould.

### (iii) Other foundry variables such As knock-out

It is a practice in foundries to remove the castings from the mould while it is still in the hot condition. Dodd (Al alloy), T.S. 18 (grey cast iron)[21] and T.S. 32 (Al alloy and steel) observed an increase in residual stress with stripping time, *i.e.*, the castings knocked out early had a lower amount of residual stress. The explanation put forward is that when the castings are knocked out early, the temperature difference between different parts of the castings drastically comes down which results in a lower magnitude of residual stress.

But Kasch and Mikelonis[18] observed the reverse in case of ductile iron. They observed a stress of 4800 psi when the casting was cooled to room temperature in the mould while the casting shaken out when the temperature of the light and heavy sections were above 1340° C, a stress of 6960 psi was observed.

The observations of Timofeev *et al.*[32] is worth mentioning here. They were investigating why the centrifugally cast pipes failed more often than the turn table cast pipes (material: grey cast iron). From the chemical content and microstructure point of view the centrifugally cast pipes were superior. On close examination they found the reason to be due to the

knock-out of the centrifugally cast pipes at high temperatures. According to them, knock-out at high temperatures induces high tangential stresses which caused the failure during testing. Slower cooling reduces the magnitude of tangential stresses.

Thus the effect of knock-out on the magnitude of residual stress is not well established and requires further detailed investigations.

The Technical Subcommittee T.S. 32 tried to find out whether the residual stresses varied when the dimension of the runner was changed. They observed an increase in residual stress with increase in the diameter of the runner (triangular grid castings). It is not clear why this should increase at all.

According to the Technical Subcommittee T.S. 32, there is a definite relationship between the structure of the casting and the residual stresses developed. When the side members of the grid showed heavy chill structure, the casting cracked in the mould itself due to high stresses. This cracking usually occurs in the web at the wider end of the grid at the junction between the side members. According to Angus and Tonks, use of deseners may provide a directional dendritic formation which in turn increases the proneness to cracking. Also the castings were more brittle in places where the graphite was in the undercooled form.

## MECHANISM OF RESIDUAL STRESS FORMATION

The stresses arising due to different cooling rates in thick and thin sections, with special reference to grid castings, is broadly explained as follows. When the molten metal is poured the thin outer members start cooling faster than the thicker member, with the result that the thinner sections shrink faster than the thicker. Thus the forces become operative which first of all produce tensile stresses in the thinner outer members and compressive stresses in the thick middle member. The yokes serve to transmit the forces and may be subjected to a certain amount of bending. Now, the mechanical strength is a temperature dependent property, and the thin outer members as a result of rapid cooling, come first within the range wherein they can take up elastic strains. When the thin members enter this range, the thick member is still in the plastic range, wherein it cannot support any elastic strain. In other words the lighter sections compress and deform plastically the thick centre member. As cooling progresses, the thin members attain temperatures wherein the rate of cooling and consequently contractions become smaller. Up to this point the outer

members are under tensile stress. After a certain time, the cooling rates of the thick and thin members become equal and finally the rate of cooling of the central member exceeds that of the thinner members. When the centre member has cooled to a temperature wherein it can take elastic strains, a process of stress reversal takes place. Some refer to it as thermal stress reversal. First the tensile stresses in the outer members decrease and then become compressive. The thick portion tries to contract, but it is restrained by the rigid outer frame. The effort by the centre member to contract and thereby to pull together the stiff outer members is resisted and this leads to tensile stresses in the thick centre member. If the tensile stress thus produced exceeds the tensile strength at those temperatures, cracking can occur. Or if the compressive stresses are high in the thin outer members, buckling of these parts can occur. Or the casting may be left in a state of balanced stress system.

As the Subcommittee T.S. 32 puts it, the overall view is complicated by the fact that the mechanical properties of the metal do not change suddenly in the manner suggested. The change is gradual and spread over a temperature range.

In the mechanism described above, local plastic deformation of one part relative to another part of the casting is an essential prerequisite. Let us consider a case wherein plastic deformation doesn't occur, but all the strains remained elastic from the moment of solidification to cooling down to room temperature. In this case the thinner sections, cooling rapidly, develop tensile stress whereas the thick portion, cooling slowly, develop compressive stresses. But the strain produced is now elastic. Later when the thicker section cools faster, the compressive stresses in the thicker sections and the tensile stresses in the thin sections decrease gradually. At all stages the deformations are in the elastic range and completely balanced. When the casting has cooled down to room temperature, no residual stresses would be present.

If the mechanism of differential cooling (with local plastic deformations) is operative, it is obvious that stresses will increase if the temperature difference between thick and thin members are increased. This can be brought out by casting conditions or increasing the difference in section thicknesses. However the increase in stress cannot go on indefinitely. When a certain value of cross-sectional ratio is crossed, though large stresses are produced in the thin outer members, this cannot cause much plastic deformation in the centre member, owing to its large area of cross-

section. This results in a lower residual stress in the centre member compared to that with a lower ratio of cross-sectional area. This is clearly demonstrated by the experiments of Dodd[14] in case of Al alloy castings in sand mould (Fig. 7). The trend of result should equally hold good for other materials, though numerical values may be different.
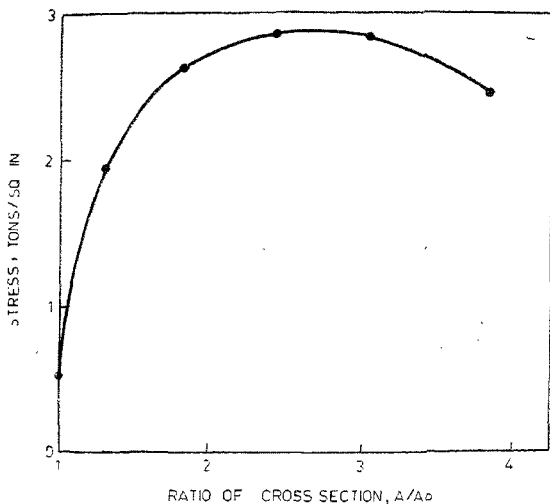


FIG. 7. Relationship between stress in centre member and ratio of cross section of centre and outer members.

T.S. 32 in their attempt to establish that the reverse is also true, increased the thickness of the centre member from very low values. As expected, when the cross-sectional area of the centre member was lower than that of the outer members, compressive residual stress was observed in the centre member. As the thickness was increased, the compressive stress decreased and finally became tensile, after passing through zero.

In materials which undergo phase changes in the solid state, accompanied by volume changes, transformation stresses also arise along with the thermal stresses. The magnitude of stresses remaining at room temperature depends on whether these phase changes, with the associated volume changes, occur at higher temperatures wherein the stresses are continuously

reduced by plastic deformation or whether the phase changes take place at a temperature when the material can take up higher elastic strains. As Patterson and Dietzel[19] point out, any alloying element which influences the rate of transition of the elastic plastic behaviour during deformation, alters the residual stresses also.

Parkins and Cowan[16] conducted a series of elegant experiments to understand the mechanism of residual stress formation in sand castings. The rectangular framework castings were heated and then cooled under conditions which would have been existing in a sand mould. Differential cooling was obtained by winding the members with suitably thick asbestos rope. The temperatures of centre member and outer members were monitored while cooling down from different temperatures. They were able to establish a linear relationship between the final residual stress and the maximum temperature difference. For non-ferrous alloys it was a monotonic increase, whereas for cast iron at a temperature difference of about 180° C, a sharp increase was observed (*See* Fig. 8). This discontinuity is associated with the Ar1 transformation. The experiment also brought out the fact that transformation taking place in one portion was able to plastically deform another part. When they cooled the samples from 730° C or below, the transformation in all the three members took place under cooling conditions which are similar, and consequently had no effect
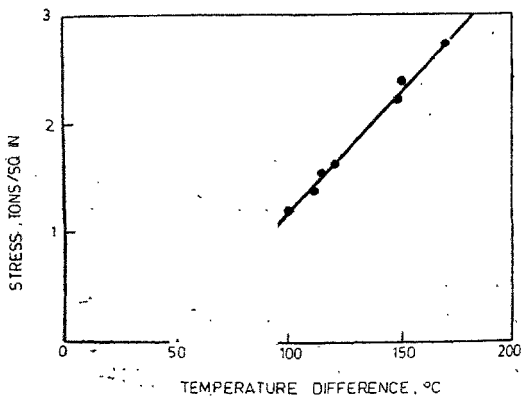


FIG. 8 *a*. Residual stress/max temperature difference relationship. Y-alloy frameworks.
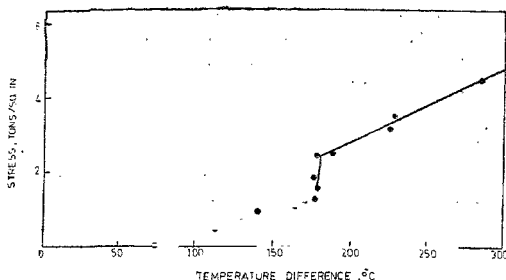
FIG. 8 *b*. Residual stress/max temperature difference relationship in cast iron frameworks

on the final value of residual stress. However, while cooling from higher temperatures, the deformations associated with the higher temperatures are not completely reversed, which adds to the final value of stress.

Now coming to mould hindrance, as in the case of phase transformations, the final values of residual stresses are altered only if sufficient temperature difference existed while cooling so that one part plastically deformed compared to the other. Parkins and Cowan[16] did a series of experiments with rectangular grid castings of different materials using sands of different strength. They summarise the results as follows: In non-ferrous alloy frameworks, the stresses may be entirely attributed to the temperature differences developed while cooling. In grey iron castings the contributions due to phase transformations and sand hindrance may be of the same order as that due to temperature differences.

T.S. 32 did experiments on cylindrical samples with heavy flanges at each end, cast in horizontal position. After removing from the mould, change in length occurred, but no residual stress could be observed. This confirms the earlier arguements that elastically balanced strains should disappear.

## RELIEF OF RESIDUAL STRESS

Do we want to remove the residual stresses completely ? The answer is we would like to remove the dangerous residual stresses. One should be clear as to the requirement. Is it just the removal of locked-in stresses that is desired or is it the distortion which one wants to avoid. From earlier

times it has been a practice to store the castings out of doors for "weathering", by which it was thought that the casting acquires dimensional stability. Even now the common recommendation one comes across is rough machine, age, and finish machine.

If the aim is just reduction of residual stresses, thermal annealing presents itself as a proven technique. But considering the ability of the casting to resist further distortion one has to consider the stress relaxation resistance also. According to Novichkov[33] it is necessary to consider the potential energy levels in addition to stress level and stress relaxation resistance.

The two traditional methods of reducing residual stresses are:

(i) Seasoning or weathering (natural ageing),

(ii) Stress-relief annealing.

Three more techniques are also being employed and/or investigated nowadays. They are:

(iii) Thermal shock,

(iv) Vibration and

(v) Static overloading.

(i) *Natural ageing*

There is controversy as to the magnitude of stress relieved by this process. However, everybody agrees that the magnitude is small, but what is important, a certain dimensional stability is obtained. Stress-relaxation resistance is increased a bit. According to Russel[31], weathering for four months relieves stress by about 15%. The experiments by Tottle[27] and Hallet[34] proved that weathering didn't relieve any stress, which ageing couldn't achieve. Hallett and Wing[23] in their experiments with different types of iron were able to observe a maximum of 10% stress-relief by prolonged ageing.

(ii) *Stress-relief annealing*

This method has been in practice from very early days. The temperature to which particular materials are to be heated can be found from the handbooks. Still it is worthwhile to recall some of the salient features brought forward by research workers. As the temperature is increased, no doubt, the stresses are relieved in a short duration, but at the same time strength and hardness come down. This is undesirable. One should use tempera-

tures which reduce the stress considerably, but does not bring down the mechanical properties. In case of iron castings there is one more factor to be taken into account. If the temperature reaches the lower limit of graphitisation range, the accompanying expansion may create new stress. The temperature chosen must be higher than when the plastic deformation[23] begins. This temperature for grey iron is between 350 and 450° C.

Many authors think that annealing above 550° C may result in a change of structure and deterioration of mechanical properties. Russel experimenting with various types of iron, both inoculated and uninoculated, observed no relief of stress up to 400° C, temperatures in excess of 525° C were required to relieve 50% or more of residual stress, even at 600° C the residual stress was not completely relieved. At 600° C he observed a falling-off of Transverse rupture strength. His recommendations are: rough machine—anneal at temperatures between 550 and 600° C—allow as much time as possible before finish machining.

The rate of heating and cooling are important. If high, especially in complicated shapes, there is a risk of failure. Experiments showed that it is not actually the rate of heating or cooling that is important, but the uniformity of heating or cooling. Zeppelzauer and Brezina[25] recommend the rate of cooling not to exceed 30 to 40°/hr. Simple shapes should be cooled in furnace up to 300° C and complicated shapes up to 100° C.

Kasch and Mikelonis[18] estimated the stress relief obtained by employing various heating cycles: (a) very fast heating rate, slow and fast cooling rate, (b) slow and fast heating rates, slow and fast cooling rates. In (a) they came to the conclusion that a cooling rate of 100° F/hr was optimum. The disastrous consequences of non-uniformity in heating rate was clearly shown by their experiments on grid castings. When the heating rate was highly non-uniform the grids cracked.

Alloying increases the temperature required for stress-relief. Some associate this with the carbide stabilizing influence of the alloying elements. For example Cr, Mo, Ni and V shift the beginning of plastic deformation to higher temperatures. Since Cr and Mo retard the decomposition of cementite at high temperatures, it is possible to remove residual stresses in alloy cast irons with these elements at high temperatures without affecting the mechanical properties adversely.

The temperatures recommended by different investigators are slightly different. Hallet and Wing obtained 82% and 95% relief when annealing

STA/8 cast iron at 600 and 650° C respectively. For centrifugal cast iron 82% at 600° C and 97% at 650° C. For 33% Cr cast iron the relief obtained at 600° C was between 10 and 25%. At 650° C they obtained a stress relief of 90%. For Ni-resist at 600° C relief of 35% and at 650° C 83% were observed. In case of 33% Cr cast iron, annealing increased the tensile strength slightly. But the tensile strength of Ni-resist was found to decrease by about 10%.

Zeppelzauer and Brezina[25] feel that the classification of grey cast iron into unalloyed, low-alloyed and high-alloyed, for the purpose of thermal stress-relief treatment is inadequate. On the basis of their investigations, they classify and recommend temperatures as given in Table I. The results given in a handbook are also included for comparison.

TABLE I

| Sl. No. | Classification | Temp. required for stress reduction of in ° C | | Data given in VDG leaflet |
|---------|----------------|---------|---------|---------------------------|
| | | 80% | 90% | |
| 1. | Unalloyed | 550 | 590 | 500 to 550 |
| 2. | Low alloyed with Cr or Ni or Sn | 565 | 595 | 550 to 600 |
| 3. | Low alloy with Cu or Mo | 590 | 615 | |
| 4. | High alloy with Cr or Ni | 595 | 625 | 600 to 650 |

S.G. iron has a higher residual stress. Transition occurs in the temperature range 500–600° C. According to Zingg,[12] at a temperature of 550° C considerable stress reduction takes place. Some books recommend a temperature of 680° C. But at this temperature hardness and tensile strength are reduced. For ferritic S.G. iron the temperature range should be between 585 and 615° C, whereas for pearlitic S.G. iron, between 570 and 595° C. In case of ferritic iron, annealing results in a lowering of hardness and UTS values, but increase in Young's modulus and elongation. This is attributed to the dissolution of the small fraction of pearlite in the

structure. In case of pearlitic SG iron, $E$ increases slightly, hardness and UTS values are altered very negligibly. No change in structure was observed.

Residual stresses resulting from compositional and structural heterogeneity in castings cannot be removed by thermal annealing.[35]

### (iii) *Thermal shock*

Thermal shock method consists in either rapid heating or rapid cooling or both. In natural ageing, stress is relieved to a small degree, and stress relaxation resistance increased slightly. Regular high temperature annealing brings down the level of residual stress drastically, but unfortunately the stress relaxation resistance also comes down. Subsequent machining may cause renewed distortion in both the cases. In this point the thermal shock method scores over the other two. Thermal shock raises the stress relaxation resistance considerably so that subsequent machining may not cause renewed distortion.

Kosowski[17] puts forward two more points in favour of thermal shock. In regular thermal annealing partial decomposition of the cementite can take place, which lowers the mechanical properties. Another point is the time factor.

Rapid heating causes permanent elongation of the casting with thicker sections and contractions of those elements with thinner sections. Rapid cooling causes deformation in the opposite direction. The rapid cooling process reduces the time necessary for repeating the process. Kosowski heated the castings in a muffled furnace to temperatures of 500, 600, 700 and 800° C respectively. After a holding time of about 5 to 8 mts the castings were taken out from the furnace and immersed in water at 20° C. This cycle was repeated till appreciable reduction in stress was obtained. As the temperature of the furnace (and hence that of the casting before quenching in water) was increased, the number of cycles required to relieve the stresses decreased. It was found that at a furnace temperature of 500° C (casting temperature 300° C) even after 50 cycles, appreciable amount of stress remained, whereas at a furnace temperature of 800° C (CT 700° C) almost complete relief of stress was observed after 3 cycles. These experiments were done with rectangular grid castings. According to him for each shape of the casting, the heating and cooling rates, and the number of cycles should be established separately.

Gerchikov and Kotsyubinskii[36] had done a fairly detailed analysis regarding the stress-relief by the thermal shock method. They established that

the thermal shock method can be applied to a fairly wide range of castings. They bring in the overload factor K which turns out to be one of the most important parameters controlling the dimensional stabilisation of castings by the thermal shock method. K is the ratio of the stress induced by thermal shock to the initial stress. A linear relationship was obtained between the reduction in distortion and the K factor. At a K value of 1·5 to 2·0 the subsequent stress relaxation was reduced to 1/10th its original magnitude. Surprisingly, the temperature he employed was between 200 and 400° C only, whereas Kosowski used higher temperatures.

To get the correct K factor, it is necessary to select the correct furnace temperature and holding time. The authors give a set of nomograms so that the required conditions can be selected with ease. They have indicated how to proceed methodically.

The method can be applied safely to castings containing residual stress not exceeding 25% of the tensile strength of the iron in bending. If it exceeds this value, there is a likelihood of casting failure during the thermal shock treatment. In those cases they recommend a low temperature annealing to bring down the residual stress level to less than 25% tensile strength, to precede the shock treatment. The authors subjected a large machine casting to this treatment and didn't observe any distortion. The nomograms, etc. developed are useful for small and medium castings weighing up to 3 to 4 tonnes. For large castings further considerations are necessary.

(iv) *Stress-relief by vibration*

The advantages of using the mechanical vibration for the relief of stress are :

(*a*) *Economy* : The cost of vibratory equipment is low compared to furnaces, especially when the parts are of large dimension. Working cost is also less for vibratory equipment compared to the equipment for thermal stress relief.

(*b*) *Time factor* : The stress relief by vibration is accomplished in a short period compared to thermal stress relief.

(*c*) It occupies less floor space and is easily portable.

(*d*) No oxide scale formation on the components stress-relieved.

(*e*) No reduction in strength and hardness values.

Glancing through the above-mentioned advantages, one may be tempted to exclaim, go in for vibration only, why resort to the old thermal

annealing at all ! But the research on this particular method has not reached such a stage that one can pick up a component, subject to vibrations as prescribed and then expect for 100% stress-relief. Conflicting opinions are expressed in the literature—one group saying that the stress-relief is complete, while the other group contend that they could not detect any relief of stress at all. A parallel to this can be found in the case of relief of residual stresses in weldings by the vibration technique. Here also same controversy exists.

One of the earliest investigations was by McGoldrick and Saunders.[37] They were not able to establish the amount of stress-relief obtained by vibration, however, a significant increase in dimensional stability was observed. The third report[38] of the Subcommittee T.S. 32 was entirely devoted to vibratory stress-relief. They took triangular grid castings (grey cast iron) and subjected them to vibration by three different methods (i) Pneumatic vibrator—3587 cycles/min, (ii) Vibrator used for knock-out grid—1,000 cycles/min, (iii) Barrelling—32 rev/min. In no case did they observe any stress relief. In another series they used loaded jigs instead of grids. Here also they didn't observe any relief of stress. They concluded that no useful relief of stress could be achieved by the simple vibration treatments applied. However, the scatter in the numerical values is too high, so that one has to take the conclusions arrived at with caution. Also the mode of mounting the grid is not indicated. This is very important as will be shown later.

Gut mounted triangular grid castings of grey iron with about $2 \cdot 5$ tons/in.$^2$ tensile residual stress in the central member on an Amsler pulsator. Initially a compressive load of about 5 tons was applied. A further fluctuating stress of 1–4 tons/in.$^2$ was superposed at a frequency of 151C/S. He determined the residual stress-relief as a function of frequency, number of vibrations, fluctuating load and initial compressive stress. In no case did he observe any decrease in residual stress. On the contrary he observed an increase in stress as a function of the fluctuating load.

Kasch and Mikelonis[18] subjected G-66–2B test castings of iron to sonic vibration. The castings were rigidly clamped to a steel plate to which the vibrator was attached. The frequency used was 160 C/S. They observed a stress-relief of the order of 6 to 10%, compared to 74% stress reduction if the castings were treated at 1100° F. They also made bigger size castings and subjected them to resonant vibration. There too they didn't observe any appreciable reduction of stress. However, from their description of clamping, it seems that the casting was simply executing reciprocatory motion, without being subject to any flexural stress. In that case, one

cannot expect any relief of stress. Buehler and Toenshoff[39] came to the conclusion that vibration is incapable of removing residual stresses.

The approach by Kotsyubinskii *et al.*,[28] Adoyan *et al.*[29, 30] and Lokshin[40] seems to be more pragmatic. Citing the controversy existing in the literature they conducted some experiments to clarify the situation. They didn't use specimens which contained stresses in the as-cast condition. But stresses were introduced externally. The shape of the specimens used by Kotsyubinskii and Adoyan is shown in Fig. 6. The distance between the cantilever arms were measured accurately, and change in this distance is used to compute the relief of stress.

Kotsyubinskii *et al.*[28] did experiments on Sch 21–40 cast iron. They found that the relief of stress was strongly dependent on the amplitude of vibration; higher the amplitude, higher the stress-relief obtained. However, one cannot go on increasing the amplitude since fatigue failure can start when the limit is crossed. The bulk of the stress reduction takes place during the first hour; extending the time leads to further reduction, but the amount of stress relieved is relatively small. It is better to limit the time to 1 or 1½ hours when 90% of stress reduction corresponding to the particular experimental conditions would have occurred. This observation is validated by other investigators also, though some vibrate it as long as 3 hrs. The manufacturers of the vibratory stress-relief equipment recommend time of only 1 hr or below.

When the frequency was varied from 7,600 to 12,000 c/min at approximately constant amplitude, the relief remained same indicating that at least in this range the effect is independent of frequency. It is dependent only on amplitude and time. The maximum stress relaxation obtained was only about 25%. But the prime advantage is that, after vibration treatment the component becomes stabilised. After the vibration treatment, there is no tendency to redistribute the residual stress, whereas in specimens not subjected to vibration treatment, the stress relaxation continues for long periods.

Adoyan *et al.*[29,30] also conducted experiments on same type of specimens. Their main aim was to establish the conditions to stress relieve specimens with different initial stresses. They did not report how much stress was relieved. Paramount importance was given to the distortion occurring after vibration treatment at different conditions. The distortion measurements were continued up to 3 or 4 months.

In this context they introduce a parameter K called the overload factor. The overload factor is defined as the ratio of the vibration amplitude to the

initial stress. The specimens were given different initial stresses, 6, 8, 10 and 15 kg/mm². The vibration amplitude was $\pm 3$ kg/mm² so that the percentage overload factor varied from 5 to 20 (K from 0·5 to 0·2). Vibration time was 3 hr at a frequency of 50 C/S. The plot of distortion *vs* time for the specimens treated this way is shown in Fig. 9. As the percen-
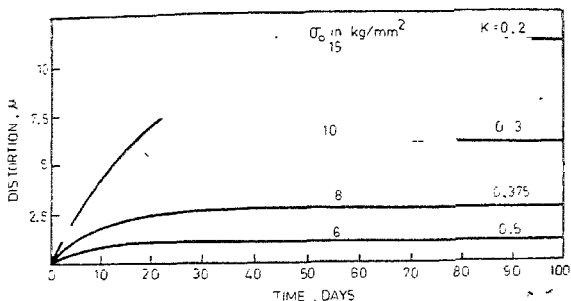


FIG. 9. Distortion of vibrated specimens.

tage overload factor increased from 20 to 50 (factor of 2·5) the subsequent distortion reduced by a factor of 10. In their second investigation also they found identical results. The surprising result is that in spite of differences in the initial stress values and vibrational amplitudes, the distortion curves correspond strictly to the K value. Whenever $K \geq 0·45$ there is practically no distortion. Hence to fully stabilise the castings correct choice of K is essential.

If the initial stress value is known, immediately one can fix the vibration amplitude to get the correct K value, subject to the condition that the fatigue limit is not crossed. For this the authors classify the castings into two groups: (a) the case where the residual stresses are below 0·25 times the tensile strength. Here vibration treatment with appropriate overload can be straightaway applied. (b) The case where the residual stress exceeds 0·25 times the tensile strength of the iron. Two alternative procedures are recommended in such cases: (i) Apply the vibration amplitude above the fatigue limit for a short duration. The time should be low. This procedure may be necessary especially in castings with a high level of residual stress. (ii) Where the residual stresses are in the range 0·25–0·75 the tensile strength, first subject the castings to thermal annealing treatment so that the residual stress is brought to the 0·1 to 0·25 tensile strength range. Then subject them to vibrational treatment with appropriate K factor.

According to Lokshin[40] useful effects of vibration are to be expected only when the object undergoes strain with every cycle of vibration. The component should be clamped in such a way that it is free to deform under elastic vibrations. The points of support should be as localised as possible. If the component performs simply reciprocatory motion along with the vibrator, no stress relaxation could be expected. Alloys with low relaxation criteria will respond more readily to vibration treatment. Lokshin's experiments were mainly with aluminium alloy specimens. He observed significant reduction in residual stress (up to 74%) of components vibrated under resonant conditions. According to him vibration treatment under sub-resonant conditions is not that effective.

Now let us consider a case where the vibration was applied to a prototype casting. The part chosen by Skazhenmik[41] was the top table of a circular grinder of Sch 21–40 iron. The rough casting weighed 175 kg, which came down to 118·5 kg after machining. The slideways were machined and finish ground prior to vibration ageing, leaving an allowance of 0·3 mm for finishing. After vibrating under 3 different conditions, the castings were set up on special racks for inspection and measurement of distortion. Simultaneously observations were also carried out on specimens (a) which were not given any treatment at all and (b) which were subjected to thermal ageing. The distortion in untreated samples (natural ageing) continued for 18 months or more; in thermally aged samples it continued for a period of 6–7 months whereas in samples subjected to vibration treatment, the distortion stopped after $3\frac{1}{2}$ months. Thus for this particular component, under the above-mentioned conditions of vibration treatment, the time required for the cessation of distortion was half that required after thermal ageing and a quarter of that required for natural ageing.

The reason for the continuance of distortion for an appreciable time after vibration may be either due to insufficient application of the overload factor or the method of clamping or both. Insufficient K will always be a problem, so long as one does not know what the initial stress level is. This immediately brings forward one of the drawbacks of the method. At least approximate knowledge of the residual stress is necessary to apply the correct amplitude. In those cases it is of immense help if the magnitude of residual stresses can be predicted from the geometrical shape of the casting and the cooling conditions. A few attempts have been made in this direction.[44, 45]

*(v) Static overloading*

In this method the component is loaded in the static condition.[42] The direction of the applied load (called overload) should be in the same direction as the residual stress. Kotsyubinskii *et al*[28] comparing the static overloading and vibration techniques, found out that for the same overload, the percentage of stress reduced by vibration is higher than that obtained by static overloading. However, the same degree of stress-relief can be obtained by increasing the magnitude of additional imposed static load. The advantage of this method over the vibration technique is that one need not be haunted by the fear of crossing the fatigue limit. It is only necessary that the RS + static load should be within the static strength of the materials, which is high.

Static overloading, like in the case of vibrational ageing, is work hardened so that stress relaxation resistance is increased.[29] In a casting of complex shape, it is rather very difficult to estimate the stresses in different sections and then apply static loading of the same sign as the residual stress at different sections. The method doesn't seem to be popular.

Novichkov[33] summarises what different treatments achieve. The parameters considered are residual stress level, stress relaxation resistance and potential energy.

| Process | Residual stress | Stress relaxation resistance | Potential energy | Remarks |
|---|---|---|---|---|
| Natural ageing | Lowers RS by 7–20% | Appreciably (?) raised | Lowered slightly | |
| Annealing in the range 550–600° C | Lowered by 85–90% | Decreased appreciably | Lowered | |
| Heating in the presence of elastic vibration | Lowered | Appreciably raised | Lowered | Practical difficulties |
| Thermal shock | Lowered | Increased | Raised | |
| Static over load and vibration | Lowered but amount depends on different parameters | Increased | | Difficulty in case of complex castings |

Heating in the presence of vibration has all the good qualities. Though beset with practical difficulties it may be worthwhile to explore this field further. Novichkov recommends another procedure; thermal cycling in the temperature range 200 to 280° C. According to him this is much more effective in giving dimensional stabilisation to the castings than annealing at high temperatures.

Adoyan *et al.*[43] also recommend low temperature 220–300° C to get better dimensional stability. They say, heat treatment below 300° C produces substantial strengthening. Residual stress is lowered by about 8% only.

Summing up, we see that different methods have different advantages. Though beset with practical difficulties, combination of two or more methods seems to be more effective. Though the mechanism of stress-relief by various methods is not clearly understood, it is legitimate to expect the graphite particles to play some role in the relief of residual stresses. The influence of graphite particles on the plastic deformation of iron castings has been analysed in detail.[46–48]

## Some practical hints to produce stress-free castings

Rather than producing castings with high stresses and then subjecting them to stress-relief treatment, the ideal thing will be to produce castings without any or very low residual stress. The detailed analysis of causes and the mechanism of residual formation are helpful in this regard. Also a thorough knowledge of how the residual stresses are altered by different parameters will help to choose conditions wherein residual stresses are minimum.

It has already been established that temperature difference existing in the casting while cooling is the main cause for the formation of residual stress. Any step taken during casting to reduce this temperature difference will result in a reduction of stress. One of the techniques usually adopted is casting into hot moulds. T.S. 32 has found substantial reduction by this procedure. When (grey cast iron) cast into moulds at room temperature, 200° C and 400° C residual stresses of 8·90 tons/in.$^2$, 5·18 tons/in.$^2$ and 3·59 tons/in.$^2$ respectively were observed. Knock-out is already discussed. Other procedures are: using sand of high thermal conductivity or metallic chills around heavy portions, running the casting through the thinner portions, etc. Some of these steps may create other foundry problems. So one has to be choosy. Kotsyubinskii[49] has developed a

system which will measure temperature at different parts of complicately shaped castings and apply forced cooling wherever necessary.

## CONCLUSION

The causes of residual stress formation seems to be fairly well understood. Due to a variety of reasons it may not be possible to take all necessary steps to eliminate residual stresses during the casting stage itself. Thus we are left with castings containing different amounts of stress, both in magnitude and direction, which varies within a casting and from casting to casting. It becomes necessary to relieve these stresses. Though a number of methods are being used, there are some limitations to each method. The mechanism behind stress-relief is not understood very clearly. This requires further study.

## REFERENCES

1. Angus, H. T. and Tonks, W. G.  *Proc. Inst. Brit. Foundrymen*, 1957, **50**, 14–18.

2. Portevin, A. and Pomey, J.  *Proc. Inst. Brit. Foundrymen*, 1955, **48**, A60–72.

3. Patterson, W. and Dietzel, G.  *Giesserei (Tech-wise-Beihefte)*, 1966, **18** (3), 151–163.

4.  *SAE Information Report*, J 936, 1965.

5.  *SAE Information Report*, TR–414, 1960.

6. Erickson, M. A.  *Symposium on Testing of Cast Iron with SR-4 Type of Gage*, pp 2–10.  ASTM special Technical Publication No. 97 (1949).

7. King, R. J.  *Symposium on Testing of Cast Iron with SR-4 Type of Gage*, pp 11–15.  ASTM Special Technical Publication No. 97 1949.

8. Stockett, S. J. and Lownie, H. W.  *Symposium on Testing of Cast Iron with SR-4 Type of Gage*, pp. 16–18.  ASTM Special Technical Publication No. 97, 1949.

9. Cameron, J. A.  *Symposium on Testing of Cast Iron with SR-4 Type of Gage*, pp. 68–69.  ASTM Special Technical Publication No. 97, 1949.

10. Flinn, R. A. and Ely, R. J.  Symposium on Testing of Cast Iron with SR-4 type of Gage, pp. 73–83.  ASTM Special Technical Publication No. 97, 1949.

11. Machin, W. and Oldham, M. C.  *Proc. Inst. Brit. Foundrymen*, 1935–36, **29**, 650-684,

12. Zingg, E.                        *Sulzer Tech. Rev.*, 1962, **44** (4), 25–34.

13. Russel, P. A.                    *Proc. Inst. Brit. Foundrymen*, 1945–46, **39**, A185.

14. Dodd, R. A.                      *J. Inst. Metals*, 1952–53, **81**, 77–81.

15. Roth and Seumel                  *Giesserei*, 1943, **30**, 153.

16. Parkins, R. N. and              *J. Inst. Metals*, 1953–54, **82**, 1–8.
    Cowen, A.

17. Kosowski, A.                     *Foundry Trade Journal*, 1968, **125**, 957–958.

18. Kasch, F. E. and                *Modern Castings*, 1969, **55**, 77–89.
    Mikelonis, P. J.

19. Patterson, W. and               *Giesserei (Tech-wiss-Beihefte)*, 1966, **18** (3), 165–178.
    Dietzel, G.

20. First Report of                 *Foundry Trade Journal*, 1952, **93**, 471–477, 505–509.
    Subcommittee T.S. 32

21. Second Report of                *Foundry Trade Journal*, 1956, **101**, 19–27.
    Subcommittee T.S. 32

22. Girshovich, N. G. and           *Russ. Cast. Prod.*, 1963, pp. 72–76.
    Simanovskii, M. P.

23. Hallett, M. M. and              *Proc. Inst. Brit. Foundrymen*, 1949, **42**, A28–35.
    Wing, P. D.

24. Kotsyubinskii, O. Yu.,          *Russ. Cast. Prod.*, 1962, p. 190.
    Oberman, I. Ya. and
    Grechikov, A. M.

25. Zeppelzauer, K. and             *Giesserei—Praxis*, 1966, **8**, 141–147.
    Brezina, P.

26. Benson, L. E. and               *Proc. Inst. Brit. Foundrymen*, 1937–38, **31**, 124.
    Allison, H.

27. Tottle, C. R.                    *Proc. Inst. Brit. Foundrymen*, 1947–48, **41**, A67–75.

28. Kotsyubinskii, O. Yu.           *Russ. Cast. Prod.*, 1961, pp. 365–368.
    *et al.*

29. Adoyan, G. A. *et al.*           *Russ. Cast. Prod.*, 1964, pp. 83–85.

30. Adoyan, G. A. *et al.*           *Russ. Cast. Prod.*, 1966, pp. 129–133.

31. Report of Subcommittee          *Proc. Inst. Brit. Foundrymen*, 1949, **42**, A61–77.
    T.S. 18

32. Timofeev, A. A. *et al.*         *Russ. Cast. Prod.*, 1967, pp. 318–320.

33. Novichkov, P. V,                 *Russ. Cast. Prod.*, 1970, pp. 484–487,

34. Hollet, M. M.                    *Proc. Inst. Brit. Foundrymen*, 1958, **51**, 355.

35. Kotsyubinskii, O. Yu.          *Russ. Cast. Prod.*, 1962, pp. 563.

36. Gerchikov, A. M. and          *Russ. Cast. Prod.*, 1970, pp. 314–317.
    Kotsyubinskii, O. Yu.

37. McGoldrick, R. T. and         *J. Am. Soc. Naval Engrs.*, 1943, **55** (4), 589–609.
    Saunders, H. E.

38. Third Report of               *Proc. Inst. Brit. Foundrymen*, 1960, **53**, 10–13, 455–458.
    Subcommittee T.S. 32

39. Buehler, H. and               *Giesserei*, 1965, **17** (4), 163–168.
    Toenshoff, H.K.

40. Lokshin, I. Kh.               *Russ. Cast. Prod.*, 1965, pp. 454–456.

41. Skazhennik, V. A. *et al.*     *Russ. Cast. Prod.*, 1967, p. 304.

42. Buehler, H. and Schepp, W.    *Giesserei (Tech-wiss-Beihefte)*, 1961, **13** (4), 215–220.

43. Adoyan, G. A. *et al.*         *Russ. Cast Prod.*, 1973, pp. 198–199.

44. Gishovich, N. G.              *Russ. Cast Prod.*, 1963, pp. 293–294.

45. Zhuravlev, V. A. *et al.*      *Russ. Cast. Prod.*, 1972, pp. 275–276.

46. Kotsyubinskii, O. Yu. and     *Russ. Cast. Prod.*, 1967, pp. 185–191.
    Oberman, Ya. I.

47. Kharpov, A. Ya. *et al.*       *Russ. Cast. Prod.*, 1972, pp. 366–367.

48. Skazhennik, V. V. *et al.*     *Russ. Cast. Prod.*, 1972, pp. 413–414.

49. Kotsyubinskii, O. Yu.         *Russ. Cast. Prod.*, 1973, pp. 140–141.