Lecture 21

Residual stresses in weld joints

This chapter defines residual stresses, and describes the mechanisms of development residual stress in weld joints. Further, the influence of residual stress on performance of weld joints has also been elaborated. Methods of controlling the residual stresses have also been presented.

Keywords: Residual stresses, transformation stress, thermal stress, quench stress, distortion, SCC, control of residual stress

21.1 Residual stresses

Residual stresses are locked-in stresses present in the engineering components even when there is no external load and these develop primarily due to non-uniform volumetric change in metallic component irrespective of manufacturing processes such as heat treatment, machining, mechanical deformation, casting, welding, coating etc. However, maximum value of residual stresses doesn't exceed the elastic limit of the metal because stresses higher than elastic limit leads to plastic deformation and thus residual stresses greater than elastic limit are accommodated in the form of distortion of components. Residual stresses can be tensile or compressive depending up on the location and type of non-uniform volumetric change taking place due to differential heating and cooling like in welding and heat treatment or localized stresses like in contour rolling, machining and shot peening etc.

21.2 Residual stresses in welding

Residual stresses in welded joints primarily develop due to differential weld thermal cycle (heating, peak temperature and cooling at the any moment during welding) experienced by the weld metal and region closed to fusion boundary i.e. heat affected zone (Fig. 21.1). Type and magnitude of the residual stresses vary continuously during different stages of welding i.e. heating and cooling. During heating primarily compressive residual stress is developed in the region of base metal which is being heated for melting due to thermal expansion and the same (thermal expansion) is restricted by the low temperature surrounding base metal. After attaining a peak value compressive residual stress gradually decreases owing to softening of metal being heated. Compressive residual stress near the faying surfaces eventually reduces to zero as soon as melting starts and a reverse trend is observed during cooling stage of the welding. During cooling as metal starts to shrink, tensile residual stresses develop (only if shrinkage is not allowed either due to metallic continuity or constraint from job clamping) and their magnitude keeps on increasing until room temperature is attained. In general, greater is degree of constraint and elastic lami of melt higher will be the value of residual stresses.

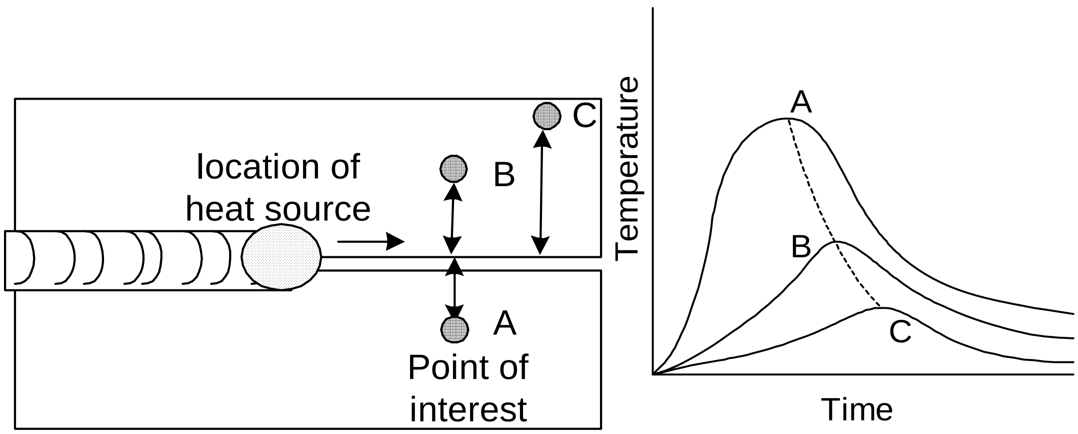


Fig. 21.1 weld thermal cycle of a) locations A, B, C and b) temperature vs time relation of A, B and C

21.3 Mechanisms of residual stress development

The residual stresses in the weld joints develop mainly due to typical nature of welding process i.e. localized heating and cooling leading to differential volumetric expansion and contraction of metal around the weld zone. The differential volumetric change occurs both at macroscopic and microscopic level. Macroscopic volumetric changes occurring during welding contribute to major part of residual stress development and are caused by a) varying expansion and contraction and b) different cooling rate experienced by top and bottom surfaces of weld & HAZ. Microscopic volumetric changes mainly occur due to metallurgical transformation (austenite to martensitic transformation) during cooling. Further, it is important to note that whenever residual stresses develop beyond the yield point limit, the plastic deformation sets in the component. If the residual stress magnitude is below the elastic limit then a stress system having both tensile and compressive stresses for equilibrium is developed.

21.3.1 Differential heating and cooling

Residual stresses develop due to varying heating and cooling rate in different zones near the weld as function of time are called thermal stresses. Different temperature conditions lead to varying strength and volumetric changes in base metal during welding. The variation in temperature and residual stresses owing to movement of heat source along the centerline of weldment is shown schematically in Fig. 21.2. As heat source comes close to the point of interest, its temperature increases. Increase in temperature decreases the yield strength of material and simultaneously tends to cause thermal expansion of the metal being heated. However, surrounding low temperature base metal restricts any thermal expansion which in turn develops compressive strain in the metal during heating. Compressive strain initially increases non-linearly with increase in temperature due to variation in yield strength and expansion coefficient of metal with temperature rise. Further, increase in temperature softens the metal, therefore, compressive strain reduces gradually and eventually it is vanished. As the heat source crosses the point of interest and starts moving away from the point of interest, temperature begins to decrease gradually. Reduction in temperature causes the shrinkage of hot metal in base metal and HAZ. Initially at high temperature contraction occurs without much resistance due to low yield strength of metal but subsequently shrinkage of metal is resisted as metal gains strength owing to reduction in temperature during cooling regime of weld thermal cycle (Fig. 21.3). Therefore, further contraction in shrinking base and weld metal is not allowed with reduction in temperature. This behavior of contraction leaves the metal in strained condition which means that metal which should have contracted, is not allowed to do so and this leads to development of the tensile residual stresses (if the contraction is prevented). The magnitude of residual stresses can be calculated from the product of locked-in strain and modulus of elasticity of metal being welded. The residual stress along the weld is generally tensile in nature while balancing compressive residual stress is developed adjacent to the weld in heat affected zone on cooling to the room temperature as evident from the Fig. 21.2 (b).

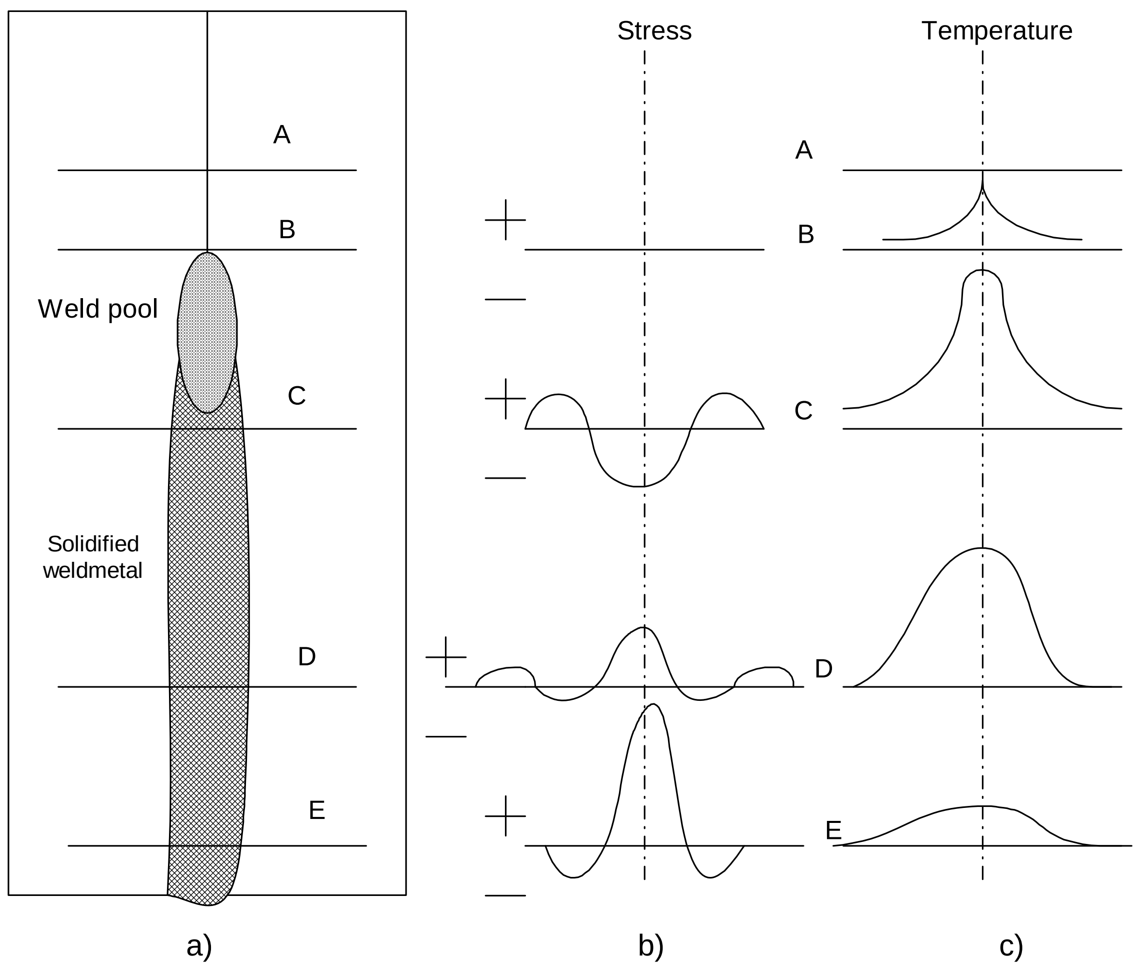


Fig. 21.2 Schematic diagram showing a) plate being welded, b) stress variation across the weld centerline at different locations and c) temperature of different locations

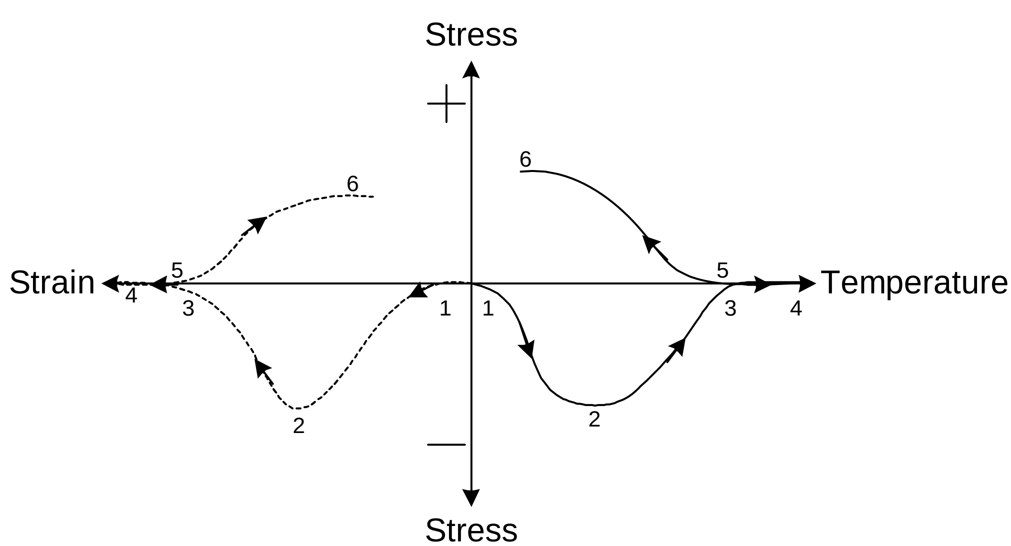


Fig. 21.3 Effect of temperature on variation in stress and strain during welding

21.3.2 Differential cooling rate in different zone

During welding, higher cooling rate is experienced by the top and bottom surfaces of weld joint than the core/middle portion of weld and HAZ (Fig. 21.4). This causes differential expansion and contraction through the thickness (direction) of the plate being welded. Contraction of metal near the surface starts even when material in core portion is still hot. This leads to the development of compressive residual stresses at the surface and tensile residual stress in the core.

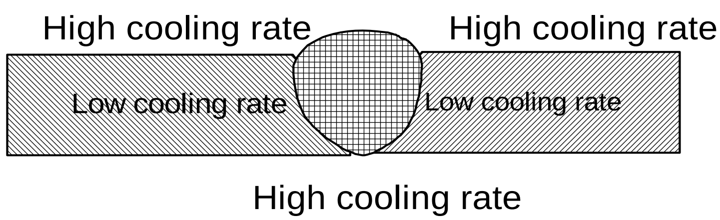


Fig. 21.4 Schematic showing different cooling rates at surface and core regions of the weld

21.3.3 Metallurgical Transformation

During welding, heat affected zone of steel and weld zone invariably experience transformation of austenite into other phases phase mixture like pearlite, bainite or martensite. All these transformations occur with increase in specific volume at microscopic level. The transformations (from austenite to pearlite and bainite) occurring at high temperature are easily accommodated with this increase in specific volume owing to low yield strength and high ductility of these phases and phase mixtures at high temperature (above 550 ^{0}C) therefore such metallurgical transformations don't contribute much towards the development of residual stresses. Transformation of austenite into martensite takes place at very low temperature with significant increase in specific volume. Hence, this transformation contributes significantly towards development of residual stresses. Depending upon the location of the austenite to martensitic transformation, residual stresses may be tensile or compressive. For example, shallow hardening causes such transformation from austenite to martensite near the surface layers only and develops compressive residual stresses at the surface and balancing tensile stress in core while through section hardening develops reverse trend of residual stresses i.e. tensile residual stresses at the surface and compressive stress in the core.

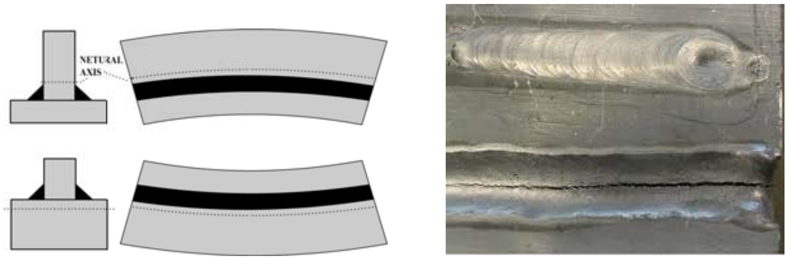
21.4 Effect of residual stresses

The residual stresses whether they are tensile or compressive type predominantly affect the soundness, dimensional stability and mechanical performance of the weld joints. Since magnitude of residual stresses increases gradually to peak value until weld joint is cooled down to the room temperature therefore mostly the effects of residual stresses are observed either near the last stage of welding or after some time of welding in the form of cracks (hot cracking, lamellar tearing, cold cracking), distortion and reduction in mechanical performance of the weld joint (Fig. 21.5).

Presence of residual stresses in the weld joints can encourage or discourage failures due to external loading as their effect is additive in nature. Conversely, compressive residual stresses decrease failure tendency under external tensile stresses primarily due to reduction in net tensile stresses acting on the component (net stress on the component: external stresses ± residual stresses). Residual stress of the same type as that of external one increases the failure tendency while opposite type of stresses (residual stress and externally applied stress) decrease the same. Since more than 90% failure of mechanical component occurs under tensile stresses by crack nucleation and their propagation under tensile loading conditions therefore presence of tensile residual stresses in combination with external tensile loading adversely affect the performance in respect of tensile load carrying capacity while compressive residual stresses under similar loading conditions reduce the net stresses and so discourage the failure tendency. Hence, compressive residual stresses are intentionally induced to enhance tensile and fatigue performance of mechanical components whereas efforts are made to reduce tensile residual stresses using various approaches such as post weld heat treatment, shot peeking , spot heating etc.

In addition to the cracking of the weld joint under normal ambient conditions, failure of weld joints exposed in corrosion environment is also accelerated in presence of tensile residual stresses by a phenomenon called stress corrosion cracking.

Presence of tensile residual stresses in weld joints causes cracking problems which in turn adversely affect their load carrying capacity. The system residual stress is usually destabilized during machining and may lead to distortion of the weld joints. Therefore, residual stresses must be relieved from the weld joint before undertaking any machining operation.



a) b)

Fig. 21.5 Typical problems associated with residual stress a) distortion and b) solidification cracking

21.5 Controlling the residual stresses

The critical applications frequently demands relieving residual stresses of weld joints by thermal or mechanical methods. Relieving of residual stresses is primarily based on releasing the locked-in strain by developing conditions to facilitate plastic flow so as to relieve stresses.

(a) *Thermal method* is based on the fact that the yield strength and hardness of the metals decrease with increase of temperature which in turn facilitates the release of locked in strain thus relieves residual stresses. Reduction in residual stresses depends on "how far reduction in yield strength and hardness take place with increase of temperature". Greater is the softening more will be the relieving of residual stresses. Therefore, in general, higher is the temperature of thermal treatment of the weld joint greater will be reduction in residual stresses.

(b) *Mechanical method* is based on the principle of relieving residual stresses by applying external load beyond yield strength level to cause plastic deformation so as to release locked-in strain. External load is applied in an area which is expected to have peak residual stresses.

(c) *Mechanical Vibration : The vibrations of a frequency close to natural frequency of* welded joint is applied on the component to be stress relieved. The vibratory stress can be applied in whole of the components or in localized manner using pulsators. The development of resonance state of mechanical vibrations on the welded joints helps to release the locked in strains so to reduce residual stresses.

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