RESIDUAL STRESS AND ITS EFFECT ON SERVICE.

By

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ABSTRACT

Presence of residual stresses in a component either improves or impairs its service life, depending on the type and distribution of stresses in relation to service stresses. This paper reviews the origin of different types of residual stresses, thermal, transformational and mechanically induced. Nature of thermal and transformational stresses involved in quenching tempering, in spot and butt welding induction and flame hardening, nitriding, case carburising, stresses of mechanical origin as in strip rolling, wire drawing, surface rolling and shot peening have been discussed with their respective stress distribution patterns. The effect of different types of residual stresses originating in these processings is discussed.

INTRODUCTION.

Residual stresses until recently had been recognised to exercise deleterious effects. For example, they are responsible for season cracking, quenching and grinding cracks, wraping and distortion during machining. But investigations have proved that residual stresses when properly balanced may contribute to the improved service life of structural members. There presence in proper manner may not only serve to minimise service failure, especially of dynamically stressed parts but may also improve design creteria of strength to weight ratio. But to achieve this, a thorough knowledge of the type and distribution of residual stresses met with is necessary.

Whenever a metal is plastically deformed, either by severe temperature gradient caused by some heat treatment operation, by forming operations such as rolling, drawing or forging, by phase transformation or by precipitation from solid solution, it is left in a state of strain. The resulting stress remaining after all external stresses have been eliminated is called residual stress. Its origin can often be analysed. For example, when a beam is bent in the plastic range, the outer fibres suffering maximum strain deform plastically while the inner having been elastically deformed, on release of stress try to compress the outer fibres thus producing compressive residual stress at outer and tensional in inner fibres. Example of other type of mismatch is quenching of steel bar which has been heated to austenitic condition. On quenching, the surface layer undergoes a martensitic transformation with consequent increase in volume. This expanded outer zone produces mismatch with the core which tries to press up the case producing compressional residual stress at the surface and tensional at the core.

The origin of residual stresses may be traced to the following causes :—

1. Thermal.
2. Mechanical.
3. Chemical.

THERMAL AND TRANSFORMATIONAL RESIDUAL STRESS :

Thermal stresses arise due to differential thermal expansion causing inhomogeneous plastic deformation in the body when the metal is heated and then suddenly cooled. It must be stated that for thermal residual stresses, when no transformation takes place, plastic deformation is essential. If the deformation occurring during cooling period remains within elastic range no residual stress remains after equilibrium temperature is attained. Over and above this simple thermal stress another due to structural change may be present if the metal is heated above the critical transformation point and quenched. For example, if steel is heated above the upper critical point A_3 and then suddenly cooled the shape and size of the volume elements change differentially due to structural changes.

The nature of residual stresses developed due to different types of thermal treatment may be summarised as follows :—

Quenching :

For simplicity consider the case of quenching of a steel cylinder. A qualitative representation of the formation of thermal stress in such case is shown in Fig. 1.

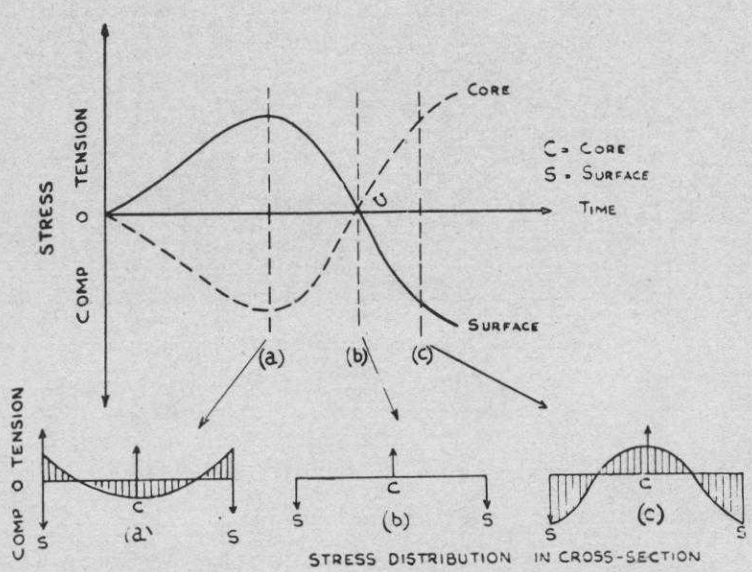

FIG. 1. Transient change of Stress Distribution in Rapidly Cooled Cylinders (Buchholtz and Bühler[1])

The first stage is given by (a). Immediately on quenching the surface temperature is quite low compared with the core; consequently the surface tries to contract but is hindered by the core which is at a much higher temperature thereby causing tensile stresses at the surface. The reverse is the case for the core which is compressed by the contracting surface producing compressional stress at the core.

The low yield strength of the core material which is at a high temperature cannot stand this compressive stress and hence it sinks plastically[2]. When the centre of the bar cools and contracts total contraction becomes more than that of surface. Thereby the tensile stress at the surface changes to compressive stress and compressive stress of the core to tensile. During this change of sign of the stress the point U ((Fig. 1) is reached, when there is no stress at the core or surface. This stress reversal takes place at relatively low temperature. The final stress distribution is given by (c) the surface being in compression and the core in tension. Almost similar phenomenon takes place in case of cooling of a hot ingot as illustrated schematically in Fig. 2.

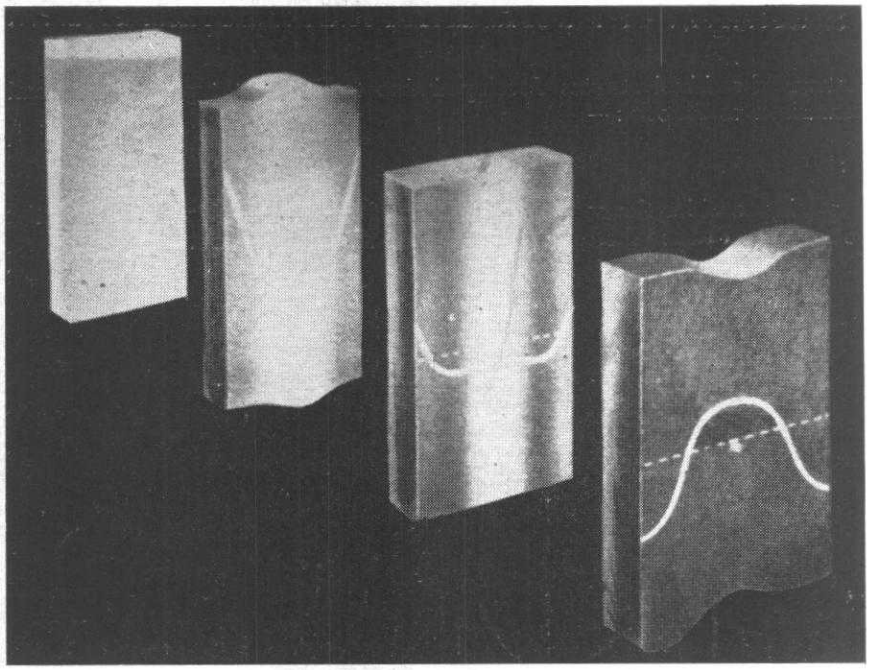

FIGURE: 2—Representation of How Residual Stresses Develop in a Cooling hot ingot[2].

In case when both transformation stress and thermal stress are involved the phenomenon producing residual stress may be divided into three distinct processes[3].

1. First thermal contraction before transformation.

2. Volume expansion due to transformation.

3. Second thermal contraction after transformation.

While processes 1 and 3 as mentioned above produce compression stress at surface, process 2 tends to produce tensional stress.

The relative contribution of the processes is difficult to estimate. But from the experimental data available[4,5] it is shown to depend on relative rate of decrease of the temperature of the surface and the core, which, in case of carbon steel again depends on the carbon content. Greater the carbon content less is the rate of decrease of the temperature[6]. While combined effect of thermal and transformation stresses are considered, Fig. 1 is important in the respect that the basis of heat treatment should be such for constructional steels that martensite formation which produces tensile transformation stress at the surface, should be complete before the temperature of the stress reversal point (Fig. 1) is reached[7]. In that case the final residual stress at the surface should always be compression. Thereby avoiding the possibility of tensile residual stress at the surface which promotes hardening cracks and fatigue failures. For high carbon and highly alloyed materials, the low temperature range of martensite transformation often results in transformation taking place after the stress reversal temperature. Thus the resulting transformaion stress overshadows small thermal stress causing resultant tensile stress at the surface[8].

Quenching and Tempering :

This process is more important, as this type of heat treatment is more employed in industry than simple quenching. The surface stress produced in such operation for plain carbon steel is always compressional[4]. But the magnitude of the stress generally falls gradually with the increase of quenching temperature.

The cooling rate from the tempering temperature also influences the final residual stress. This is illustrated in Fig. 3 for .30% carbon steel with different rate of cooling from the tempering temperature.

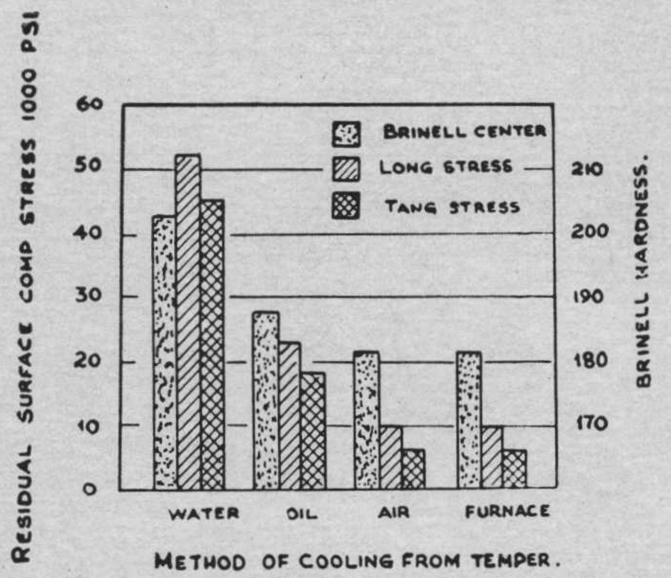

FIG. 3. Influence of Method of Cooling from Tempering Temperature of 1200°F on Residual surface stress in 0.30%C steel water quenched from 1560°F.

Welding :

Welding involves localized heating. The material in the hot localized zone seeks to expand. But expansion in the plane of the plate is restricted by the surrounding cold material. Since due to high temperature, the yield stress of the metal is considerably lowered, permanent plastic compression takes place giving rise to tensional residual stress at the centre of the heated zone and compression in the adjacent zone. But it will be wrong to consider welding stress to be simply thermal stress. Additional stress may arise from volume change arising from phase transformation[9] that may also occur. The stress distributed in case of spot welding was investigated by Siebel and Pfender[10]. Nature of stress distribution as given by them is, illustrated in Fig. 4. Similar stress distribution has also been obtained by Buhler and Lohman[11].

For Butt welding the distribution of stress is as shown in Fig. (5)[12].

Investigations[9, 12] carried out to find the influence of different welding procedure on the magnitude and distribution of residual stress reveal little effect.

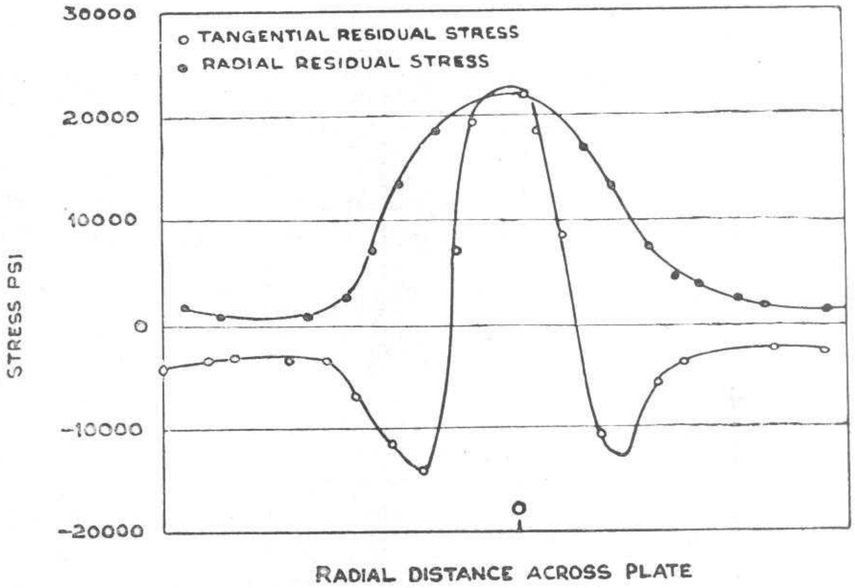

FIG. 4. Tangetial and Radial Stress Distribution in a Strip Heated Locally and Cooled[10].

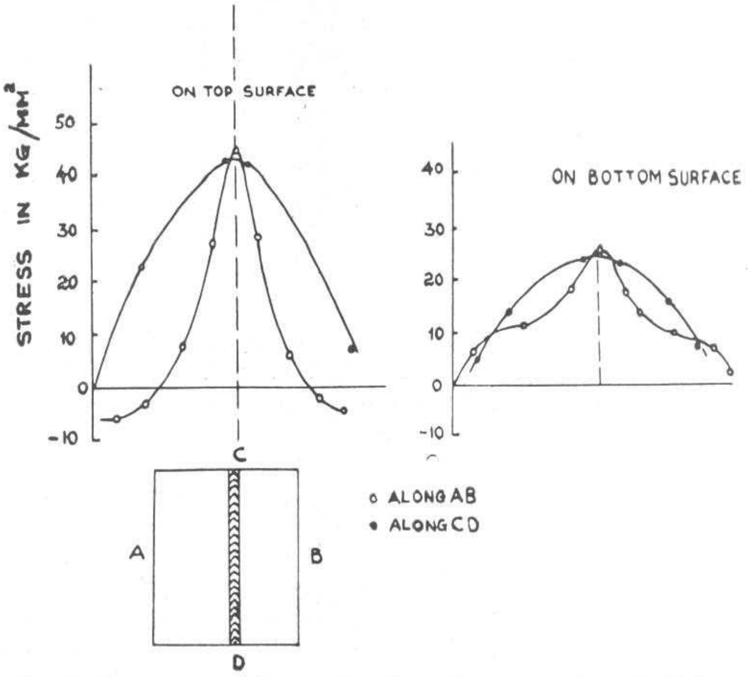

FIG. 5. Transverse and Longitudinal Stress Patterns in Butt Welded Structure[12].

Induction and Flame Hardening:

Rapid heating of the outer surface as effected by induction hardening causes the outer layer to expand. The compressive stress exerted by the cold inner layer causes it to yield plastically If it is cooled in usual course tensional residual stress is produced on the surface. But in usual quenching operation following induction heating, residual stress due to transformation is also introduced which is compressive at the surface layer. As to the net effect due to quenching after induction heating it has been found that the residual stress at the surface is compressive, [13], [14].

In the case of flame hardening the material at the surface is affected in the similar way and the surface residual stress is also found to be compressive [15, 16]. A schematic picture of the internal stress as a result of induction and flame hardening given by Almen[13] can be seen in Fig. 6(a). It can be seen that the surface just below the hardened case has tensional residual stress.

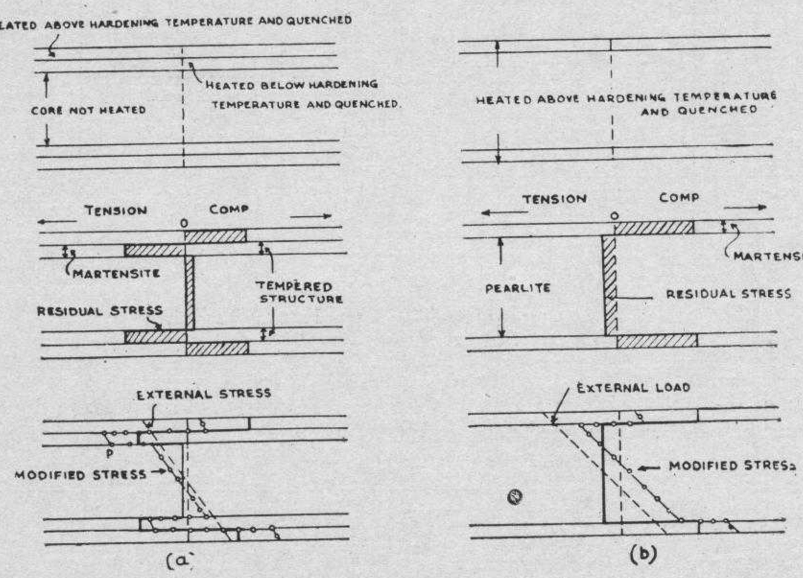

FIG. 6. Surface and Sub-surface Stress Residual Stress in a Round Bar Resulting from Surface Hardening[13].

Surface stress in the case of fatigue being tensional in nature, when imposed on it, gives rise to a peak (P) tensional stress just below the hardened case. This explains the sub-surface fracture as observed in case of induction and flame hardened pieces.

Nitriding and Case Carburising:

In all cases of nitriding and case carburising a considerable amount of compressive stress is found to be introduced in the surface layer (Fig. 5(b)). It has been found that the increase in the volume of the nitrided layer is responsible for this compressive stress.

MECHANICALLY INTRODUCED RESIDUAL STRESS

Cold working that results in nonuniform plastic flow gives rise to mismatch between the portions thereby producing residual stress. Like thermal and transformational stresses, no generalised picture of the stress patterns in cold worked material can be given except in over simplified cases like plane bending of a uniform beam. This is due to the lack of knowledge of the stress involved in different cold working operations and flow of metal under those influences. The nature of residual stresses created in some of simplified industrial forming processes is given below.

Strip Rolling:

The case may be simplified by taking the case of true flat strip with constant reduction in thickness through out the width. In such case two types of stress distribution is effected, Fig. 7(a), 7(b)[2]. It should be mentioned that stress of type (a) has not been directly or experimentally observed but is inferred from the analogous behaviour of strip which is surface rolled.[2]

The type (b) i.e. tensile residual stress at the surface and compressive inside has been observed[17] under rolling conditions in which plastic deformation has penetrated throughout the

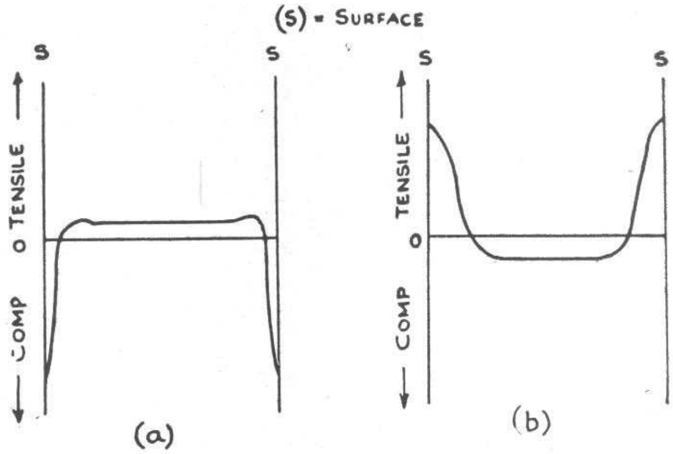

Fig. 7—Two types of Residual Stress Patterns Thought to Exist in Rolled Strip[2].

entire thickness of the strip. The magnitude of the stress at the rolling surface depends upon the roll diameter, strip thickness and reduction of strip thickness[2]. Lighter reduction gives relatively high stress.

Wire Drawing :

Similar to strip rolling wire drawing gives rise to two types of stress patterns; one for very small reduction percentage and a second for higher percentage of reduction. The stress of the first type due to Bühler and Buchholtz[18] is illustrated in Fig. 8(a). It may be seen that in this case both longitudinal and tangential residual stresses are compressional at the outer surface and tensional at the core. The stress pattern changes completely when the reduction percentage is high. In that case the outer surface has tensile residual stress and the core compressional. This is true for both longitudinal and tangential stress Fig. 8(b)[19].

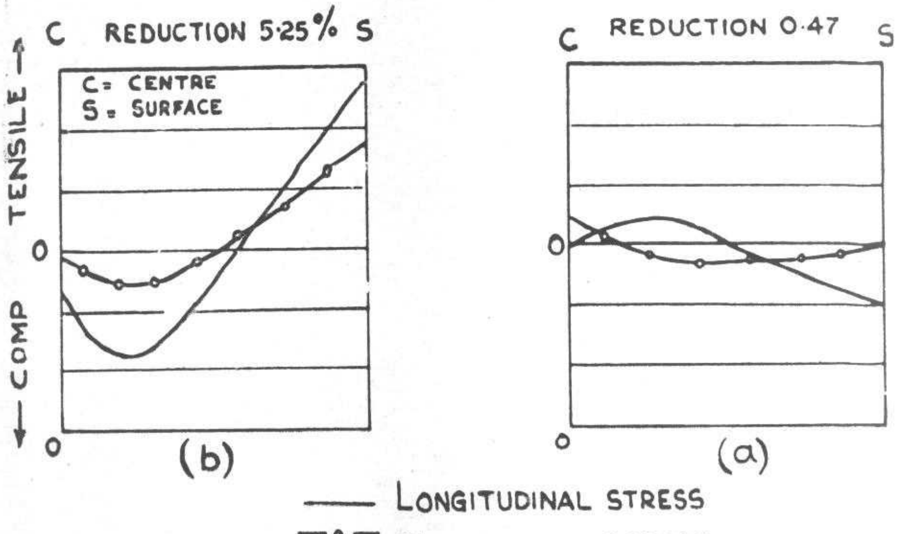

Fig. 8—Longitudinal and Tangential Residual Stresses in Steel Rods Drawn to Different Amounts[18]

In actual wire drawing process in industry the second type of residual stress is only encountered due to the high percentage of reduction. As to the magnitude of the longitudinal residual stress and its relation to die angle an approximate data given by Linicus and Sach[20] is graphically represented in Fig. 9.

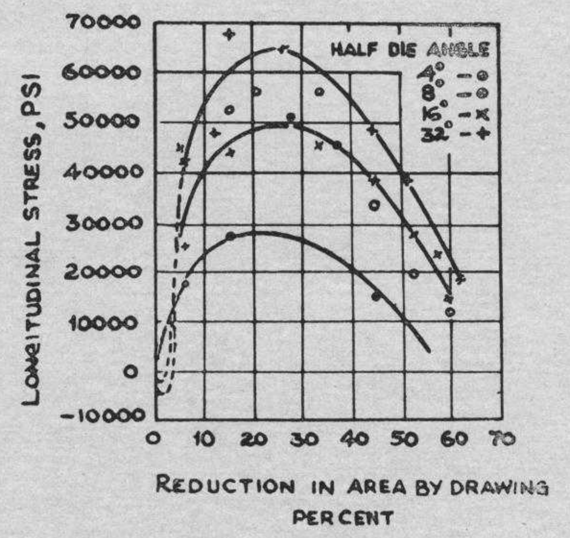

Fig. 9—Approximate Longitudinal Residual Stresses at the Surface of Cold Drawn Brass Wire as a Function of Reduction in Area (Reduction made by Single pass)[20].

It may be noted that for single passes, greater the die angle greater the longitudinal residual stress for same percentage of reduction.

Surface Rolling and Shot Peening :

These two operations are utilized when it is desired to put the surface of a part in residual compressive stress. These operations deform a small thickness of the surface plastically without affecting the bottom layer, thereby the condition for the development of residual stress is met. The process of surface rolling is similar in operation to the way a bar is treated in roll straightener. The rolls press the rotating piece which also advances slowly thereby forming close overlapping thread of plastically deformed surface. The general nature of residual stress distribution is illustrated in Fig. (10)[21].

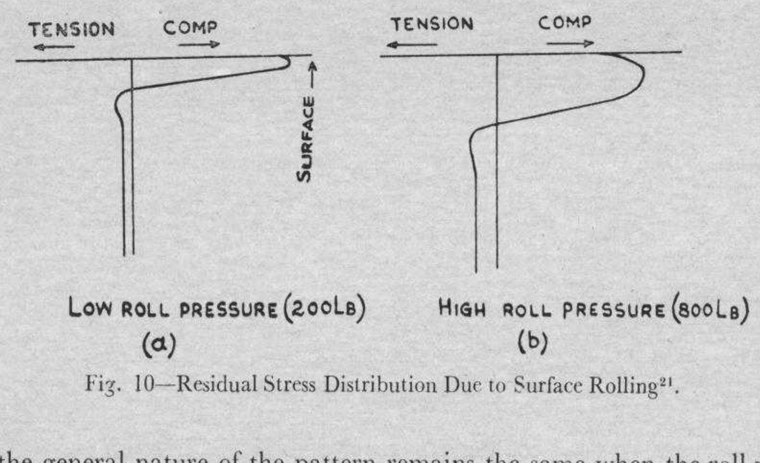

Fig. 10—Residual Stress Distribution Due to Surface Rolling[21].

Though the general nature of the pattern remains the same when the roll pressure remains within certain limit the depth of compression increases with roller load[21]. There is also a slight tendency of the compressive stress to decrease as roller load in increased. The magnitude of the stress increases almost linearly with the roller angle but the depth of compression is hardly affected.

Shot peening is the operation of striking the surface of a metal part with small globular shots with such velocity as to deform the surface plastically without affecting the inner zone. Hence residual compressive stress of the same nature as that in surface rolling is developed. This subject has been dealt elaborately in a separate paper presented at this symposium and hence only to be mentioned here. The type of stress distribution due to shot-peening is similar to that given in Fig. 10(a). The peak value of the compressive stress and the depth of surface stressed compressively varies with shot size and speed.

CHEMICALLY INTRODUCED RESIDUAL STRESS:

When due to some chemical change in a part of a body the size of a volume element is altered a mismatch is produced with the surrounding and internal stress is developed. An example being the state of stress existing between the oxide coating formed on a metal body and the body itself. This subject being of little significance in engineering industries is beyond the scope of this paper.

EFFECT OF RESIDUAL STRESS:

Reason for innumerable service failures may be traced back to high residual stress of one or the other kind. Warping and distortions after heat treatment or machining are always associated with residual stresses. Quick rate of temperature change as encountered in quenching operations often lead to crack particularly when such operation results in high tensile stress at the surface. Tensile surface stress makes the surface very sensitive later on to frequent grinding cracks, stress corrosion and premature fatigue failure. As in cooling, quick rate of heating is also detrimental in some cases. As the transient thermal stress sometimes becomes so great as to cause cracking. Fig. 11[8] shows the crack formation in an ingot heated too rapidly. This is attributed to such transient residual stress.

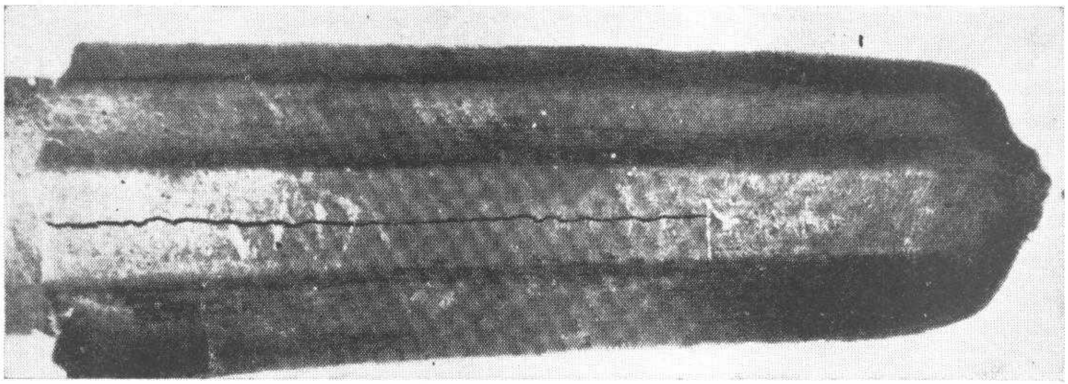

Fig. 11—Ingot Cracked as Result of Too Rapid Heating (SAE 3245 Steel)

One type of heat cracking commonly known as fire cracking is also due to heating stressed metals. As usual explanation is that residual stress in conjunction with thermal stress exceeds the fracture stress of the metal.

Deformation, cracking and even complete rupture of castings during manufacture or service is not uncommon. In many cases it has been found that internal stress in mainly responsible for them. Along with other foundry practice the variation of cooling rate in sections with different thickness and phase change during cooling are responsible for the development of internal stress in castings. Frequent distortions observed during machining of a casting is attributed to redistribution of residual stress brought out by the removal of a portion of metal. Investigation[22] shows that the usual practice of weathering of castings is not helpful for removal of the stress. Based largely on published informations a stress releaving heat treatment has been recommended[22] to be suitable for castings.

There is little evidence to state authoritatively about the effects of residual stress arising out of welding. But it is generally thought that the high tensile residual stress existing near the welded joints causes yield at a lower load. Residual stress is also sometimes thought to affect welded structure by facilitating brittle fracture. The safety of a welded structure against fracture is increased by stress releaving treatment.

Cold drawing and cold rolling processes as mentioned previously generally produce tensile surface stresses. Sometimes this stress may be so high that the material cracks during the forming process.

An example of tubes cracked after the second cold draw pass can be seen in Fig. 12[8].

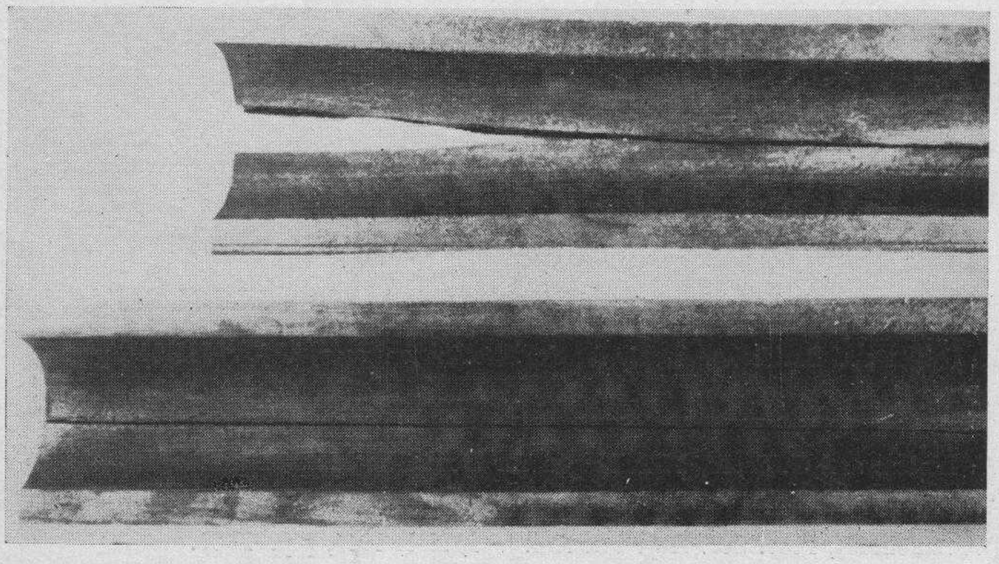

Fig. 12—Residual Stresses Causing Longitudinal Cracks Originating from Inner-Tube Wall.

A compressive residual stress at the surface always leads to increased fatigue resistance. So flame and induction hardening, nitriding, case carburising, surface rolling and shot peening which result in a compressively stressed surface layer show invariably increased fatigue life. Effects of these surface treatments on the fatigue behaviour have been fully reviewed already in a separate paper[23]. It should be noted that flame and induction hardenings have a peak tensile residual stress just below the hardened core, which promotes sub-surface fatigue failure.

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