

# Weld Repair of Creep Damaged Steel

## 1. SCOPE

This Note provides guidance on the repair of carbon-manganese and creep-resisting steels containing chromium, molybdenum and vanadium that have been in high temperature service for extended periods.

## 2. CREEP

Figure 1, a typical stress/strain diagram for ductile steel, shows that the application of stress results in a certain amount of strain. Most steel structures operate at stress levels below the yield strength in an "elastic" regime where the applied stress is proportional to the resultant strain with the relationship between stress and strain being described by Hooke's law and strain response by the Elastic or Young's Modulus.

If the applied stress is maintained constant at levels approaching or exceeding the yield strength, for a sufficient time, the amount of strain increases. With most metals and alloys, this only happens at elevated temperatures. The effect is known as CREEP and is defined as "continuing plastic flow under constant conditions of stress".

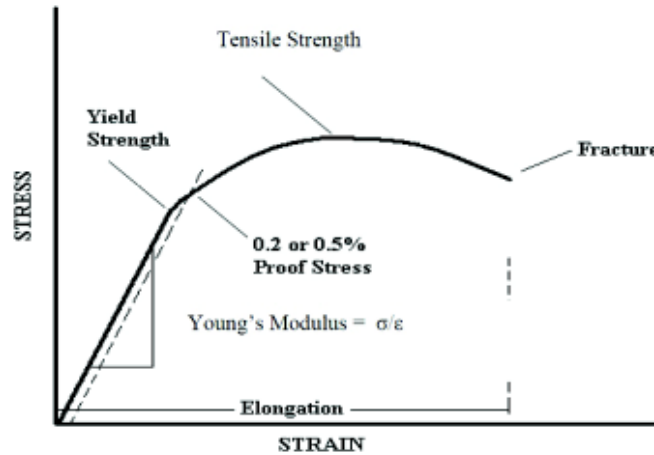


Figure 1. Typical stress-strain diagram

Note: For clarity the slope of the curve in the elastic region has been exaggerated

## 3. INFLUENCE OF TEMPERATURE

The typical stress/strain or load/extension curve depicted in Figure 1 is established at room temperatures. If such short term tests are carried out at elevated temperatures this curve changes as in Figure 2, and a number of physical properties change as shown in Figure 3.

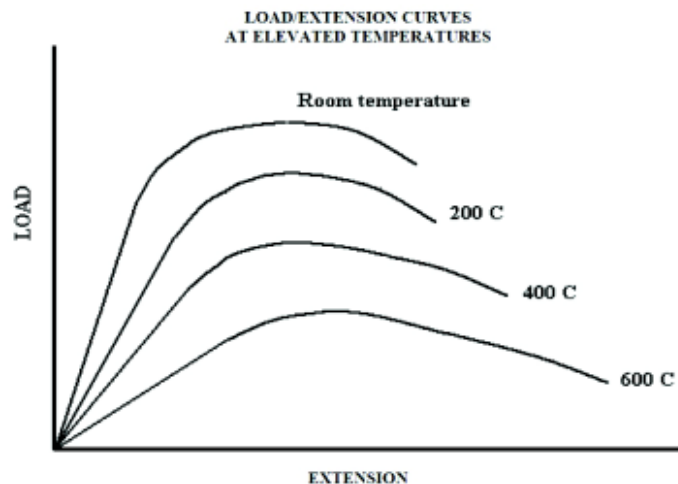


Figure 2. Short term load/extension plots at various temperatures.

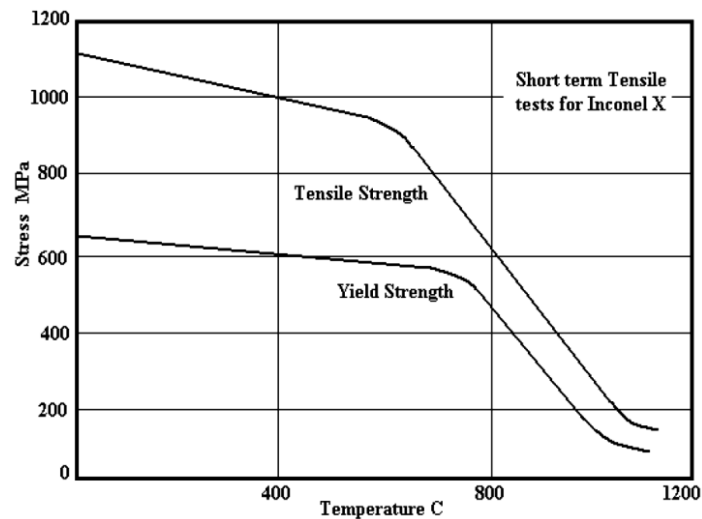


Figure 3. Effect of temperature on yield and tensile strength for Inconel X

Figures 2 and 3 show how increasing temperature results in reduction of Yield strength, Tensile strength and Elastic modulus with an increase in Elongation.

#### 4. INFLUENCE OF TIME

Short-term tensile tests do not give any indication of what changes occur over time when materials operate at high temperatures. The only way to determine the effect of time is to test material over long periods. There are FOUR main factors governing creep behaviour: TIME, TEMPERATURE, STRESS and STRAIN.

One of the standard methods to determine the effect of time is the Stress-Rupture test. The data is presented as the stress required to rupture a specimen in 10, 100, 1000 or more hours, at a given temperature. A logarithmic plot of stress versus time is used to present the data. A family of stress rupture curves at three elevated temperatures is given in Figure 4.

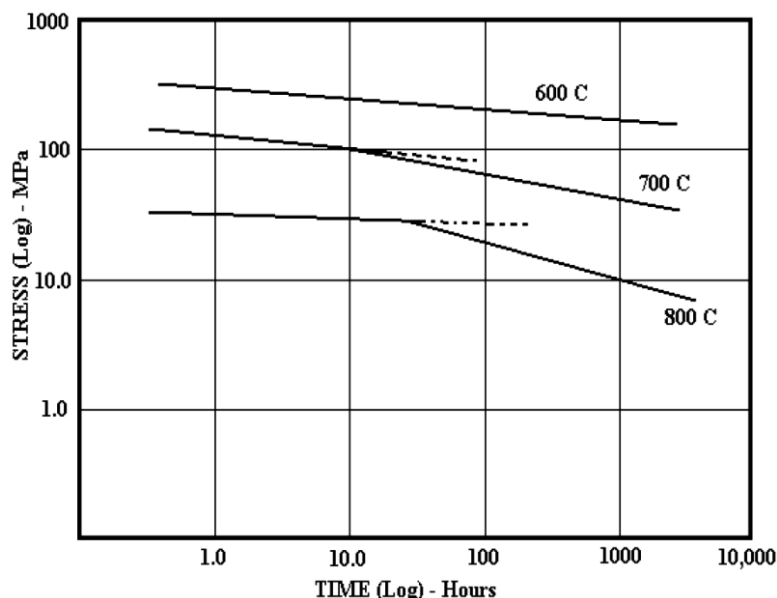


Figure 4. Typical representation of stress-rupture data for a given material.

Although a 1000 hour test provides useful data, it cannot predict what changes may occur over a 100,000 or more hour operating life nor an indication of the microstructural changes that occur. For a better understanding, specimens would have to be creep tested for that period. It is normal in presenting creep data to plot STRAIN (often shown as Extension) as a function of TIME, Figure 5.

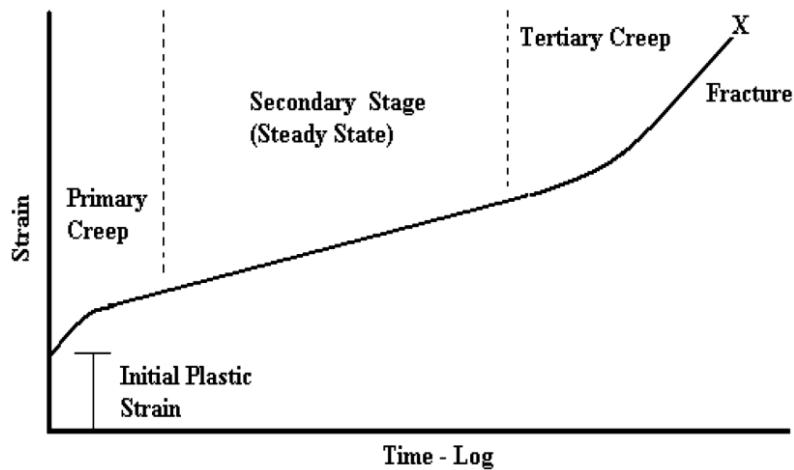


Figure 5. Typical creep curve showing the effect of time on strain for a given temperature and load or stress

Table 1 compares the creep test and stress rupture test.

Table 1. Comparison of stress rupture and creep testing

Creep Test	Stress Rupture Test
Measures strain versus time at constant temperature and load or stress	Measures stress versus time to rupture at constant temperature
Relatively low loads and creep rates.	Higher loads and creep rates.
Long duration, 2,000 to 10,000 hours. Not always to fracture.	Shorter duration, less than 1,000 hours typically. Always to fracture.
Strain measured accurately using sensitive equipment (inductance gauges) to determine creep rate. Strains typically less than 0.5%.	Simpler less sensitive strain measuring equipment (dial gauges). Time and strain to fracture measured. Strains typically up to 50%.

## 5. THE PROCESS OF CREEP

Creep is a complex engineering phenomenon and has been the subject of extensive research. Furthermore there are different mechanisms of creep at different combinations of temperature and stress. Generally creep degradation manifests itself as voiding leading to orientated voiding, then micro-cracking and eventually macro-cracking as damage progresses. Basic understanding of the creep process begins with the consideration that all metals are crystalline in structure and consist of numerous grains orientated in various directions.

Under applied stress there is relative movement along the grains boundaries in the direction of the imposed load. This results in straining of the metal. The sliding of the grains results from interatomic bonds failing preferentially along the grain boundaries. Grain boundaries are the weak zones at high temperatures. Within the grains there are local voids in the atomic lattice known as dislocations. These dislocations allow the atoms within the grain to slide relative to each other, with the region of most dislocations being at grain boundaries. This movement of dislocations eventually results in voids or cavities being formed within the structure at grain boundaries.

Two ways of combating creep are firstly to eliminate grain boundaries and secondly to introduce hard particles into the lattice structure to impede the relative movement of dislocations and grain boundaries.

Eliminating grain boundaries by using single crystal technology has been applied in the gas turbine (jet) engines, but it is too expensive and impracticable to apply to elevated temperature pressure plant, although there is a tendency to use coarse grain steels.

The formation of carbides within the steel microstructure provides a dispersion of hard particles that impedes creep by restricting the sliding of grains and movement of dislocations. Iron carbide ( $Fe_3C$ ) is the particle, or more correctly the precipitate, that governs strength and creep resistance in

structural steels. At elevated temperatures Fe<sub>3</sub>C becomes unstable and begins to revert back to iron and carbon (spheroidisation and graphitisation). Hence, for elevated temperature service, more stable carbides are required. Chromium, molybdenum and vanadium all produce carbides with superior elevated temperature performance and these elements form the basis of most high temperature steels currently in use. However even high temperature carbides eventually spheroidise after prolonged periods.

So the process of creep involves the movement of dislocations around carbides, the relative movement of grains, void formation and grain boundary sliding.

The typical creep curve shown in Figure 5 has three distinct regions:

- **Primary Creep Range.** This is where there is an instantaneous plastic strain and increasing creep rate until a stable situation is reached.
- **Secondary or Steady State Creep Range.** Here microstructural behaviour is slow and predictable. This region represents the useful life of component.
- **Tertiary Creep Range.** This is where microstructural degradation starts and the physical properties begin to deteriorate at an ever-increasing rate.

## 6. STEADY STATE CREEP

In steady state or secondary creep the strain rate is constant because the rate of strain hardening is balanced by the rate of recovery – more specifically there is a balance between a hardening effect associated with dislocation movement and dynamic recovery associated with substructure development. Far more importantly, the minimum creep rate under constant load can be determined mathematically enabling designers and engineers to calculate the life of a component under creep loading conditions. The steady state creep rate increases exponentially with increasing stress in accordance with a power function of stress versus temperature that can be mathematically represented by an Arrhenius expression,  $\dot{\epsilon} = S \sigma^n \exp(Q/RT)$ , where;

$\dot{\epsilon}$  = steady state creep rate  
 S = a constant  
 $\sigma$  = stress  
 n = stress exponent

Q = activation energy for atomic motion  
 R = universal gas constant ( 8.314J/mole K)  
 T = absolute temperature

This exponential relationship can be represented in a logarithmic form as a straight line relationship as shown in Figure 5 or in terms of steady state creep rate versus stress at a given temperature as shown in Figure 6. Steady state creep can be governed by a diffusion controlled process (diffusion creep) at low stresses and a dislocation controlled process (power law creep) at higher stresses as can be seen in Figure 6.

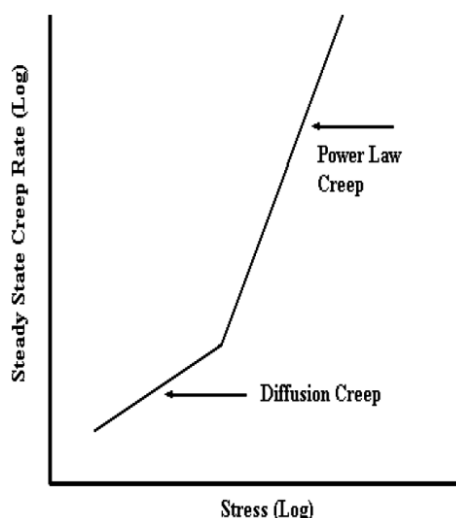


Figure 6. Diagrammatic representation of diffusion and power law creep.

Note: both the Strain Rate and Stress are expressed in logarithmic scales indicating an exponential relationship

## 7. CREEP DAMAGE

The relationship between stress and creep strain predicts that at a given material and operating temperature, the areas that show signs of damage first will be areas of high stress.

Therefore, creep damage occurs on at areas of high primary, secondary or peak stresses such as large stub to header connections, tee pieces, bends, etc. before it occurs on straight lengths of pipe.

These areas also have welds, and it is often welds or, more precisely the Heat Affected Zones (HAZs) that suffer damage first. Welds and their associated HAZs are more susceptible than parent material to creep because they are often in a position of high stress and the HAZ microstructure is not as good as the parent metal microstructure from a creep resistance perspective.

## 8. TERTIARY CREEP

During the Steady State range, the process is one of dislocation movement, dislocation blocking by precipitates and grain boundaries then dislocation climb and then further movement.

The Tertiary Creep range is important because metallurgical damage such as voids and microcracking begins to occur, Figures 7 and 8. The onset of Tertiary Creep is a sign that structural damage is occurring and the component is nearing an end to its design life even though the actual time to rupture can be long.

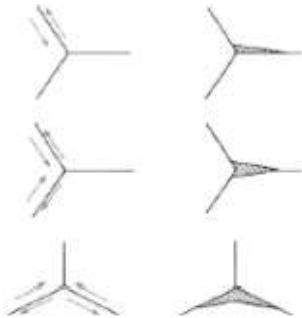


Figure 7. Formation of wedge cracks at grain boundaries

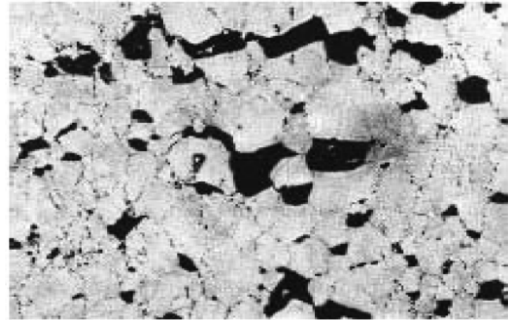


Figure 8. Voids in creep ruptured Nimonic 80A

## 9. CREEP IN WELDS

Welds and HAZs suffer creep damage as much, if not more than parent materials. The consistent location of the damage has resulted in a classification system:

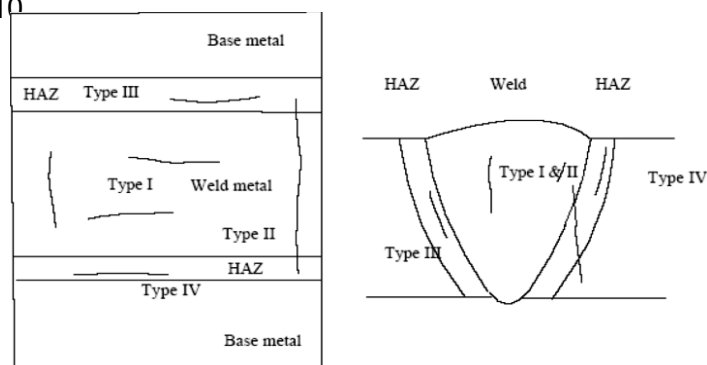
Type I Damage is transverse or longitudinal and is confined to the weld metal.

Type II As with Type I but grows into the adjacent heat affected zone.

Type III Damage in the coarse-grained HAZ i.e. nearer the fusion line.

Type IV Damage originates in or propagates into the inter-critical HAZ.

The creep damage results in cracking shown diagrammatically in Figure 9. An example of HAZ Type IV creep damage is shown in Figure. 10



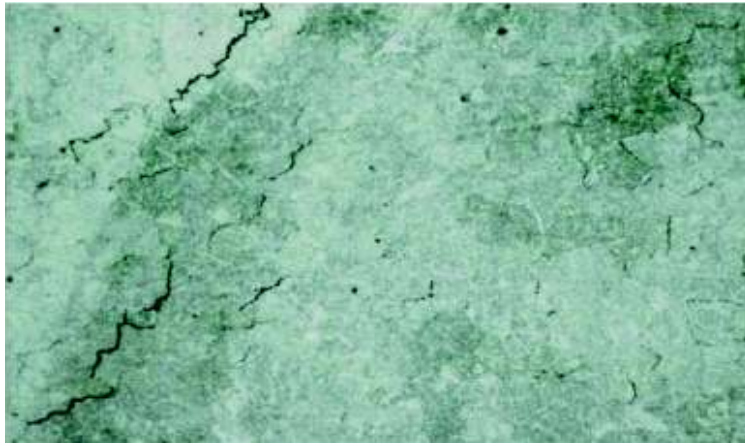


Figure 10. Extensive Type IV creep damage in a heat affected zone

### 10. METALLURGICAL CHANGES THAT OCCUR DURING CREEP

The two diffusion controlled processes that change the microstructure are spheroidisation and graphitisation. The normal microstructure of creep resisting steels (up to 5%Cr) is ferrite and pearlite, Figure 11, or ferrite and bainite. However, the iron carbide precipitate present in pearlite or bainite is not the equilibrium state for carbon in iron. Under long term, high temperature exposure, spheroidisation occurs and the morphology changes from platelets to spheres, Figure 12.

Spheroidisation result is a loss in strength and ductility. The HAZ of welds is more prone to this than parent materials.

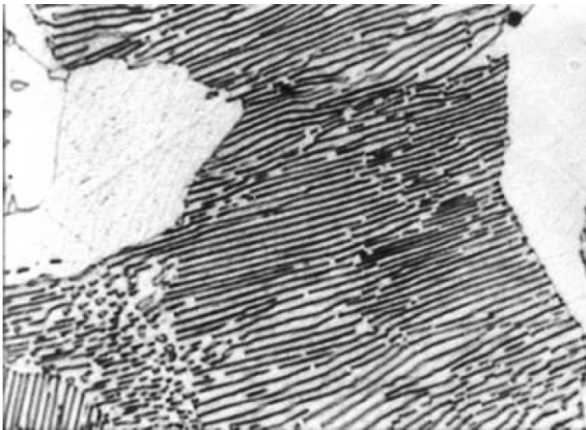


Figure 11. Pearlite at high magnifications showing alternate layers of ferrite and cementite (Fe<sub>3</sub>C) in pearlite.

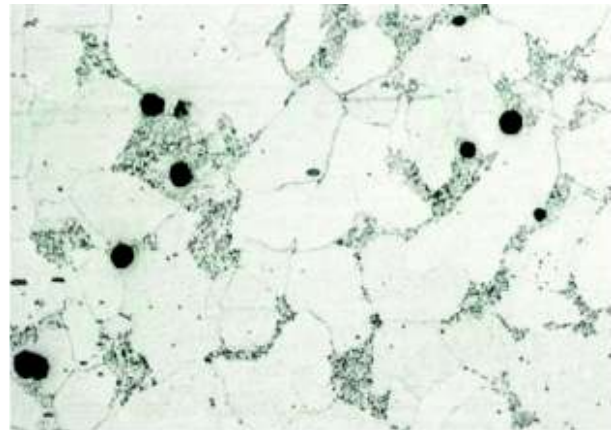


Figure 12. Spheroidisation and graphitisation of the HAZ after long term exposure at high temperature.

## 11. LOSS OF DUCTILITY

Most engineering alloys eventually lose ductility during high temperature service due to creep damage. This has been shown to be a function of temperature and strain rate. In some alloys loss of ductility in the form of temper embrittlement occurs very quickly in a given temperature range.

At a given strain rate, ductility first decreases with increasing temperature, due mainly to grain boundary sliding and crack formation. At higher temperatures however, ductility improves due to recovery and relaxation of local stress concentrations. However, loss of ductility should always be expected in creep damage materials.

## 12. THE EFFECT OF WELD REPAIR ON CREEP DAMAGED MATERIAL

Weld repairs to creep damaged materials often result in further cracking in the HAZ of the repair weld. Figure 13 shows the typical cracking that can occur during the repair welding of a set-in header that has been in service for an extended period at high temperature. To explain why the HAZ is so susceptible to cracking one needs to consider the effect of residual stress on the integrity of the aged HAZ microstructure.

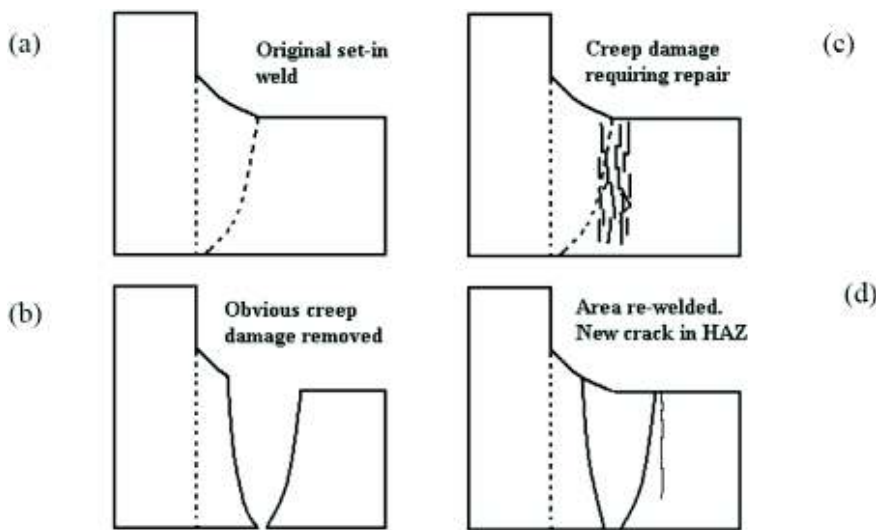


Figure 13. Repair welding of a set-in stub on a pressure plant header

## 13. RESIDUAL STRESS IN WELDS

Because of the severe thermal cycle imposed by the welding process residual stresses at levels up to the yield strength of weld and parent metal can occur. Figure 14 shows a typical residual stress profile that can occur in a butt weld.

Figure 14 shows that residual stresses up to 400 MPa can develop in welds and more importantly in the Heat Affected Zones. For a creep damaged material that has lost its ductility the consequence is often cracking. Lack of ductility results in an inability to accommodate the strains induced by the residual stress. Lack of ductility diminishes the capacity of the steel to yield. Thus the yield and tensile strength merge the as the capacity to accommodate strain as shown in Figure 1 diminishes towards zero.

Thus a welding regime is required that reduces residual stresses induced as a result of welding. Referring back to figure 2 a general reduction in yield strength occurs with increasing temperature. Hence reducing residual stresses can be achieved by using high pre-heats and proceeding from welding directly to post weld stress relief.

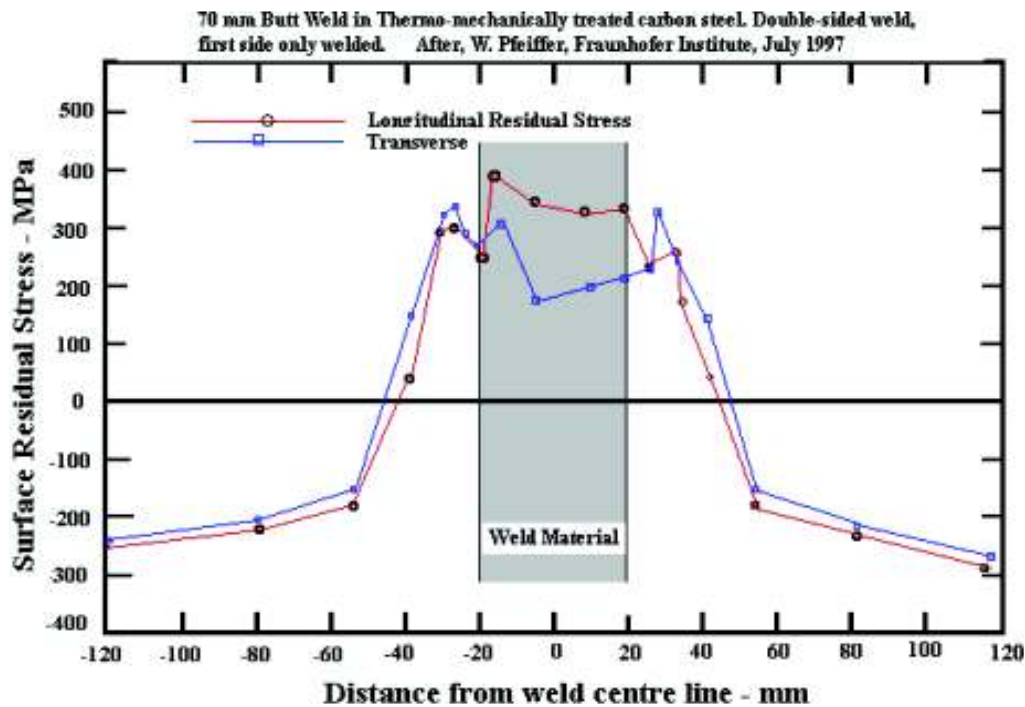


Figure 14. Typical residual stress profile for a butt weld

#### 14. GUIDELINES FOR THE REPAIR OF CREEP DAMAGED STEELS

For repair welding of creep damaged materials (typically Chromium-Molybdenum steels) a qualified welding procedure is required. When developing the procedure the following 10-step sequence should be followed:

1. Preheat to at least 250°C using controlled electric resistance heating elements;
2. Use consumables that match the alloy content of the parent metal;
3. Weld with stringer beads keeping heat input to a minimum (~1 KJ/mm) with a 350°C maximum inter-pass temperature, ensuring freedom from defects.
4. On completion of welding, maintain preheat and dress the weld surface smooth by careful grinding;
5. Proceed directly to the postweld heat treatment stage by re-setting electrical resistance elements or coils to the stress relief position;
6. Keep the heating rate to a maximum of 50°C per hour and aim for the upper end of the postweld heat treatment temperature range for the material;
7. Holding time should be in accordance with the relevant fabrication standard but for a minimum of 2 hours at the stress relief temperature;
8. Control cool at 50°C per hour to 300°C;
9. Slow to cool to room temperature;
10. When cold, perform NDE utilising a procedure that specifically addresses potential cracks in the HAZ.

It should be noted that in most cases such repairs should only be regarded as temporary in nature until replacement material can be obtained. This is because the HAZ will remain susceptible to the onset of type IV cracking and the adjacent aged steel that already has diminished properties will become increasingly difficult to weld. Alternatively it may be possible to achieve a significant life after welding if the creep damage is fully removed and a controlled deposition process (see the WTIA Technical Guidance Note TGN-PE-02 on temper bead welding) is used. Replication can be used to determine the extent of creep damage which may extend a significant distance into the parent metal.