6. Residual Stress and Distortion

Residual stresses are those stresses that would exist in a structure or component after all external loads have been removed. Reaction stresses are long-range residual stresses that arise from restraint of welds. There are two principle sources of residual stress: uneven plastic deformation, and uneven solid phase change. In steels, the change from austenite to ferrite, martensite or bainite results in a volumetric expansion of about 14%. If this occurs unevenly, which is usually where cooling rate is high, then residual stress is created. Residual stresses may be created during the following processes.

- Forming processes, particularly cold forming (casting, plate and section rolling, forging, roll bending, pressing etc)
- Heat treatment, particularly when the cooling rate is high (quenching, air cooling thin sections), or uneven composition
- Cutting (shearing, flame cutting)
- Fabrication and Assembly (fit-up, jacking sections together)
- Joining (Welding, brazing, bolted connections)
- Finishing (Machining, grinding, shot blasting)

6.1. Residual Stress From a Thermal Gradient

One common cause of residual stress is the uneven plastic deformation due to a thermal gradient. Wherever there is a temperature gradient, constrained thermal expansion leads to stress. If the resultant strain is plastic, a residual stress is introduced when the temperature gradient disappears. High temperatures are not necessary, only sufficient to induce plastic strain.

This effect is shown using the simple model illustrated in Figure 65. Three bars of equal length and cross section area are fixed together at their ends with rigid restraints. If the middle bar is heated, it is constrained from expanding naturally by the outer bars. Consequently compressive elastic stress increases in the middle bar (Curve AB), balanced by tensile elastic stresses of half the magnitude in the outer bars. Removal of the heat during this stage will allow the assembly to return to its original state.

As the temperature is raised there becomes a point (Point B) at which the compressive yield strength is exceeded, beyond which the middle bar becomes plastic and suffers permanent compression. The outer (cold) bars remain elastic because the stress is only half that in the centre bar and the yield strength is not exceeded. As the temperature of the middle bar is raised, three things happen. Firstly increasing plastic deformation occurs (upsetting). Secondly the material work hardens and thirdly the yield strength decreases.

The net effect is a slight reduction in stress as temperature increases (Curve BC). It is because of the upsetting that residual stress is created when the temperature difference is removed.

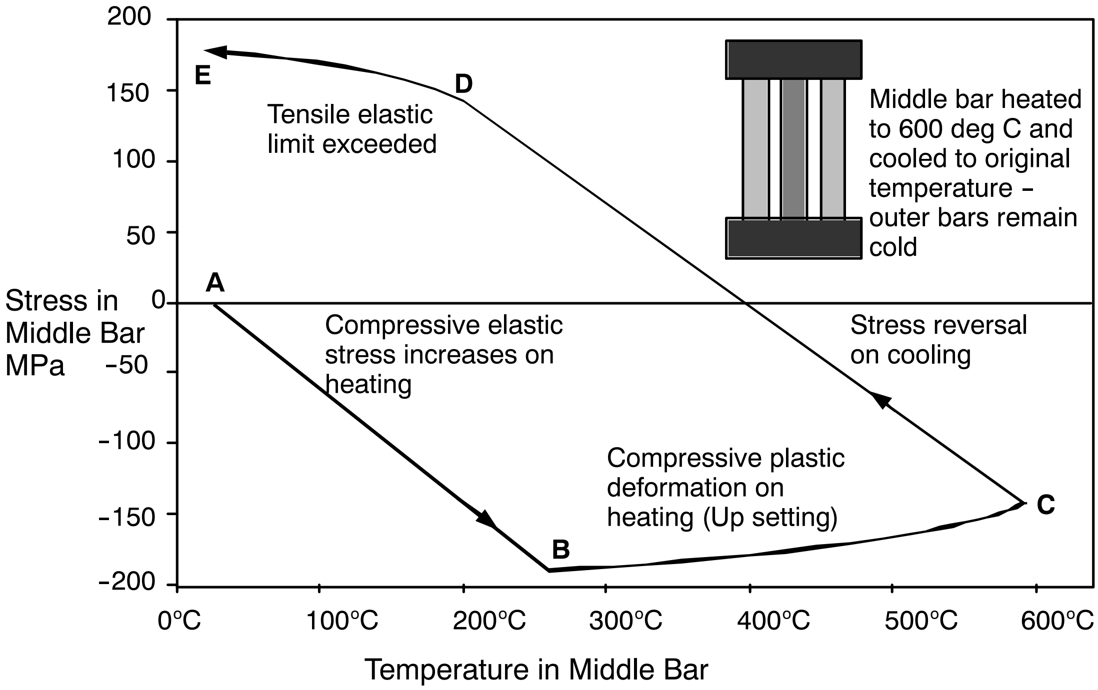

Figure 65 Development of Residual Stress by Temperature Gradient

Heating is ceased when the middle bar reaches 600°C (Point C), and the assembly is allowed to cool. As the middle bar cools, the compressive stress in it rapidly falls, and will change to tension because of the loading applied by the sidebars. Very soon the tensile stress reaches the tensile yield strength (Point D), and during further cooling the stress in the centre bar is limited by the yield strength at the particular temperature (Curve DE). When the assembly has cooled, stress in the centre bar will be at room temperature yield strength. It will be balanced by stresses of half yield strength in the outer bars. If the end restraints are removed the stress will be released, but the centre bar will have been shortened. The outer bars will be their original lengths unless stresses have been sufficient to permanently stretch them.

This simple model illustrates the development of residual stresses without a phase change during thermal processes such as welding, flame cutting and flame shrinkage. The essential factors are:

- A thermal gradient (dependant on rate of heating and thermal conductivity).
- Constraint inhibiting free expansion
- Local stresses rising above yield so that local plastic deformation (upsetting) occurs.
- Reversal of stress as the assembly cools.

Residual stress is dependent on the level of constraint and the thermal gradient. Material properties such as yield strength, Young's modulus, coefficient of thermal expansion, and thermal conductivity, all affect the level of stress. Stiffness of the section is also important, if the thermal gradient causes predominantly elastic out of plane bending instead of plastic compression, the residual stresses will be lower. Instead of residual stress, distortion is created.

6.2. Residual stress in welds

It is possible to visualise the residual stress created in a butt weld by considering the simplified example of a hot bar (representing a weld) being fixed between to cold pieces of plate. As the heat flows out into the plate from the bar, it causes the nearest edges to expand. If this expansion were free, it would cause the plate to bend as shown in Figure 66 (a). However thermal expansion is restrained and yielding (upsetting) occurs instead. When the assembly cools and the thermal gradient disappears, the stresses are reversed as in (b).

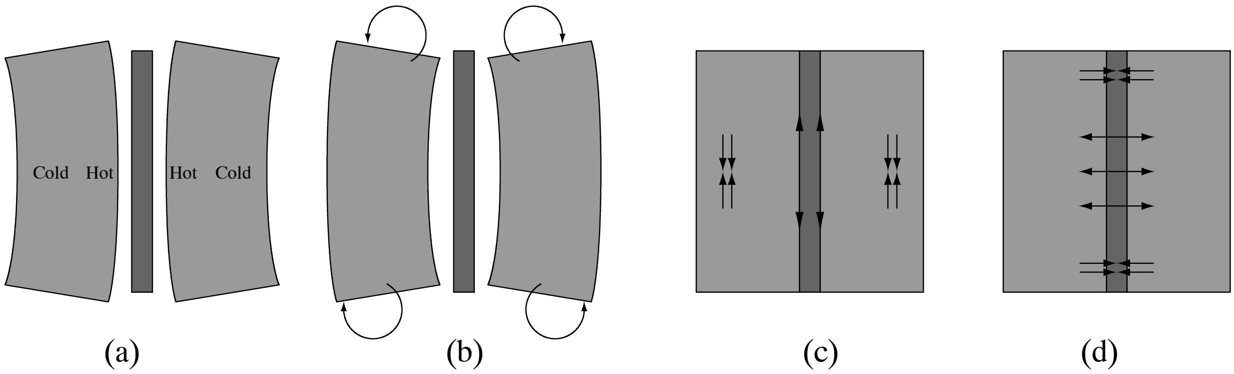

Figure 66 Creation of residual stress

In reality the plates are welded together. To straighten the plates, the weld, as is shown in (b), exerts a bending force. This results in the pattern of longitudinal stress shown in (c) and transverse stress in (d).

Measurements of residual stress in real welds show this model is quite accurate in predicting the residual stress in single pass welds. Figure 67 shows the residual stress distribution of a single pass weld made automatically with no intermediate stops and starts. Real welds, which are usually multipass, have numerous stops and starts, are of complex shape, and therefore have a more complicated stress field. Residual stress varies through the thickness of thicker sections.

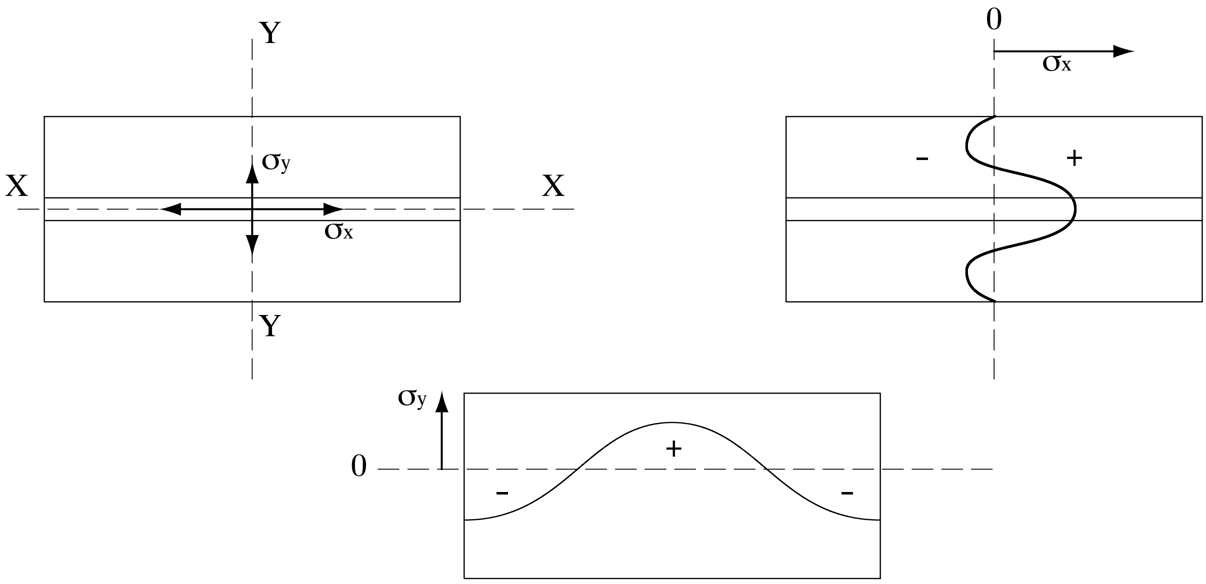

Figure 67 Residual Stresses in a Butt Weld

Most of the residual stress arises because of heating of the plate edges by the weld. Only a small proportion is from cooling and shrinkage of the weld metal. Residual stress is relatively localised in a large weldment.

6.2.1. Restraint and reaction stresses

The stresses described as residual stress above are short range and arise because of local heating of the weld edges. Reaction stresses are transverse to the weld and extend a long way from it. The magnitude and dimensions of external restraint preventing free contraction determine them. They are dependent on the degree of restraint, K, which is defined in terms of dimensions and the modulus of elasticity, E, in Figure 68 below.

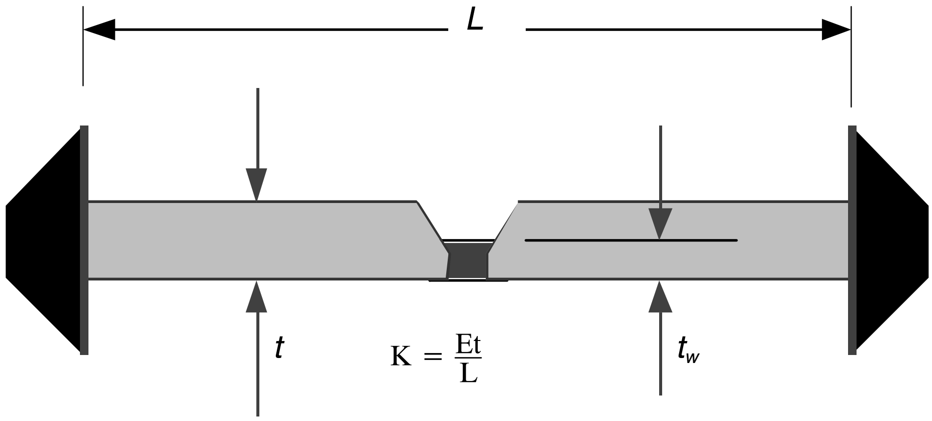

Figure 68 Definition of restraint

Free contraction essentially occurs in two stages. The first stage occurs while the weld is hot and lasts a relatively short time. Heat flows out radially from the weld, causing local contraction. While the heat is still between the reference points, little further contraction then occurs. When heat is conducted past the reference points Stage 2 contraction then commences and continues until the weldment has completely cooled.

6.2.2. Fabrication stresses

Although it is not good practice, fabricators can sometimes use considerable force to fit members together. Hydraulic jacks, chain blocks, levers and even large weights can be used to force members together until they are held with heavy tack welds. This practice can lock considerable amounts of stress, which can extend over a considerable area. It is worth limiting the amount of force that a fabricator can use to pull items together, for example to a 2 tonne chain block. (The actual capacity depends on the material thickness). Fabricators should be encouraged to trim items to fit, or to use buttering to close excessive gaps, rather than spring components together and use heavy tack welds. If force has to be used, then it is preferable to bend the item until it yields and fits without any force.

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Successful Welding of Steel Structures

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