

**CUKUROVA UNIVERSITY  
INSTITUTE OF NATURAL AND APPLIED SCIENCES**

**MSc THESIS**

**Baki ÇELİK**

**THERMALLY INDUCED DISTORTION AND RESIDUAL STRESSES  
IN WELDED JOINTS**

**DEPARTMENT OF MECHANICAL ENGINEERING**

**ADANA, 2009**

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**INSTITUTE OF NATURAL AND APPLIED SCIENCES**

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IN WELDED JOINTS**

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**A MASTER OF SCIENCE THESIS**

**DEPARTMENT OF MECHANICAL ENGINEERING**

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**ÖZ**  
**YÜKSEK LİSANS TEZİ**

**KAYNAKLI BAĞLANTILARDA ISI İLE OLUŞAN ÇARPILMALAR VE  
ARTIK GERİLMELER**

**Baki ÇELİK**

ÇUKUROVA ÜNİVERSİTESİ  
FEN BİLİMLERİ ENSTİTÜSÜ  
MAKİNE MÜHENDİSLİĞİ ANABİLİM DALI

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Kaynak işlemindeki ısı kaynağına, malzemenin ısı tepkisi bazen artık gerilme, çarpılma ve içyapıdaki değişikliklerden dolayı malzemenin mekanik özelliklerinin değişimi gibi mekanik problemlere sebep olur. Bölgesel ısınma ve soğumadan dolayı kaynaklı parçalarda artık gerilmeler ve çarpılmalar meydana gelir. Artık gerilmeler dış kuvvetler ile birleştiği zaman kaynaklı parçanın servis süresi içerisinde beklenmedik hatalar gözlenebilir. Çarpılmalar, kaynaklı parçaların boyutsal hassasiyetini etkiler. Bu nedenle kaynak işleminden sonra düzeltme işlemlerine ihtiyaç duyulur.

Kaynak işleminden önce artık gerilmelerin ve çarpılmaların dağılımı ve miktarının önceden tahmin edilebilmesi araştırmacılar için önemli bir konu olmuştur. Bu çalışmada, SYSWELD sonlu eleman paket programı modellemede kullanılmıştır. Modelleme ile kaynak sonrası malzemenin durumu önceden tahmin edilebildiği gibi kaynak parametrelerinin optimizasyonu da sağlanabilmektedir.

Anahtar Kelimeler: Artık Gerilmeler, Çarpılmalar, Sonlu Elemanlar Yöntemi ile Kaynak Analizi, SYSWELD.

## **ABSTRACT**

### **MSc THESIS**

# **THERMALLY INDUCED DISTORTION AND RESIDUAL STRESSES IN WELDED JOINTS**

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Assist. Prof. Dr. Ali KOKANGÜL

The thermal response of materials to a welding heat source sometimes causes mechanical problems, e.g. residual stresses and distortion and changes in mechanical properties due to changes in the microstructure. Residual stresses and distortions take place in weldments due to local heating and cooling. When this residual stresses combine with the external forces, unexpected failure can be observed during service life of weldments. The distortion can effect the dimensional accuracy of the weldments. Therefore some additional straightening processes are needed after welding process.

Prediction of the amount and the distribution of residual stresses and distortion before welding has been an important subject for researchers. In this thesis, SYSWELD finite element package program was used in modelling. The situation of the material after welding can be estimated by modelling, also the optimisation of welding parameters can be done.

**Key Words:** Residual Stresses, Distortions, Welding Analysis with Finite Element Method, SYSWELD.

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## 1. INTRODUCTION

Many metallic structures in industry are assembled through some kind of welding process which is composed of heating, melting and solidification using a heat source such as arc, laser, torch or electron beam. The highly localized transient heat and strongly nonlinear temperature fields in both heating and cooling processes cause nonuniform thermal expansion and contraction, and thus result in plastic deformation in the weld and surrounding areas. As a result, residual stress, strain and distortion are permanently produced in the welded structures. High tensile residual stresses are known to promote fracture and fatigue, while compressive residual stresses may induce undesired, and often unpredictable, global or local buckling during or after the welding. It is particularly evident with large and thin panels, as used in the construction of automobile bodies and ships. These adversely affect the fabrication, assembly, and service life of the structures. Therefore, prediction and control of residual stresses and distortion from the welding process are extremely important in the ship building and automotive industry (Zhu , 2002).

The heat supplied during arc welding is responsible for the changes in the microstructures, and development of residual stresses and distortions. Welding process parameters like electrode diameter, electrode travel speed, thickness of the workpiece material, current and voltage greatly affect the temperature distribution patterns and hence residual stresses and distortions. A large number of models have been reported in the published literature to predict temperature distributions, residual stresses and distortions in the welded joints. Most of them have concentrated on a 2-D approximation of a 3-D problem and have advocated the need for 3-D simulation so that they can be better utilized for simulating the behavior of a complete welded structure. The important process characteristics which are required to be considered in any simulation are; moving heat source, arc travel speed, heat input, temperature-dependent material properties.

Residual stresses and distortions are unavoidable in welding, and the effects of these stresses and distortions on welded structures cannot be disregarded. Determining residual stresses and distortions is thus an important problem. However,

accurate prediction of residual stresses and distortions induced by the welding process is extremely difficult because the thermal and mechanical behaviour in welding include local high temperature, temperature dependence of material properties, and a moving heat source. Finite element simulation of the welding process is highly effective in predicting thermomechanical behaviour (Mahapatra, 2006).

This thesis performs thermal elasto-plastic analysis using finite element (FE) techniques to analyse the thermomechanical behaviour and evaluate the residual stresses and angular distortions of the T-Joint fillet welds. Additionally, it also considers the effects of heat input, welding speed and restraint condition on residual stresses and distortions.

In FE simulation of welding which may include validation of material properties, FE model, analysis technique, temperature distribution, deformation and residual stresses need to be implemented. For this simulation SYSWELD software package program was used. The main objective of the present work is to describe general behaviour of the T-Joint weld under different parametric studies and different parametric studies are performed to evaluate the effects of these parameters one by one.

## **1.1. Welding**

### **1.1.1. General Principles**

Welding is a process in which materials of the same fundamental type or class are brought together and caused to join (and become one) through the formation of primary chemical bonds under the combined action of heat and pressure.

A weld can be made homogeneous, as when two parts made from the same austenitic stainless steel are joined with a filler of the same alloy, or they can be made to be intentionally dissimilar (heterogeneous), as when two parts made from gray cast iron are joined with a bronze filler metal. Similarly, two polymers can be joined and made to be homogeneous if they are of identical type or composition, as

when two pieces of thermo-plastic polyvinyl chloride are thermally bonded or welded, or heterogeneous when two unlike but compatible thermoplastics are joined by thermal bonding. Alternatively, a compatible thermoplastic filler could be used as what is called an adhesive, and, when this is the situation, the result can also correctly be called a weld.

The key in each case is that even when the material across the joint is not identical in composition (i.e., homogeneous), it is essentially the same in atomic structure, thereby allowing the formation of chemical bonds: primary metallic bonds between similar or dissimilar metals, primary ionic or covalent or mixed ionic-covalent bonds between similar or dissimilar ceramics, and secondary hydrogen, van der Waals, or other dipolar bonds between similar or dissimilar polymers. The problem comes about when the materials to be joined are fundamentally different in structure at the atomic or (for polymers) molecular level. When this is the case, welding by the strictest definition cannot be made to occur. An example is the joining of metals to ceramics or even thermoplastics to thermosetting polymers. In both cases, the fundamental nature of the bonding that must take place differs from that in at least one of the joint elements. Clearly, there must be a disruption of bonding type across the interface of these fundamentally different materials. And for the case of a thermoplastic being joined to a thermoset, a degree of ionic bonding can occur in the thermoset to cause cross-linking, but not so in the thermoplastic. Thus, a dissimilar adhesive alloy is required to bridge this fundamental incompatibility. In short, the key is achieving continuity of structure by forming chemical bonds, and this limits possibilities to like types or classes even if not identical compositions of materials.

The second common and essential point among definitions is that welding applies not just to metals. It can and often does apply equally well to certain polymers, crystalline oxide or nonoxide ceramics, intermetallic compounds, and glasses. The process being performed may not always be called welding – it may be called thermal bonding for thermoplastics, or fusion bonding or fusion for glasses – but it is welding! With the emergence and increasing application of so many different

materials of different fundamental types, welding will remain a viable process for joining.

The third essential point is that welding is the result of the combined action of heat and pressure. Welds can be produced over a wide spectrum of combinations of heat and pressure: from essentially no pressure when heat is sufficient to cause melting, to where pressure is great enough to use gross plastic deformation when no heat is added and welds are made cold. Welding is a highly versatile and flexible joining process, enabling the joining of many different materials into many different structures to obtain many different properties for many different purposes.

The fourth essential point is that an intermediate or filler material of the same type, even if not same composition, as the base material(s) may or may not be required. There are a host of reasons why such a filler might be required or desired..

The fifth and final essential point is that welding is used to join parts, although it does so by joining materials. It is this goal that often places additional constraints and demands on the welding process as it is selected and applied. Creating a weld between two materials requires producing chemical bonds by using some combination of heat and pressure. How much heat and how much pressure is partially dictated by the inherent nature of the material(s) being joined. But, how much heat and how much pressure also depends on the nature of the actual parts or physical entities being joined. Among other things, part shape, critical part dimensions, and part and assembly (i.e. joint) properties must also be dealt with by preventing intolerable levels of distortion, residual stresses, or disruption of chemical composition and microstructure (Zhu, 2002).

### **1.1.2. Advantages and Disadvantages of Welding**

Like all joining processes, welding offers several advantages but has some disadvantages as well. The most significant advantage of welding is undoubtedly that it provides exceptional structural integrity. producing joints with very high efficiencies. The strength of joints that are welded continuously (i.e., full length, without intentional skipped areas) can easily approach or exceed the strength of the

base material(s). The latter situation is made possible by selecting a joint design that provides greater cross-sectional area than the adjoining joint elements and/or filler that is of higher strength than the base material(s). Another advantage of welding is the wide range of processes and approaches that can be selected and the correspondingly wide variety of materials that can thus be welded. Almost all metals and alloys, many (thermoplastic) polymers, most if not all glasses, and some ceramics can be welded, with or without auxiliary filler.

Still other advantages of welding are that (1) there are processes that can be performed manually, semiautomatically, or completely automatically; (2) some processes can be made portable for implementation in the field for erection of large structures on site or for maintenance and repair of such structures and equipment; (3) continuous welds provide fluid tightness (so welding is the process of choice for fabricating pressure vessels); (4) welding (better than most other joining processes) can be performed remotely in hazardous environments (e.g., underwater, in areas of radiation, in outer space) using robots; and (5) for most applications, costs can be reasonable. The exceptions to the last statement are where welds are highly critical, with stringent quality requirements or involving specialized applications (e.g., very thick section welding).

The single greatest disadvantage of welding is that it precludes disassembly. While often chosen just because it produces permanent joints, consideration of ultimate disposal of a product (or structure) at the end of its useful life is causing modern designers to rethink how they will accomplish joining.

A second major disadvantage of many welding processes is that the requirement for heat in producing many welds can disrupt the base material microstructure and degrade properties. Unbalanced heat input can also lead to distortion or the introduction of residual stresses that can be problematic from several standpoints. A third serious consideration, but not necessarily a disadvantage, is that welding requires considerable operator skill, or, in lieu of skilled operators, sophisticated automated welding systems. Both of these along with the aforementioned specialized applications, can lead to high cost.

Many metallic structures in industry are assembled through some kind of

welding process which is composed of heating, melting and solidification using a heat source such as arc, laser or electron beam. The highly localised transient heat and strongly nonlinear temperature fields in both heating and cooling processes cause nonuniform thermal expansion and contraction, and thus result in plastic deformation in the weld and surrounding areas. As a result, residual stress, strain and distortion are permanently produced in the welded structures. High tensile residual stresses are known to promote fracture and fatigue, while compressive residual stresses may induce undesired, and often unpredictable, global or local buckling during or after the welding. Therefore, knowledge of the heat input intensity and the temperature gradients in the workpiece and prediction of residual stresses and distortion from the welding process are extremely important (Messler, 1999).

### **1.2. Thermally Induced Distortion and Residual Stresses During Welding**

Thermal stresses or thermally induced stresses arise from a material or mechanical structure being acted upon by a temperature gradient or a temperature change. There are three principal examples:

1. Stresses induced by a volumetric change, either expansion or shrinkage, associated with some change of phase in the material of construction.
2. Stresses induced by a difference in coefficient of thermal expansion (CTE) between two materials linked together, known as a CTE mismatch.
3. Stresses induced by a temperature gradient resulting in differential rates of expansion (on heating) or contraction (on cooling) within the volume of the material or within the structure.

For stresses to arise from a phase change, temperature must change to cause the phase change. For stresses to arise from a difference in coefficients of thermal expansion, the temperature may be changing or it may have stabilized. For stresses to arise from differential rates of expansion or contraction, the temperature must change and produce a gradient, which may or may not persist. Whether the temperature gradient persists or not, the thermally induced stresses from this source persist.

When a metal solidifies after having been made molten, unlike water, its

specific volume decreases. This volumetric shrinkage gives rise to thermally induced stresses in the surrounding metal, which must react somehow. If free to move, the surrounding metal will move to accommodate the shrinkage. If not free to move, the solidifying volume of metal will either yield or fracture by cracking in tension.

If strips of two metals with different coefficients of thermal expansion are joined along their length at some temperature, as the temperature changes from this point, the materials respond differently. On heating, one will expand faster than the other while the temperature is changing, and more than the other when the temperature change has ceased. On cooling, the reverse will occur: One will contract faster during cooling, and will have contracted more when cooling has ceased. The result will be a stress, with the higher CTE material causing bending of a straight two-layer strip toward the lower CTE material on heating. If the two-layer strip starts out straight while hot, the lower CTE material will cause bending of the couple toward itself on cooling. If motion or distortion cannot take place in response to the different CTEs, the stresses that would normally cause that motion or distortion will be trapped in the material as "locked-in" stresses. This source of thermally induced stress is commonplace, and, thus, must be carefully considered whenever two different materials are joined (which is probably far more often than one might think).

A well-known example of thermally induced stresses arising as the result of a temperature gradient being present in a material or structure is when a very hot, dry glass cooking pot is suddenly placed into cold water. The outside of the walls and bottom of the glass pot cool faster than the insides as a result of thermal momentum exacerbated by glass poor thermal conductivity, causing the outsides to contract faster and more than the insides. This places the outside layers of the pot's walls and bottom in tension, causing catastrophic fracture in such an inherently brittle material! A similar thing happens in any material or structure anytime there is a difference in temperature across any dimension, through the thickness or along a length or width, although sometimes the material (or part) yields (usually by bending or buckling) only if it has sufficient ductility. In fact, in all of these examples, and many situations in welding, thermally induced stresses are actually the result of thermally induced strains. The material undergoes, some change in dimensions, locally, and a stress

arises, more generally.

If a thermally induced strain or stress is able to do so, it will cause a material or structure to respond by distorting. While the origin of thermally induced stresses often arises with relatively small dimensional changes, from some localized phenomena, the distortion that can result is often much more generalized, up to and including the entire structure. If thermally induced strains or stresses from one of the sources are unable to cause a material or structure to respond by distorting macroscopically, it will either cause it to deform microscopically (e.g., yield or crack) or result in stresses that (as opposed to being applied) are "locked in." Locked-in stresses are called residual stresses (Grong, 1994). An example of how distortion and residual stresses might arise from the same applied temperature change is shown schematically in Figure 1.1.

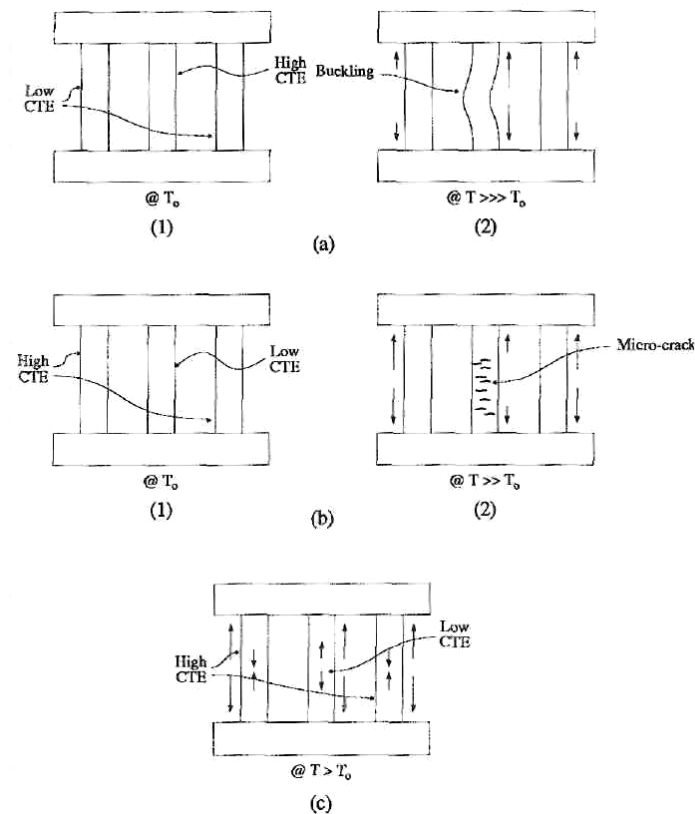


Figure 1.1. Illustration of thermally induced stresses leading to (a) macroscopic distortion, (b) microscopic distortion, or (c) residual stresses (Grong, 1994).

When stresses can cause macroscopic distortion, they will do so, and, in the process of causing this distortion, the thermally induced stresses are relieved; at least to below the yield stress, and, possibly, to lower levels due to creep. When stresses cannot cause macroscopic distortion, they either cause microscopic distortion or deformation (often in the form of cracking, but, possibly, in the form of localized yielding) to relieve themselves, or they are locked in to become residual stresses. In this last case, thermally induced stresses are not relieved, they are locked in! Locked-in or residual stresses are consequences that are rarely good, the exception being where compressive residual stresses can be induced to offset at least the initial levels of applied tensile stresses, as in prestressed cement or concrete, or thermally or chemically tempered glass.

### **1.2.1. Causes of Residual Stresses in Weldments**

Thermally induced residual stresses can arise from any process that involves heat, whether that process is primarily a thermal process, such as heat treatment or welding, or not. In machining, for example, one source of residual stresses is localized heating from the friction of and work done by the cutting tool on the workpiece. When expansion and contraction associated with this heating and subsequent cooling is not free to take place because of constraint imposed by surrounding material that has not been heated, residual stresses develop. Proof that such stresses are induced is clear when a steel part is ground and cracks at its surface. But, just because cracks don't form, doesn't mean that no stresses were induced, only that they weren't high enough to cause cracking 'by exceeding the fracture strength of the material.

In structures that are welded, called weldments, residual stresses arise from two situations and mechanisms:

1. Structural mismatching
2. Uneven distribution of nonelastic strains whether from mechanical or thermal sources.

### 1.2.1.1. Residual Stresses From Mismatch

The simple example of residual stresses arising from structural mismatching is that of bars of different lengths being forcibly connected as shown in Figure 1.2. Tensile stress is produced in the shorter, middle bar, Q, as a result of joining by any method. At the same time, compressive stresses are produced in the longer, outboard bars, P and P'. Compressive stresses arise to balance the tensile stress, so the overall system is in mechanical equilibrium. A similar situation arises when such a three-bar arrangement consists of a continuous middle bar of different composition and coefficient of thermal expansion than the two outboard bars. If the end members (or caps) and the middle bar are heated to 595°C, in this example, and then cooled to room temperature while the two outside bars are kept at room temperature the 'hold time, the stress-versus-temperature response plotted in Figure 1.3 arises in the middle bar. These, as well as the stresses produced in the outside bars, are residual stresses. The two outside bars resist the deformation of the middle bar; first its expansion, then its contraction. The stress in each outside bar (where, for this example, the outside bars have equal cross-sectional areas) is half the value of the stress in the middle bar, but of opposite sign or type, that is, compression versus tension, or vice versa. When the middle bar is heated, compressive stresses arise in it because its expansion is restrained by the outside bars.

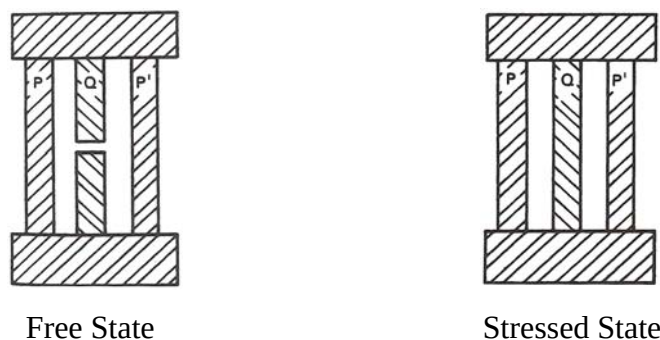


Figure 1.2. Residual stresses produced when bars of different lengths are forcibly joined into what is known as a 'three-bar arrangement' (Grong, 1994).

As the temperature of the middle bar increases, the magnitude of the compressive

stress that arises increases along line AB in Figure 1.3, until at point B (approximately 170°C) the yield strength in compression is reached. As the temperature increases beyond this level, the stress in the middle bar is limited to the yield strength, which decreases with increasing temperature as shown by curve BC. When the middle bar reaches 595°C, heating is stopped (i.e. point C is reached).

As temperature decreases from point C, that is, as the middle bar cools and the response of the middle bar is elastic, the stress first drops rapidly, at some point changes to tension, and soon reaches the yield strength in tension (at point D). As temperature decreases further, stress in the middle bar is again limited by its yield strength (this time in tension), as shown by curve DE. Thus, a residual stress, equal

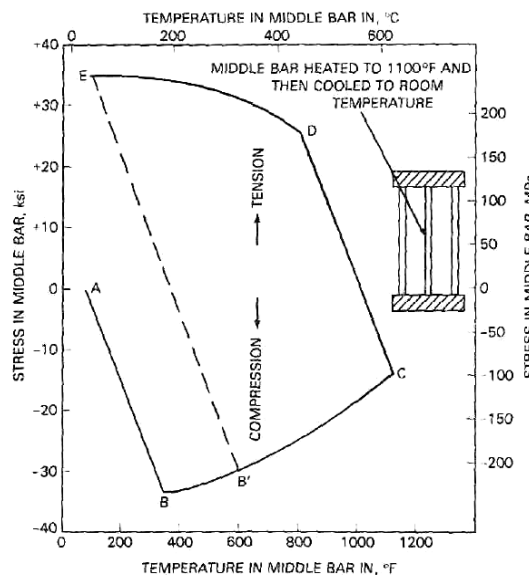


Figure 1.3 Effect on residual stresses of heating restrained bars (or volume elements in a weld) (Benli, 2004).

to the yield strength in tension, is set up in the middle bar. Residual compressive stresses of half this value are set up in each outside bar to balance the system mechanically. If heating of the middle bar had been stopped between points B and C, and the bar allowed to cool back to room temperature, tensile stresses would have developed elastically along a line parallel to B'E until the yield strength was reached on curve DE. At room temperature, the final residual stress state would be the same,

that is, residual tensile stress equal to the yield strength in the middle bar, and compressive stresses of half this value in the outside bars (Benli, 2004).

### 1.2.1.2. Residual Stresses From Nonuniform, Nonelastic Strains

When metal is heated uniformly, it expands uniformly, and no thermally induced stresses arise that can lead to either locked-in stresses or distortion.

If, on the other hand, heating is done nonuniformly, thermal strains and stresses develop, these thermally induced stresses, which can become locked in as the result of the structure being restrained from distorting, obey the following relationships (for a plane-stress residual stress field where  $\sigma_z = 0$ ).

1. Strains consist of elastic and plastic components given by:

$$\varepsilon_x = \varepsilon_x' + \varepsilon_x''$$

$$\varepsilon_y = \varepsilon_y' + \varepsilon_y''$$

$$\gamma_{xy} = \gamma_{xy}' + \gamma_{xy}''$$

where  $\varepsilon_x, \varepsilon_y$  and  $\gamma_{xy}$  are components of total strain;  $\varepsilon_x', \varepsilon_y'$ , and  $\gamma_{xy}'$  are the elastic strain components; and  $\varepsilon_x'', \varepsilon_y''$  and  $\gamma_{xy}''$  are the plastic strain components.

2. Hooke's law applies to the stress and elastic strain, so that

$$\varepsilon_x' = \frac{1}{E(\sigma_x - \nu\sigma_y)} \quad (1.1)$$

$$\varepsilon_y' = \frac{1}{E(\sigma_y - \nu\sigma_x)} \quad (1.2)$$

$$\gamma_{xy}' = \frac{1}{G} \tau_{xy} \quad (1.3)$$

3. Stress must be in equilibrium, so that

$$\frac{d\sigma_x}{dx} = \frac{d\tau_{xy}}{dy} \quad (1.4)$$

$$\frac{dT_{xy}}{dx} = \frac{d\sigma_{xy}}{dy} \quad (1.5)$$

4. The total strain must be compatible according to

$$\left( \frac{d^2 \varepsilon'_x}{dy^2} + \frac{d^2 \varepsilon'_y}{dx^2} - \frac{d^2 \gamma'_{xy}}{dxdy} \right) + \left( \frac{d^2 \varepsilon''_x}{dy^2} + \frac{d^2 \varepsilon''_y}{dx^2} - \frac{d^2 \gamma''_{xy}}{dxdy} \right) = 0 \quad (1.6)$$

Equations indicate that residual stresses exist when the value of R, called incompatibility, is not zero, where R is given by

$$R = -\frac{d^2 \varepsilon''_x}{dy^2} + \frac{d^2 \varepsilon''_y}{dx^2} - \frac{d\gamma''_{xy}}{dxdy} \quad (1.7)$$

In other words, incompatibility can be considered to be the cause of residual stresses.

Calculation of the stresses for given values of strain requires that there is no applied stresses acting at the same time, and the history of residual stress formation must be known (Benli, 2004).

### 1.2.2. Causes of Distortion in Weldments

Distortion in a weldment can arise when thermally induced stresses are unrestrained. Three fundamental dimensional changes taking place during welding can cause distortion in weld-fabricated structures or weldments: (1) transverse shrinkage that occurs perpendicular to the weld line, (2) longitudinal shrinkage that occurs parallel to the weld line, and (3) any angular change that consists of rotation that occurs around the weld line.

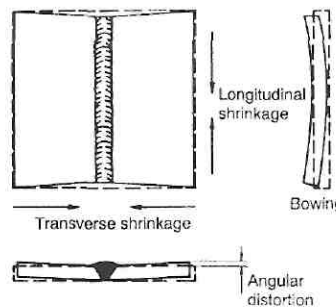


Figure 1.4 Fundamental dimensional changes that can take place in weldments: transverse shrinkage, longitudinal shrinkage, and angular distortion or bowing (Conrardy, 2005).

These three- dimensional change are shown in Figure 1.4.

The amount of transverse shrinkage that occurs is affected by the size (width and volume) of the weld and, so, the process, heat input, and joint configuration, the thermophysical properties of the base material, and the degree of restraint applied to the joint. The amount of shrinkage increases as the degree of restraint decreases. Since the amount of restraint almost always varies along the length of the weld, so, too, does the amount of transverse shrinkage. Normally, transverse shrinkage is greater in the center of a weld pass or run than near the ends. Longitudinal shrinkage in a butt joint is usually much less than transverse shrinkage, typically 1/1000 of the weld length. Angular distortion is the result of nonuniformity of transverse shrinkage through the thickness. This is largely a function of the joint configuration and weld cross-sectional shape (Conrardy, 2005).

### **1.2.3. Typical Residual Stresses in Weldments**

The distribution of temperature transverse to the weld line is shown in Figure 1.5b for four locations along the weld, A, B, C, and D. Along section A-A, which lies just ahead of the welding source, the temperature change due to the approaching arc is virtually zero. Along section B-B, on the other hand, the distribution of temperature is very steep, as this section passes through the arc. Some short distance behind the arc, the temperature distribution is less severe (since cooling has already begun), as shown for section C-C, and still further back, along section D-D, the temperature distribution along the line has dropped back to near that before welding was begun (Kou, 2003).

At section A-A, thermally induced stresses due to welding are almost zero. Stresses in regions immediately below the arc and weld pool in section B-B are also almost zero because molten metal cannot support a load. Stresses in the heat-affected region on either side of the weld pool, however, do exist, and are compressive because thermal expansion in these very hot regions is restrained by surrounding metal at lower temperature, of higher strength, and without having

experienced similar expansion. The limit of these compressive stresses is set by the yield strength of the metal in the heat-affected region. Where the temperature is the highest, which is nearest the fusion zone, the yield strength is lowest. The yield strength increases with increasing distance from the weld pool, so the compressive residual stress increases to its peak level.

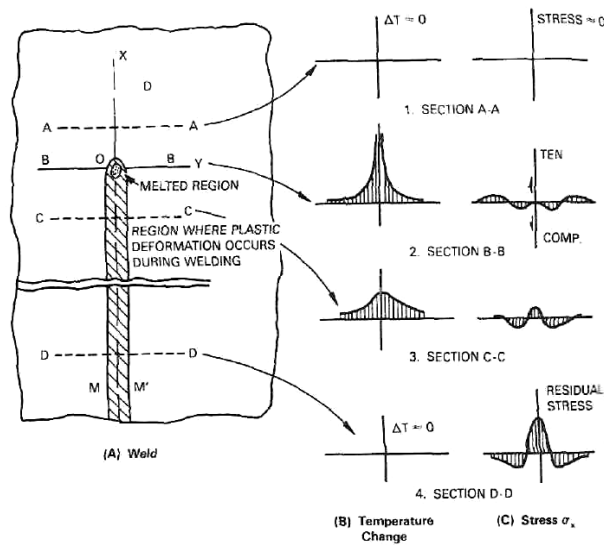


Figure 1.5 Typical distribution of temperature and stress at several locations in a bead-on-plate weld (Kou, 2003).

At some point away from the weld line, tensile stresses will arise to balance the compressive stresses induced by thermal expansion. This is essential for the system or weldment to be in mechanical equilibrium. The instantaneous stress distribution is shown in Figure 1.5.

At section C-C, the weld and heat-affected zone have cooled considerably. As they did so, they tried to shrink, and tensile stresses developed in and near the fusion zone. These tensile stresses were again balanced by compressive stresses to maintain mechanical equilibrium. The stress distribution is shown in Figure 1.5.

Very far behind the arc, the final, stable residual stress distribution for a bead-on-plate weld is shown in Figure 1.5 for section D-D. High residual tensile stresses exist in the fusion and heat-affected zones, with compressive stresses in the unaffected base metal to balance the tensile stresses.

A typical distribution of both longitudinal and transverse residual stresses for a single-pass weld in a butt joint is shown in Figure 1.6. According to Masubuchi and Martin (1961), the distribution of longitudinal residual stress ( $\sigma_x$ ) can be approximated by

$$\sigma_x = \sigma_m \left[ 1 - \left( \frac{y}{b} \right)^2 \right] e^{-1/2(y/b)^2} \quad (1.8)$$

Where  $\sigma_m$  is the maximum residual stress, which usually reaches no more than the yield strength of the base metal. The parameter  $b$  is the width of the tension zone of  $\sigma_x$ .

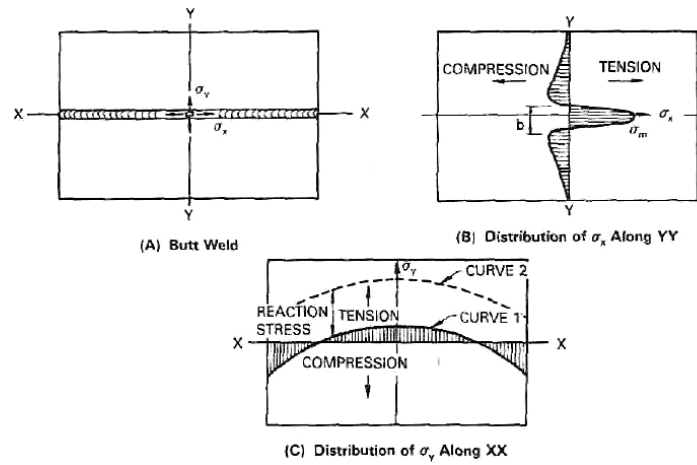


Figure 1.6. Typical distribution of (a) residual stresses (b) transverse to the butt weld line and (c) longitudinal to the butt weld line (Masubuchi and Martin, 1961).

#### 1.2.4. Effects of Distortion in Weldments

The degree or extent of distortion is affected by several factors, including (1) the geometry or configuration of the joint (butt, fillet, or T, etc.), as these each affects mass distribution; (2) the type of weld preparation (single- or double-Y, J-, square-butt, etc.); (3) the width or volume of the weld (related to the next factor); (4) the heat input from the process; (5) the arrangement of structural elements in the weldment (as these

influence structural stiffness and restraint); and (6) the sequence in which welds are made (sequence can help balance or offset thermally induced stresses).

The obvious consequences or effects of distortion in weldments are (1) loss of required dimensions; (2) misalignment of structural elements to allow proper support and transfer of applied loads; (3) inability to fit one welded subassembly onto, into, or with another (i.e., fit-up); (4) jamming or binding of a weldment in tooling used to hold structural elements in place during welding; and (5) loss of aesthetics (Messler, 1999).

### **1.2.5. Effects of Residual Stresses**

The effects or consequences of residual stresses introduced into a structure by and during welding are often less obvious, but can be at least as detrimental as distortion. Basically, applied stresses and residual stresses add vectorially, depending on both magnitude and relative direction. As a result, applied tensile stresses add to residual tensile stresses, but are reduced by residual compressive stresses. Applied compressive stresses are reduced by residual tensile stresses, but add to residual compressive stresses. The result may be that tensile fracture or compressive buckling (depending on which situation occurs). The effect of uniform external loads on the residual stress distribution of a welded butt joint is shown in Figure 1.7.

Based on analysis, the effects shown in Figure 1.7., may be summarized as follows:

1. The effect of weld-induced residual stresses on the performance of a welded structure is significant only for phenomena that occur at low applied stresses, such as brittle fracture, fatigue, and stress-corrosion cracking.
2. As the level of applied stress increases, the effect of residual stresses decreases. (This is because higher applied stresses overwhelm residual stresses by causing generally yielding.)
3. The effect of residual stress on the performance of welded structures under applied stresses greater than the yield strength is negligible.
4. The effect of residual stress tends to decrease after repeated loading.

Residual stresses affect the performance of weldments in several ways. They reduce the fracture strength of a weldment, often to very low levels, resulting in rapid, brittle fracture. The cause of brittle fracture is largely the complexity of the stress state (which is often triaxial), and residual tensile stresses cause more problem than residual compressive stresses.

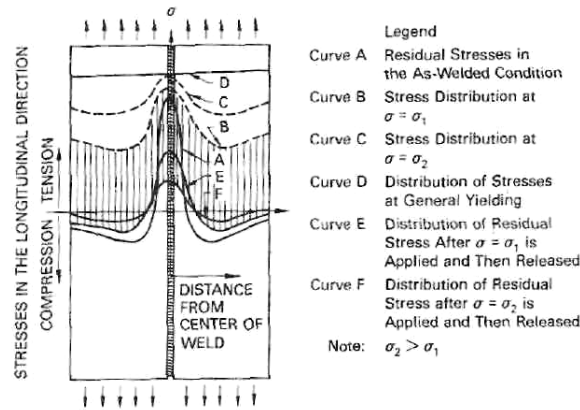


Figure 1.7 Effect of uniform external loads on the residual stress distribution of a welded butt joint (Kou, 2003).

Compressive residual stresses can cause buckling under compressive loading. This is a particular problem in thin columns or thin plates. In either case, localized buckling of a key structural member can lead to overall failure of the structure by shifting loads to other members, and exceeding their designed load limit.

Fatigue strength and life are affected in complex ways. They are increased in areas of compressive residual stresses, and decreased in areas of tensile residual stresses. Almost always, welding produces stress risers that aggravate fatigue, for example, undercut (near bead crowns or roots), ripples, pores, rakes, and metallurgical "notches" from sharp phase and property transitions.

Susceptibility to corrosion is increased by the presence of residual stresses almost without exception. This is particularly true for stress-corrosion cracking, which is exacerbated by the presence of residual tensile stresses (Kou, 2003).

### 1.2.6. Measurement of Residual Stresses in Weldments

Measuring residual stresses, including magnitude and sign (i.e., compression or tension), as a function of location, possibly in three directions, is far from trivial in reality, even if not in principle. In fact, there are many methods for measuring residual stresses in metals that are also generally applicable in weldments, and these can be divided into three classifications; (1) stress-relaxation methods, (2) x-ray (and, more recently, neutron) diffraction methods, and (3) cracking methods. While no method is perfect, by any means, each has its merits, advocates, and appropriateness.

As a group, stress-relaxation methods determine residual stresses by measuring the magnitude sign and direction of strain released by cutting the sample containing these stresses and monitoring the strain released through some type of electrical or mechanical gauge. These methods provide reasonably accurate and reliable quantitative data, with some limitations imposed by sample geometry (especially, 3-D complexity). Specific techniques exist for sample of different size and shape (especially, thin, 2D sheets or plates, or thick, 3D solids), using different means and manner of cutting (eg., drilling, boring, sectioning, and machine milling), and different means of monitoring strain release (eg., physical distortion of overlaying grids, mechanical measurement instruments or gauges, electrical-resistance strain gauges, brittle coatings to provide visual indications of strain changes). As a group, x-ray diffraction methods determine residual stresses by measuring their effect on the lattice parameter of the metal in which they are contained. Tensile residual stresses cause the lattice to expand, increasing the normal lattice parameter, while compressive residual stresses cause the lattice to contract, decreasing the normal lattice parameter, both in proportion to the magnitude of the stresses present. These methods generally suffer from being slow, requiring specialty equipment and skillful operators, and not being very accurate.

A small group of techniques is available that monitor the effect of residual stresses on cracking induced by hydrogen (embrittlement) or stress corrosion (Murugan, 2001).

### **1.2.7. Residual Stress Reduction and Distortion Control**

#### **1.2.7.1 The Interplay Between Residual Stresses and Distortion**

Distortion occurs as a result of unbalanced thermally induced stresses, if the material or structure is free to respond to those unbalanced stresses, that is, if the material or structure is not restrained. Residual stresses occur as the result of unbalanced thermally induced stresses, being prevented from causing distortion, and, thereby, being partially relieved, when the material or structure is restrained. Thus, it should come as no surprise that attempting to prevent or reduce distortion must be done in such a way that intolerable residual stresses do not result instead. Contrarily, attempting to relieve residual stresses once they have developed from welding must be done in such a way that unacceptable distortion does not result.

#### **1.2.7.2. Controlling or Removing Residual Stresses**

Although the effects of residual stresses on the service performance of a welded structure vary significantly, depending on their severity and the impact of their occurrence, it is generally preferable to keep residual stresses to a minimum. Precautions to reduce residual stresses can take two forms: prevention or remediation. To prevent development of residual stresses it is crucial to reduce the effects of heat during welding. One way is to employ cold, nonfusion welding processes, but this is seldom a viable option. Another approach is to employ hot, nonfusion processes to eliminate shrinkage associated with solidification of any fusion zone. (There is still thermal contraction in any heat-affected zone that must be dealt with or tolerated, but the major source of residual stress, volumetric shrinkage upon solidification, is eliminated.) A third approach is to minimize the volume of molten weld metal so as to minimize shrinkage associated with solidification. This can be done by judicious choice of joint preparation. For example, a U-groove could be used in place of a V-groove, because U-grooves require less filler. It is also desirable to use the smallest

groove size (regardless of geometry) and the smallest angle (for a V) and root opening that will still permit adequate accessibility for welding and production of a sound weld. Part of the effectiveness of a small root opening is to prevent or limit shrinkage across the joint.

. Remediation of residual stresses once they arise in a weldment is accomplished by postweld thermal treatment called thermal stress relief. Heating lowers the yield strength of the base material and allows localized relaxation of residual stresses, primarily by plastic deformation and secondarily by creep. To prevent the structure from distorting as a result of the residual stresses being redistributed, critical weldments should be stress relieved while still restrained in a fixture (sometimes, but not always, the same one in which they were welded).

It is also possible to relieve residual stresses by mechanical means, or at least to redistribute these stresses to reduce peak levels. Proven methods includes, hammer peening, shot peening, and planishing. A method called vibratory stress relief uses the energy of elastic waves introduced by physically shaking a structure or impacting it with a transducer (e.g., ultrasonic) to cause stress reduction. However, the amplitude of vibration (often having to be at the frequency of natural resonance of the structure, or one of the harmonics of this frequency) can cause damage from fatigue.

#### **1.2.7.3. Controlling or Removing Distortion**

To prevent distortion, there are several viable approaches. First, distortion can be minimized by proper design. This means, among other things (1) employing the minimum number of parts and, thus, a minimum amount of welding; (2) properly preparing the joint (especially for unrestrained butt joints) to minimize angular distortion (e.g., use double-V or double-U as opposed to single-V or single-U configurations to balance heat input and shrinkage); and (3) using minimum-sized fillet welds. Second, distortion can be minimized by proper assembly procedures, such as (1) presetting members to compensate for angular distortion from shrinkage; (2) assembling the weldment so that it is nominally correct before welding and then

using some form of restraint to minimize distortion from welding; and (3) sequencing welding to balance heat input and create offsetting shrinkage/distortion. The advantage of presetting (shown in Figure 1.8a) is that there are few or no residual stresses once the part has been welded and seeks its own location. A consequence of rigid fixturing is that it introduces residual stresses at the expense of freedom from distortion (Figure 1.8b).

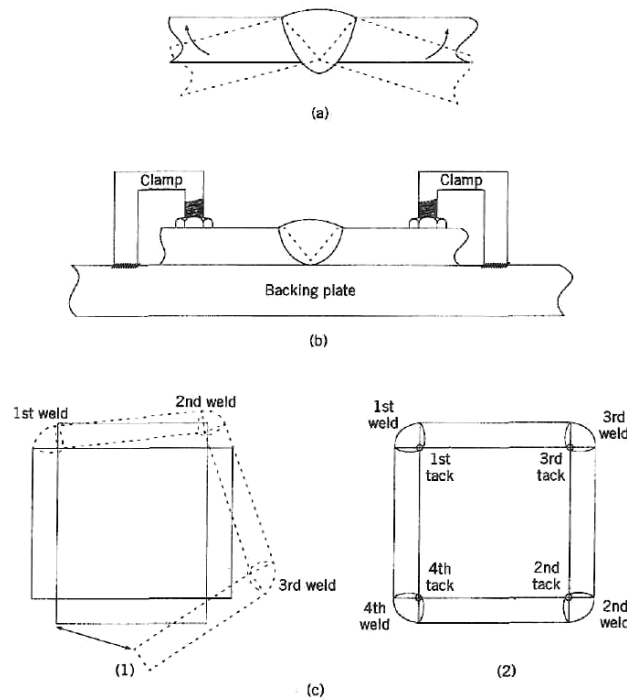


Figure 1.8. Techniques for preventing or minimizing distortion, including (a) presetting, (b) rigid fixturing, and (c) sequencing welds or weld sequencing (Mochizuki, 2004).

Proper sequencing certainly helps to minimize distortion, but also results in residual stresses, as the structure is eventually forced to fit together (Figure 1.8.c). Preheating can be used to reduce distortion in a weldment by minimizing temperature gradients that lead to nonuniform elastic contraction.

### 1.2.8. Numerical Methods for Estimating Residual Stresses

Direct measurement techniques undoubtedly provide the most reliable estimates of residual stresses in welds and weldments, despite accuracy limitations,

but great benefit can be derived from predictions obtained from models. Such methods allow convenient assessment of the influences of process, process parameters, and procedures on the residual stress state that will develop. This knowledge, even though providing trends at best, can help in deciding on the need for and value of preheat or postheat on preventing hydrogen cracking.

Since residual stresses in welds involve both elastic and plastic deformation, any model must deal with this complex elastic-plastic treatment. Recent advances in computer technology and computing techniques based on finite-element methods have helped greatly, with agreement between predictions and measurements steadily improving. The computational procedure involves calculating the elastic-plastic strain increments of a network or mesh of volume elements surrounding and including the weld over a range of time intervals appropriate to the welding thermal cycle imposed. While accuracy increases with the use of smaller volume elements, this accuracy comes at the expense of capacity of the computer and time for computing

The total strain increment over a temperature interval of interest is given by the matrix

$$d\varepsilon^T = (\alpha)dT \quad (1.9)$$

Where  $d\varepsilon^T$  refers to strain from thermal expansion,  $d\varepsilon$  can be expressed in terms of elastic ( $\varepsilon^e$ ), plastic ( $\varepsilon^p$ ), and thermal ( $\varepsilon^T$ ) strain contributions:

$$d\varepsilon = d\varepsilon^e + d\varepsilon^p + d\varepsilon^T \quad (1.10)$$

The increment of stress is then obtained from the product of the matrix [D] and the strain increment:

$$\{d\sigma\} = \{[D]d\varepsilon\} \quad (1.11)$$

The stress change within a given volume element in the vicinity of a weld varies with temperature in accordance with the simplified equation:

$$\Delta\sigma = \alpha\Delta TE \quad (1.12)$$

where  $\alpha$  is the coefficient of thermal expansion and  $E$  is the elastic modulus. The temperature change ( $\Delta T$ ) comes from the temperature distribution obtained from solution of the general equation of heat flow, simplified to the degree necessary and possible. This being the case,  $\Delta\sigma$  depends on the thermal factors  $q$  and  $k$  (for all three orthogonal directions) and on the material properties of  $\alpha$ ,  $E$  and  $\sigma_y$ , all of which vary with temperature. If a phase transformation occurs during cooling, whether in the fusion zone or heat-affected zone, it contributes an additional factor, in terms of dilatation, given by

$$\varepsilon_d = \frac{5}{6} \left\{ \left( \frac{\Delta V}{V} \right) \left( \frac{\sigma}{\sigma_y} \right) \right\} \quad (1.13)$$

where  $\sigma$  is the applied stress and  $\sigma_y$  the yield stress of the parent phase (e.g., austenite) before transformation.  $\Delta V$  is the volume change associated with the phase change, while  $V$  is the volume of the parent phase.

While accuracy of results vary depending on the fineness of the mesh employed and on ability to incorporate properties as a function of temperature, they can be more than good enough to determine trends and aid in selection process, parameters, and procedures (Sunar, 2006).

### 1.3. The Flow of Heat in Welds

In fusion welding, a source of energy is necessary to cause the required melting of the materials to be joined. Even after the net energy from the source is transferred to the workpiece as heat, not all of that heat contributes to cause melting to produce the weld. Some is conducted away from the point of deposition, raising the temperature of material surrounding the zone of fusion and causing unwanted metallurgical and geometric changes.

It is important to first consider how that heat is distributed once it reaches the workpiece, that is, how it flows. How that heat is distributed directly influences the rate and extent of melting, the rate of cooling and solidification in the fusion zone, and the rate and extent of peripheral heating and cooling in the heat-affected zone. The rate and extent of melting, in turn, directly affects the weld volume and shape,

homogeneity through convection, the degree of shrinkage and attendant weldment distortion, and susceptibility to defects. The rate of solidification determines the solidification structure (including substructure) and, thus, properties. The rate and extent of peripheral heating affects the development of thermally induced stresses acting on the fusion zone (which contribute to fusion zone defect formation), the rate of cooling in the fusion zone (which controls solidification mechanics and determines final fusion zone structure and properties), the rate and level of heating in the heat-affected zone (which can cause degradation of properties), the rate of cooling in the heat-affected zone (which determines the final structure and properties in this zone), and the degree and nature of distortion and/or residual stresses in the weldment (Kim, 1998).

### **1.3.1. The Welding Thermal Cycle**

If thermocouples are placed at various points along the path of a weld, resumed to have been started in the middle of a plate to avoid edge effects, as shown in Figure 1.9a, then a series of thermal cycles are obtained, as shown Figure 1.9b. Each individual thermocouple responds, in turn, to the approach of the heat source, with a rapid rise in temperature to a peak, a very short hold at that peak, and then a rapid drop in temperature once the source has passed by. Some short time after the heat from the source (electric arc) begins being deposited, it can be seen that the peak temperature, as well as the rest of the thermal cycle, reaches a state of quasi-steady state. This quasi-steady state (or quasi-stationary condition) is the result of a balance having been achieved between the rate of energy input and the rate of energy loss or dissipation due to conduction into the cooler regions of the workpiece or loss to the environment.

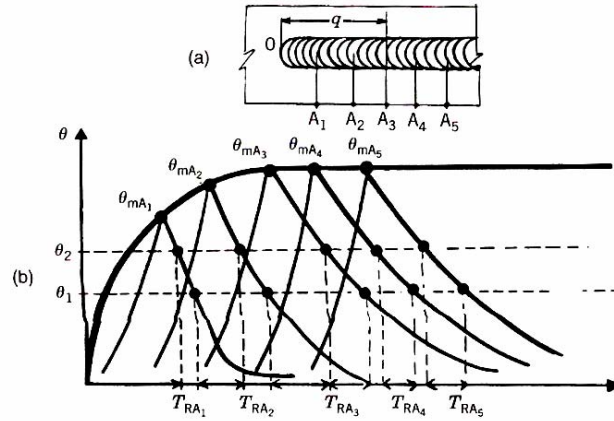


Figure 1.9 Schematic of (a) thermocouple placement along the path of a moving heat source and (b) the thermal cycle produced at each point to yield an overall response (Messler, 1999).

Because of the establishment of quasi-steady state (even for a moving heat source), thermal cycles (temperature-time curves) can be determined for points distributed progressively further from the centerline of the path of the welding heat source along a line perpendicular or transverse to the weld path. Temperature-time traces for three points, A, B, and C, are shown in Figure 1.10, with the following observations:

1. The maximum temperatures reaching above  $T_m$  decrease with increasing distance from the source, and more or less abruptly depending on the temperature gradient that characterizes the particular process (especially its energy density and distribution, and also its net heat input).

2. Peak temperature separates the heating portion of the welding thermal cycle from the cooling portion, and expresses the fact that points closest to a weld are already cooling, while points farther away are still undergoing heating. This phenomenon explains certain aspects of phase transformations that go on in the heat-affected zone, as well as differential rates and degrees of thermal expansion and contraction that lead to thermally induced stresses and, possibly, distortion.

3. Given the arrangement of the thermal history curves, the rate of cooling (measured from the maximum temperature) decreases with distance from the weld line. However, the cooling portion of curves rapidly produces tightly grouped rates

as cooling progresses, so that by the time temperature drops to a certain point, the cooling rates are quite similar.

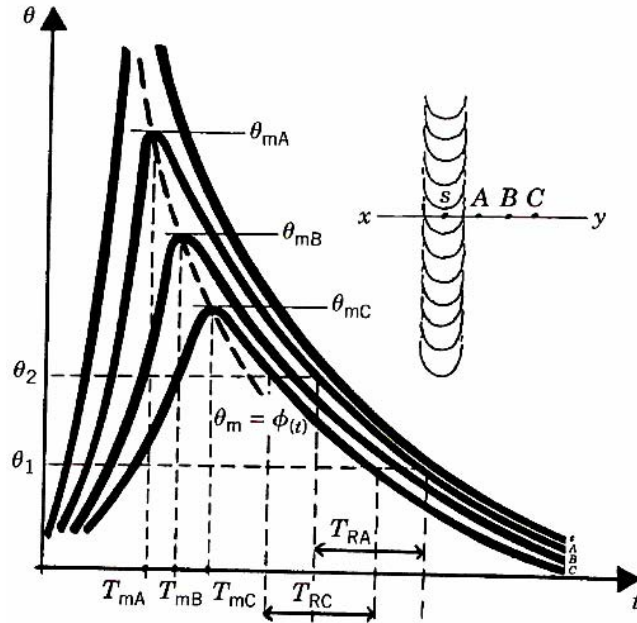


Figure 1.10 Schematic of temperature-time traces for three points located along a line perpendicular to a weld during passage of a moving welding heat source. Note the displacement in the times of occurrence of the maximum temperatures and the quasi-steady-state nature of cooling times in the lower portion of the curves (Messler, 1999).

### 1.3.2. The Generalized Equation of Heat Flow

The thermal conditions in and near the fusion zone of a fusion weld must be maintained within specific limits to control metallurgical structure, residual stresses and distortions, and chemical reactions (e.g. oxidation) that result from a welding operation. Of specific interest are (1) the solidification rate of the weld metal, (2) the distribution of maximum or peak temperature in the weld heat-affected zone, (3) the cooling rates in the fusion and heat-affected zones, and (4) the distribution of heat between the fusion zone and the heat-affected zone.

The transfer of heat in a weldment is governed primarily by the time--dependent conduction of heat, which is expressed by the following general equation

of heat flow:

$$\begin{aligned} pC(T) \frac{d(T)}{d(t)} = \frac{d}{dx} \left[ k(T) \frac{d(T)}{dx} \right] + \frac{d}{dy} \left[ k(T) \frac{d(T)}{dy} \right] + \frac{d}{dz} \left[ k(T) \frac{d(T)}{dz} \right] \\ - pC(T) \left( V_x \frac{dT}{dx} + V_y \frac{dT}{dy} + V_z \frac{dT}{dz} \right) + Q \end{aligned} \quad (1.14)$$

where

$x$  = coordinate in the direction of welding (mm)

$y$  = coordinate transverse to the welding direction (mm)

$z$  = coordinate normal to weldment surface (mm)

$T$  = temperature of the weldment, (K)

$k(T)$  = thermal conductivity of the metal (or ceramic) ( $\text{J/mm s}^{-1}\text{K}^{-1}$ ) as a function of temperature

$p(T)$  = density of the metal (or ceramic) ( $\text{g/mm}^3$ ) as a function of temperature

$C(T)$  = specific heat of the metal (or ceramic) ( $\text{J/mm s}^{-1}\text{K}^{-1}$ ) as a function of temperature

$V_x, V_y$ , and  $V_z$  = components of velocity

$Q$  = rate of any internal heat generation, ( $\text{W/mm}^3$ )

Despite its complexity, all the terms in this equation are straight forward, except  $Q$ , which deserves some explanation. For most processes, energy from the source is deposited on the surface of the workpiece, with heat then being conducted or generated and conducted inward, by a melt-in or conduction mode. For some processes, as the energy density of the source becomes higher, some, most, or all of the energy or heat, depending on how high the energy density is, is deposited below the surface. This is the case for processes operating in the keyhole mode (e.g., PAW, LBW, or EBW), as well as for some high-intensity arc processes like SAW.

Surface heating is usually characterized by a heat-flux distribution,  $q(x, y)$  applied over a relatively small area of the workpiece surface, rather than from internal generation ( $Q$ ). This distribution is given by:

$$k(T) \frac{d(T)}{dz} = q(x, y) \quad (1.15)$$

where  $q(x, y)$  is given in  $\text{W/mm}^2$  and is directed onto the surface at  $z = 0$ . Heat is then lost to the surroundings by a combination of radiation and convection and conduction.

Whether this general equation needs to be solved for one, two, or three dimensions depends on the weldment and weld geometry, including whether the weld penetrates fully or partially and is parallel sided or tapered, and the relative plate thickness. A two dimensional solution is most useful in relatively thin weldments or in thicker weldments where the weld is full penetration and parallel-sided (as in EBW) to assess both longitudinal and transverse heat flow. A full, three-dimensional solution is required for a thick weldment in which the weld is partial penetration or non-parallel-sided (as is the case for most single or multipass welds made with an arc source). Examples of situations requiring one-, two-, or three-dimensional solutions are given in Figure 1.11.

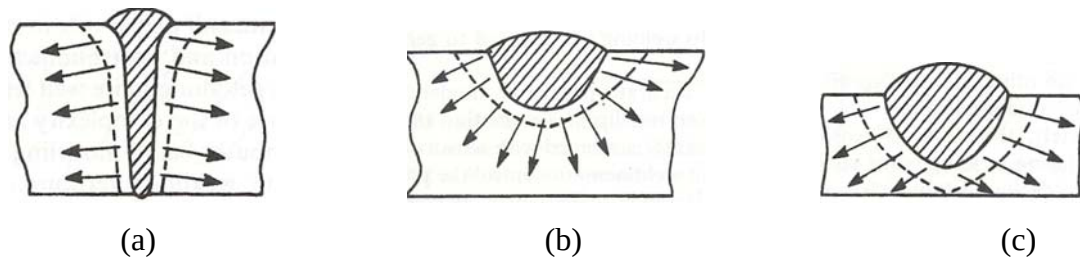


Figure 1.11 Schematic of the effect of weldment and weld geometry on the dimensionality of heat flow: (a) two-dimensional heat flow for full penetration welds with parallel sides (as in EBW and some LBW); (b) three-dimensional heat flow for partial penetration welds in thick plate; and (c) an intermediate, 2.5-D, condition for near-full penetration welds (Kou, 2003) .

### 1.3.2.1. Rosenthal's Simplified Approach

The key to Rosenthal's solution is the assumption of quasi-steady state. First critical assumption was that the energy input from the heat source used to make the weld was uniform and moved with a constant velocity  $v$  along the  $x$ -axis of a fixed

rectangular coordinate system. The net heat input to the weld under these conditions is given by :

$$H_{net} = \frac{q}{v} \text{ (in J/m)} \quad (1.16)$$

And the heat or energy  $q$  for an arc welding process is given by

$$q = \eta EI$$

where  $\eta$  is the transfer efficiency of the process.  $E$  and  $I$  are the welding voltage and current, respectively, and  $v$  is the velocity of welding or travel speed (m/s). Rosenthal further assumed the heat source to be a point source, with all of the energy being deposited into the weld at a single point.

Rosenthal next simplified the general heat flow equation in two ways: (1) by assuming that the thermal properties (thermal conductivity,  $k$ , and product of the specific heat and density,  $C\rho$ ) of the material being welded are constants; and, (2) by modifying the coordinate system from a fixed system to a moving system (Goncalves, 2006).

The solutions are for the thin plate, where

$q$  = heat input from the welding source (J/m)

$k$  = thermal conductivity ( $J / ms^{-1} K^{-1}$ )

$\alpha$  = thermal diffusivity =  $k / \rho C$  ( $m^2 / s$ )

$K_0$  = a Bessel function of the first kind, zero order

$R = (\xi^2 + y^2 + z^2)^{1/2}$ , the distance from the heat source to a particular fixed point (m).

$$T - T_0 = \frac{q}{2\pi k} e^{-v\xi/2\alpha} K_0 \frac{vR}{2\alpha} \quad (1.17)$$

On the other hand, for the thick plate

$$T - T_0 = \frac{q}{2\pi kd} e^{-v\xi/2\alpha} \frac{e^{-vR/2\alpha}}{R} \quad (1.18)$$

Where  $d$  = depth of the weld (which for symmetrical welds is half of the weld width, since  $w=2d$ )

When the position from the weld centerline is defined by a radial distance,  $r$ , where  $r = z^2 + y^2$ . For the thin plate, the time-temperature distribution is

$$T - T_0 = \frac{q/v}{d(4\pi k \rho C t)^{1/2}} e^{-r^2/4\alpha t} \quad (1.19)$$

and for the thick plate is

$$T - T_0 = \frac{q / \nu}{2\pi kt} e^{-r^2 / 4\alpha t} \quad (1.20)$$

## 2. PREVIOUS STUDIES

### 2.1. Models for Welding Heat Sources

#### 2.1.1. Theoretical Formulations

The basic theory of heat flow that was developed by Fourier and applied to moving heat sources by Rosenthal and Rykalin in the late 1930s is still the most popular analytical method for calculating the thermal history of welds. Rosenthal's point or line heat source models are subject to a serious error for temperatures in or near the fusion zone (FZ) and heat affected zone (HAZ). The infinite temperature at the heat source assumed in this model and the temperature sensitivity of the material thermal properties increases the error as the heat source is approached. To overcome most of these limitations several authors (Goldak, Andersson, Krutz, Taylor, Segerlind, Friedman) have used the finite element method (FEM) to analyze heat flow in welds. Since Rosenthal's point or line models assume that the flux and temperature is infinite at the source, the temperature distribution has many similarities to the stress distribution around the crack tip in linear elastic fracture mechanics. Therefore many of the FEM techniques developed for fracture mechanics can be adapted to the Rosenthal model. Certainly it would be possible to use singular FEM elements to analyze Rosenthal's formulation for arbitrary geometries. This would retain most of the limitations of Rosenthal's analysis but would permit complex geometries to be analyzed easily. However, since it would not account for the actual distribution of the heat in the arc and hence would not accurately predict temperatures near the arc. Pavelic (1969) first suggested that the heat source should be distributed and he proposed a Gaussian distribution of flux deposited on the surface of the workpiece in 1969. Figure 2.1 represents a circle surface heat source and a hemispherical volume source, both with Gaussian normal distribution (bell shape curves), in a mid-thick plate. The geometrical parameters of heat flux distribution are estimated from the results of weld experiments (molten zone, size and shape and also temperature cycle close to molten zone).

The subsequent works of Andersson, Krutz, Segerlind and Friedman(1978) are particularly notable. Pavelic's 'disc' model is combined with FEM analysis to achieve significantly better temperature distributions in the fusion and heat affected zones than those computed with the Rosenthal model.

While Pavelic's 'disc' model is certainly a significant step forward, some authors have suggested that the heat should be distributed throughout the molten zone to reflect more accurately the digging action of the arc. This approach was followed by Paley in 1975 who used a constant power density distribution in the fusion zone (FZ) with a finite difference analysis, but no criteria for estimating the length of the molten pool was offered.

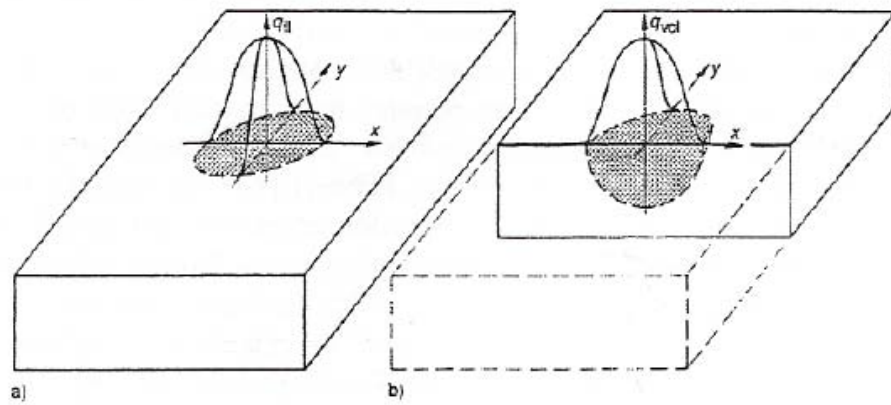


Figure 2.1. Heat source distribution in weldment: circular form surface source (a) and hemispherical volume source (b); Gaussian distribution of the surface related source density  $q_s$  and volume  $q_{vol}$  related source density  $q_{vol}$  (Goldak, 2005)

In addition, it is difficult to accommodate the complex geometry of real weld pools with the finite difference method.

The analyst requires a heat source model that accurately predicts the temperature field in the weldment. A non-axisymmetric three dimensional heat source model achieves this goal. It is argued on the basis of molten zone observations that this is a more realistic model and more flexible than any other model yet proposed for weld heat sources. Both shallow and deep penetration welds can be accommodated as well as asymmetrical situations.

The proposed three-dimensional 'double ellipsoid' configuration heat source model is the most popular form of this class of heat source models. It is shown that the 'disc' of Pavelic and the volume source of Paley and Hibbert and Westby are special cases of this model. In order to present and justify the double ellipsoid model, a brief description of the Pavelic 'disc' and of the Friedman modification for FEM analysis is necessary.

### 2.1.2. Heat Sources

#### 2.1.2.1. Gaussian Surface Flux Distribution

In the 'circular disc' model proposed by Pavelic, the thermal flux has a Gaussian or normal distribution in the plane, Figure 2.2. :

$$q(r) = q(0)e^{-Cr^2} \quad (2.1)$$

Where:

$q(r)$  = Surface flux at radius  $r$  ( $W / m^2$ )

$q(0)$  = maximum flux at the center of the heat source ( $W / m^2$ )

$C$  = distribution width coefficient ( $m^{-2}$ )

$r$  = radial distance from the center of the heat source (m)

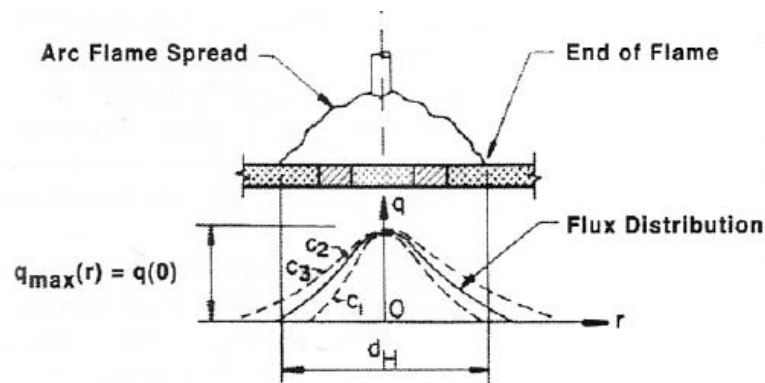


Figure 2.2. Circular disc heat source (Pavelic, 1969)

A simple physical meaning can be associated with  $C$ . If a uniform flux of magnitude  $q(0)$  is distributed in a circular disk of diameter  $d = 2 / \sqrt{C}$ , the rate of

energy input would be  $\eta IV$ , i.e., the circle would receive all of the energy directly from the arc. Therefore the coefficient,  $C$ , is related to the source width; a more concentrated source would have a smaller diameter  $d$  and a larger value of  $C$ . To translate these concepts into practice, the process model for the normal distribution circular surface of the heat flux for laser beam welding and submerged arc welding, is illustrated in Figure 2.3.

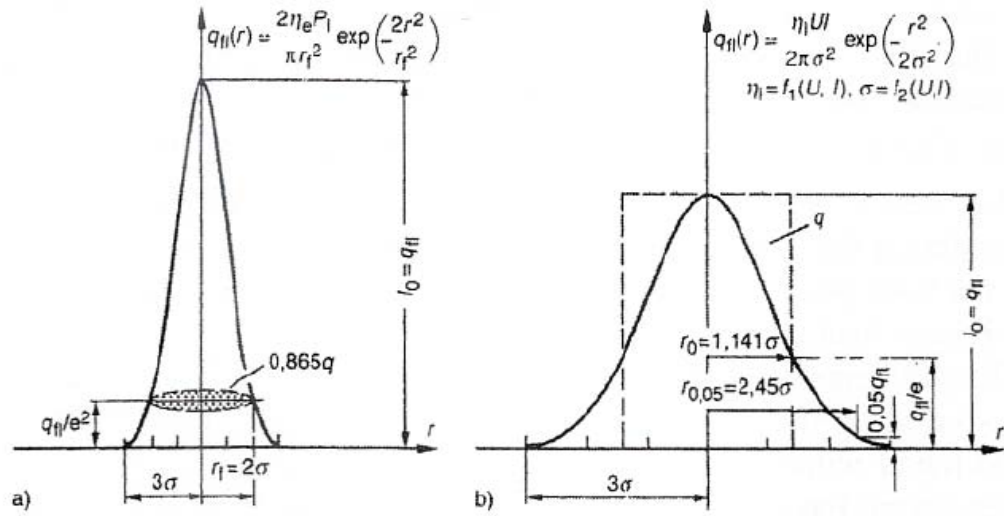


Figure 2.3. Normal distribution circular surface heat source and related parameters (radial distance from center  $\sigma$ ) by laser beam welding (a) and by submerged arc welding (b); with laser efficiency coefficient  $\eta_e$ , the laser power  $P_1$ , the focus diameter  $2r_f$ , the arc efficiency coefficient  $\eta_1$ , voltage of arc  $V$ , the current  $I$ , the maximum flux at the center of the heat source  $q(0)$  equal intensity  $I_0$ , Euler number  $e=2,71828...$ ; (Radaj, 2000)

The curve of the submerged arc welding is wide and low and the curve of the laser beam welding is in contrast, narrow and high. The laser beam has high intensity and a small diameter. The laser power  $P_1$  on the surface of the workpiece considering the efficiency coefficient is used as heat flux (power)  $q$  and/or heat power density  $q_{II}$ . The circular normal distribution is described by the focus radius  $r_f = 2\sigma$  which contains 86% of the heat power.

The arc welding has less intensity and larger diameter. The arc power  $VI$  on the surface of the workpiece considering the arc efficiency coefficient is used as heat

flux  $q$  and/or heat power density  $q_{\eta}$ . For the circular normal distribution two different descriptions are used. The source radius  $r_{0.05}$ , in this heat power density is reduced by 5% (Rykalin, 1974) or the source radius  $r_0$  of a same power source with constant heat power density (Ohji et al, 1992). The particular problem which exists for the definition of the heat source in arc welding is that both the arc efficiency  $\eta_1$  and the radial distance from the center  $\sigma$  are functions of the voltage  $V$  and the current  $I$  of the arc (Sudnik and Erofeew, 1986).

The effective radius  $r_0$  and/or  $r_{0.05}$  of the circular surface heat source are derived from the maximum surface width of the molten zone. The heat flow density from the surface  $q_{\eta}(x,y)$  for known  $r_0$  and/or  $r_{0.05}$  is defined from the power data of the weld heat source, considering the heat transfer efficiency. This is shown in Figure 2.3. for the laser beam welding and arc welding. If weld metal is added the related heat should be considered (Radaj, 2000).

Friedman (1975) and Krutz and Segerland (1978) suggested an alternative form for the Pavelic 'disc'. Expressed in a coordinate system that moves with the heat source as shown in Figure 2.4., Eq. (2.2) takes the form:

$$q(x, \xi) = \frac{3Q}{\pi c^2} e^{-3x^2/c^2} e^{-3\xi^2/c^2} \quad (2.2)$$

where:

$Q$  = energy input rate (W)

$c$  = is the characteristic radius of heat flux distribution (m)

It is convenient to introduce an  $(x, y, z)$  coordinate system fixed in the workpiece. In addition, a lag factor  $\tau$  is needed to define the position of the source at time  $t = 0$ , Figure 2.4.

The transformation relating the fixed  $(x,y,z)$  and moving coordinate system  $(x,y, \xi)$  is:

$$\xi = z + v(\tau - t) \quad (2.3)$$

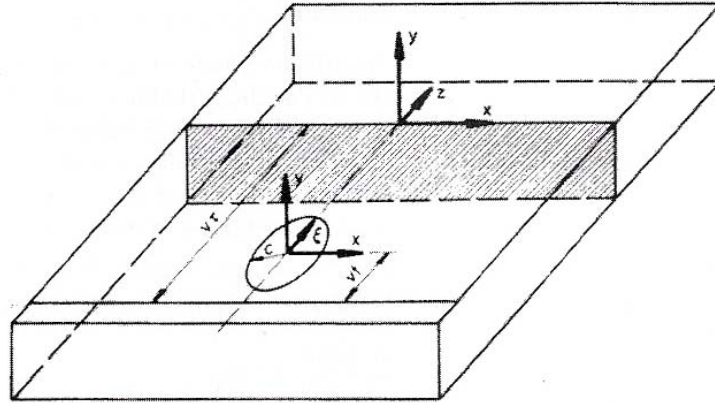


Figure 2.4. Coordinate system used for the FEM analysis of disc model according to Krutz and Segerlind (1978)

where  $v$  is the welding speed (m/s). In the  $(x, y, z)$  coordinate system Eq. (2.2) takes the form:

$$q(x, y, t) = \frac{3Q}{\pi c^2} e^{-3x^2/c^2} e^{-3[z+v(\tau-t)]^2/c^2} \quad (2.4)$$

For  $x^2 + \xi^2 < c^2$ . For  $x^2 + \xi^2 > c^2$ ,  $q(x, \xi, t) = 0$

To avoid the cost of a full three-dimensional FEM analysis Andersson (1978), assume negligible heat flow in the longitudinal direction; i.e.,  $\partial T / \partial z = 0$ . Hence, heat flow is restricted to an  $x$ - $y$  plane, usually positioned at  $z = 0$ . This has been shown to cause little error except for low speed high heat input welds. The disc moves along the surface of the workpiece in the  $z$  direction and deposits heat on the reference plane as it crosses. The heat then diffuses outward ( $x$ - $y$  direction) until the weld cools.

#### 2.1.2.2. Hemi-spherical Power Density Distribution

For welding situations, where the effective depth of penetration is small, the surface heat source model of Pavelic, Friedman and Krutz has been quite successful. However, for high power density sources such as the laser or electron beam, it ignores the digging action of the arc that transports heat well below the surface of the weld pool. In such cases according to Goldak (2005) hemispherical Gaussian

distribution of power density ( $W / m^3$ ) would be a step toward a more realistic model. The power density distribution for a hemispherical volume source can be written as:

$$q(x, y, \xi) = \frac{6\sqrt{3}Q}{c^3 \pi \sqrt{\pi}} e^{-3x^2/c^2} e^{-3y^2/c^2} e^{-3\xi^2/c^2} \quad (2.5)$$

where  $q(x, y, \xi)$  is the power density ( $W / m^3$ ). Eq. (2.5) is a special case of the more general ellipsoidal formulation developed in the next section.

Though the hemispherical heat source is expected to model an arc weld better than a disc source, it, too, has limitations. The molten pool in many welds is often far from spherical. Also, a hemispherical source is not appropriate for welds that are not spherically symmetric such as a strip electrode, deep penetration electron beam, or laser beam welds. In order to relax these constraints, and make the formulation more accurate, an ellipsoidal volume source has been proposed (Goldak, 2005).

### 2.1.2.3. Ellipsoidal Power Density Distribution

The Gaussian distribution of the power density in an ellipsoid with center at (0,0,0) and semi-axis a, b, c parallel to coordinate axes x, y,  $\xi$  can be written as:

$$q(x, y, \xi) = q(0) e^{-Ax^2} e^{-By^2} e^{-C\xi^2} \quad (2.6)$$

where  $q(0)$  is the maximum value of the power density at the center of the ellipsoid. .

Conservation of energy requires that:

$$2Q = 2\eta VI = 8 \int_0^\xi \int_0^y \int_0^x q(0) e^{-Ax^2} e^{-By^2} e^{-C\xi^2} dx dy d\xi \quad (2.7)$$

where;

$\eta$  = Heat source efficiency

V = Voltage

I = Current

Evaluation of Eq. (2-7) produces the following:

$$2Q = \frac{q(0)\pi\sqrt{\pi}}{\sqrt{ABC}} \quad (2.8)$$

$$q(0) = \frac{2Q\sqrt{ABC}}{\pi\sqrt{\pi}} \quad (2.9)$$

To evaluate the constants, A, B, C, the semi-axes of the ellipsoid a, b, c in the directions x, y,  $\xi$  are defined such that the power density falls to 0.05 q(0) at the surface of the ellipsoid. In the x direction:

$$q(a,0,0) = q(0)e^{-Aa^2} = 0.05q(0) \quad (2.10)$$

Hence

$$A = \frac{\ln 20}{a^2} \approx \frac{3}{a^2} \quad (2.11)$$

Similarly

$$B = \frac{3}{b^2} \quad (2.12)$$

$$C = \frac{3}{c^2} \quad (2.13)$$

Substituting A,B,C from Eqs. (2-11) to (2-13) and q(0) from Eq. (2-9) into Eq. (2-6):

$$q(x,y,\xi) = \frac{6\sqrt{3}Q}{abc\pi\sqrt{\pi}} e^{-3x^2/a^2} e^{-3y^2/b^2} e^{-3\xi^2/c^2} \quad (2.14)$$

The coordinate transformation, Eq. (2-3), Figure 2.4., can be substituted into Eq. (2-14) to provide an expression for the ellipsoid in the fixed coordinate system.

$$q(x,y,z,t) = \frac{6\sqrt{3}Q}{abc\pi\sqrt{\pi}} e^{-3x^2/a^2} e^{-3y^2/b^2} e^{-3[z+v(\tau-t)]^2/c^2} \quad (2.15)$$

If heat flow in the z direction is neglected, an analysis can be performed on the z-y plane located at z = 0 which is similar to the 'disc' source. The power density is calculated for each time increment, where the ellipsoidal source intersects this plane.

#### 2.1.2.4. Double Ellipsoidal Power Density Distribution

Goldak (2005) has started that the calculation experience with the ellipsoidal heat source model revealed that the temperature gradient in front of the heat source was not as steep as expected and the gentler gradient at the trailing edge of the molten pool was steeper than experimental measurements. To overcome this limitation, two ellipsoidal sources were combined by Goldak (2005), as shown in Figure 2.5. The front half of the source is the quadrant of one ellipsoidal source, and the rear half is the quadrant of another ellipsoid. The power density distribution along the  $\xi$  axis is shown in Figure 2.5.

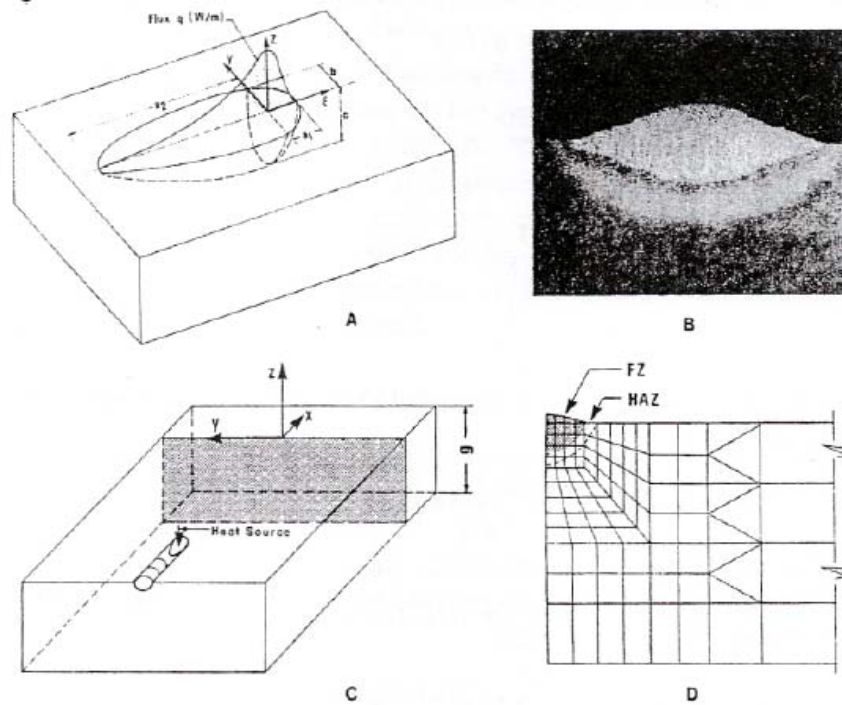


Figure 2.5. Double ellipsoid heat source configuration together with the power distribution function along the  $\xi$  axis (A), Cross-section of an SMAW weld bead on a thick plate low carbon steel ( $V=30$  volts,  $I=265$  amps,  $v=3.8$  mm/s,  $g=38$  mm,  $T_o=20.5$  °C) (Goldak, 2005).

In this model, the fractions  $f_f$  and  $f_r$  of the heat deposited in the front and rear quadrants are needed, where  $f_f + f_r = 2$ . The power density distribution inside the front quadrant becomes:

$$q(x, y, z, t) = \frac{6\sqrt{3}f_f Q}{abc\pi\sqrt{\pi}} e^{-3x^2/a^2} e^{-3y^2/b^2} e^{-3[z+v(\tau-t)]^2/c^2} \quad (2.16)$$

Similary, for the rear quadrant of the source the power density distribution inside the ellipsoid becomes:

$$q(x, y, z, t) = \frac{6\sqrt{3}f_r Q}{abc\pi\sqrt{\pi}} e^{-3x^2/a^2} e^{-3y^2/b^2} e^{-3[z+v(\tau-t)]^2/c^2} \quad (2.17)$$

In Eqs. (2.16) and (2.17), the parameters  $a$ ,  $b$ ,  $c$  can have different values in the front and rear quadrants since they are independent. Indeed, in welding dissimilar metals, it may be necessary to use four octants, each with independent values of  $a$ ,  $b$  and  $c$ .

In cases where the fusion zone differs from an ellipsoidal shape, the use of other models have been proposed for the flux and power density distribution. It has been suggested, for example, in welds with a cross-section shaped as shown in Figure 2.6., four ellipsoid quadrants could be superimposed to more accurately model such welds.

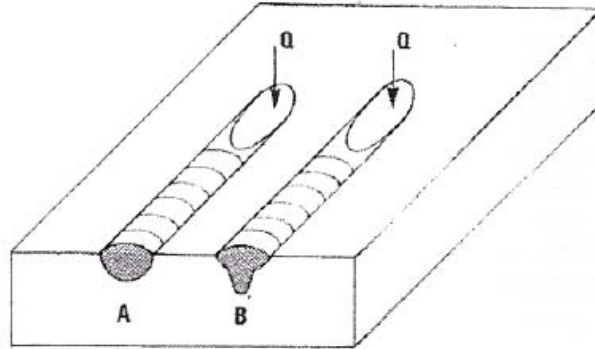


Figure 2.6. Cross-sectional weld shape of the fusion zone where a double ellipsoid is used to approximate the heat source (A), compound double ellipsoids must be superimposed to more accurately model such welds.

For deep penetration electron and laser beam welds, a conical distribution of power density which has a Gaussian distribution radially and a linear distribution axially has yielded more accurate results, Figure 2.7.

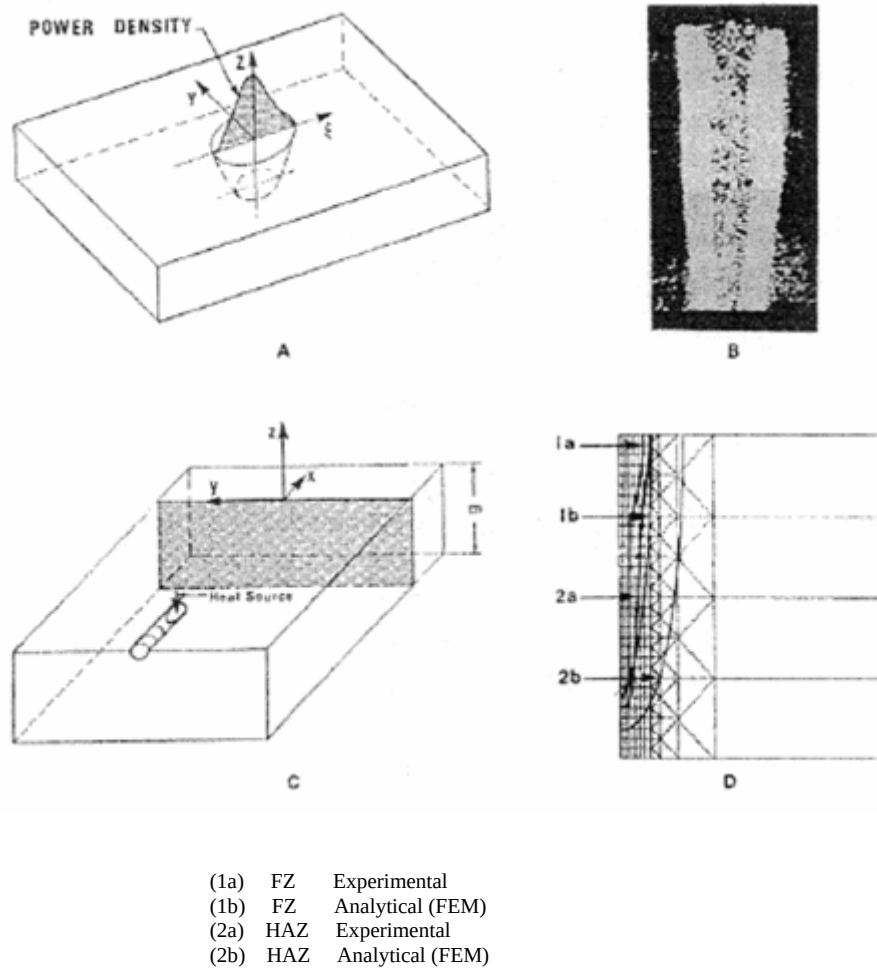


Figure 2.7. A conical weld heat source used for analyzing deep penetration electron beam or laser welds; conical source (A), typical electron beam weld (B), cross-sectional kinematic model with reference plane (c) and computed and measured Fusion zone (FZ) and heat affected zone (HAZ) boundaries, ( $V=70$  kV,  $I=40$  mA,  $v=4.23$  mm/s,  $g=12.7$  mm and  $T_0 = 21^\circ\text{C}$ ) (Goldak, 2005).

The analyst must specify these functions or at least the parameters such as weld current, voltage, speed, arc efficiency and the size and position of the discs, ellipsoids and/or cones. In some cases the weld pool size and shape can be estimated from cross-sectional metallographic data and from weld pool surface ripple markings. If such data are not available, the method for estimating the weld pool dimensions suggested by Bibby et al (1985) for deep penetration electron beam or laser welds should be used.

The size and shape of the heat source model is fixed with the ellipsoid parameters by Goldak (2005) defined in Figure 2.6. It was reported that good agreement between actual and computed weld pool size could be obtained if the size selected is about 10% smaller than the actual weld pool size with this model. If the ellipsoid semi-axes are too long then the peak temperature is too low and the fusion zone too small. Goldak's experiments showed that accurate results could be obtained when the computed weld pool dimensions were slightly larger than the ellipsoid dimensions. Chakravarti et al (1985) have studied the sensitivity of the temperature field to the ellipsoid parameters. He found that ellipsoid parameters must be smaller than the weld pool size to provide accurate results.

#### **2.1.2.5. Evaluation of the Double Ellipsoid Model**

In order to minimize the computing cost the initial analysis was done by Goldak (1984) in the plane normal to the welding direction as shown in Figures 2.8 and 2.9. Thus, heat flow in the welding direction was neglected. This simplification is accurate in situations where comparatively little heat flows from the arc in the welding direction. This is reasonable when the arc speed is high. An estimate of the effect of this approximation has been given by Andersson (1978) who argues that the errors introduced by neglecting heat flow in the direction of the moving electrode are not large, "except in the immediate vicinity of the electrode."

In order to demonstrate the flexibility and assess the validity of the double ellipsoidal heat source model two quite different welding situations were considered by Christensen in 1965. The first case analyzed was a thick section (10cm) submerged arc bead-on-plate (low carbon structural steel) weld shown schematically in Figure 2.8. The welding conditions are also contained in the Figure 2.8.

Christensen reported a 800 to 500 °C cooling time of 37 seconds for this weld and the FZ and HAZ sizes shown in the diagram. FEM mesh used to calculate these quantities has also been shown in this figure. The temperature distribution in the 'cross-section analyzed' is calculated for a series of time steps as the heat source passes.

Experimental  
 Voltage : 32 V  
 Current : 117 A  
 Welding Speed : 0.005 m/s  
 Efficiency : 0.95

Ellipsoidal Parameters  
 (Equations 2.16,2.17)

Semi-axes

a : 2.0

b : 2.0

$C_1$  : 1.5

$C_2$  : 1.5

Heat Input Fractions

$f_f$  : 0.6

$f_r$  : 0.6

| Boundaries    | Calculated | Experimental |
|---------------|------------|--------------|
| FZ ( $x_1$ )  | 1.6 cm     | 1.4 cm       |
| HAZ ( $x_2$ ) | 2.1 cm     | 2.1 cm       |

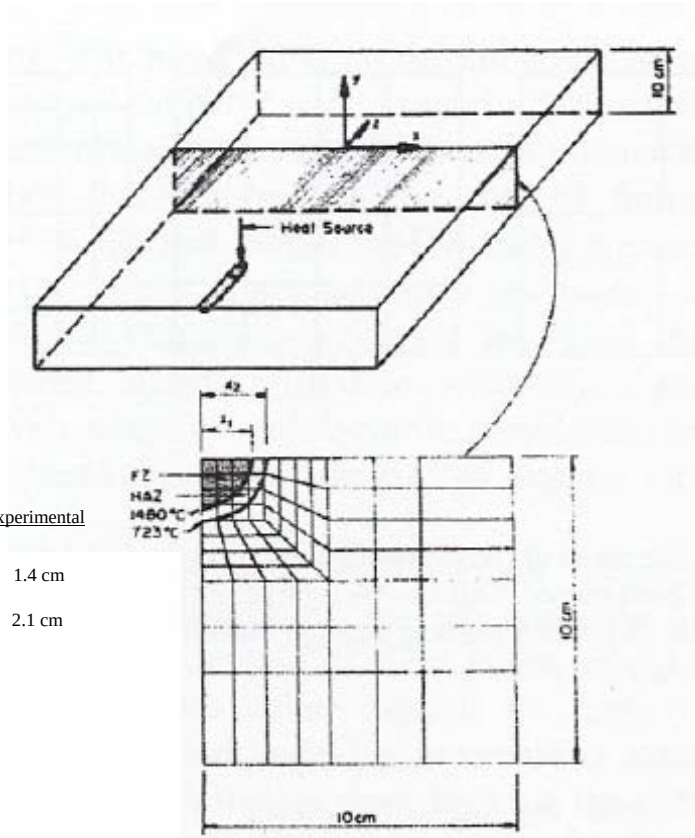


Figure 2.8. Experimental arrangement and FEM mesh for the thick section bead on plate weld (Goldak, 1984).

In this way the FZ and HAZ cross-sectional sizes could be determined, and from the time step-temperature data the cooling time 800 to 500 °C was calculated. The second welding situation was taken from the work of Chong (1982), shown as Figure 2.9.

It is a partial penetration electron beam bead-on-plate (low carbon steel) weld. Traditionally the Rosenthal 2D model would be used to analyze this weld. However, there is some heat flow through the thickness dimension since the penetration is partial and, of course, the idealized line heat source is suspect. The ellipsoidal model can be easily adapted to this weld geometry by selecting appropriate characteristic ellipsoidal parameters. A cooling time (800 °C to 500 °C) of 1.9 seconds was measured by Chong (1982) and the FZ and HAZ dimensions were reported.

The point, line and plane sources idealize a heat source which in reality is distributed. At the heat source, the error in temperature is large, usually infinite.

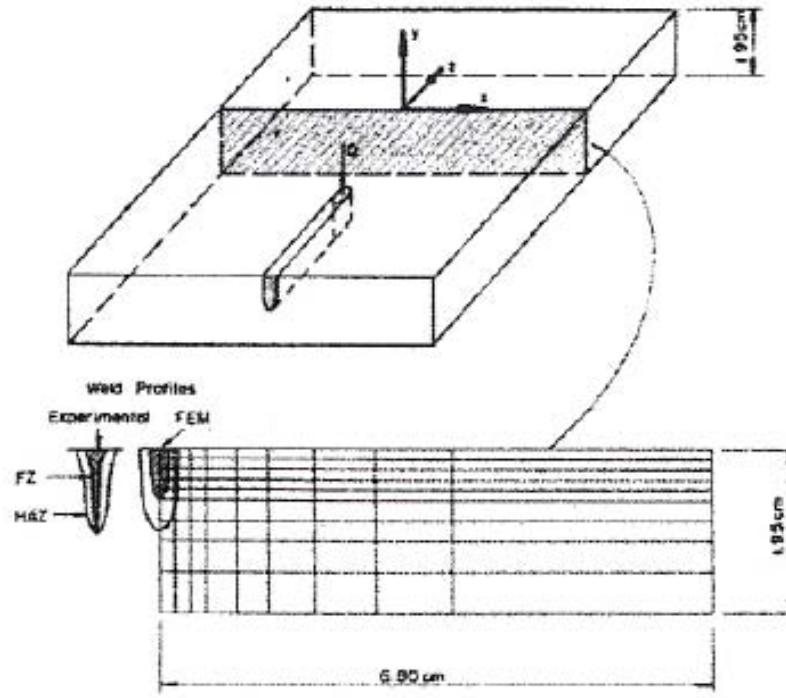


Figure 2.9. Experimental arrangement and FEM mesh for the deep penetration weld (Chong, 1982).

Near the heat source the accuracy can be improved by matching the theoretical solution to experimental data. This is usually done by choosing a fictitious thermal conductivity value .

With numerical methods, these deficiencies have been corrected and more realistic models that are just as rigorous mathematically have been developed by Chakravarti et al, (1985). Perhaps the most important factor is to distribute the heat rather than assume point or line sources. Temperature dependent thermal conductivity and heat capacity can be taken into account, Figures 2.10 and 2.11. In addition, temperature dependent convection and radiation coefficients can be applied to the boundaries. For the radiation and convection boundary conditions, a combined heat transfer coefficient was calculated from the relationship:

$$H = 24.1 \times 10^{-4} \varepsilon T^{1.61} \quad (2.18)$$

where  $\varepsilon$  is the emissivity or degree of blackness of the surface of the body. A value of 0.9 was assumed for  $\varepsilon$ , as recommended for hot rolled steel (Rykalın, 1974).

Mills (2002) also present thermo-physical properties for selected commercial alloys. The thermal conductivity of steels at room temperature is reduced by increasing the amount of alloy substances, Figure 2-10. This situation is limited to the phase change temperature  $A_1$ , from where the variation disappears in the slight rise of the curve.

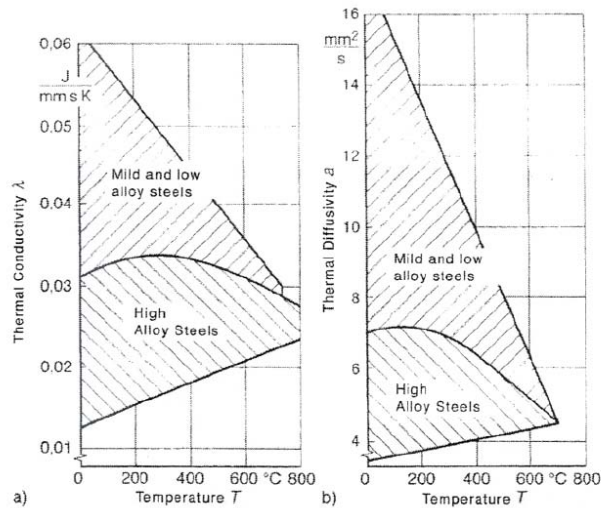


Figure 2.10. Thermal conductivity (a) and Thermal diffusivity (b) of steels as function of temperature (Miles, 2002).

The specific heat capacity for some steels as a function of temperature is shown in Figure 2.11.

Figure 2.12. shows the density for some steels as a function of temperature.

As shown in Figure 2.5. there are four characteristic length parameters that must be determined. Physically these parameters are the radial dimensions of the molten zone in front, behind, to the side and underneath the arc.

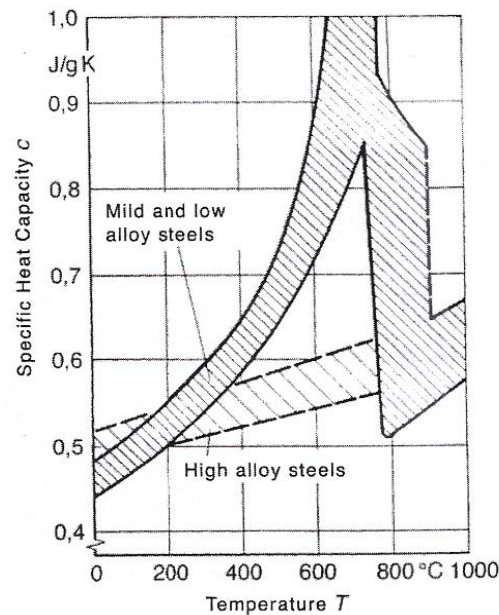


Figure 2.11. Specific heat capacity for some steels as function of temperature, latent heat at phase change temperature for ferrite pearlite and at phase change temperature for ferrite austenite ; from (Richter, 1973).

If the cross-section of the molten zone is known from experiment, these data may be used to fix the heat source dimensions. For example, the width and depth are taken directly from a cross-section of the weld. In the absence of better data, experience suggests it is reasonable to take the distance in front of the heat source equal to one-half the weld width and the distance behind the heat source equal to twice the width. If cross-sectional dimensions are not available Christensen's expressions can be used to estimate these parameters. Basically Christensen defines a non-dimensional operating parameter and non-dimensional coordinate systems. Using these expressions, the weld pool dimensions can be estimated.

The non-dimensional Christensen method was used to fix the ellipsoidal flux distribution parameters for the thick section bead on plate weld shown in Figure 2.8. The cross-sectional dimensions were reported by Chong, and the half-width dimension was applied to the flux distance in front of the electron beam heat source while the twice-width distance was applied behind the *EB*. The heat input fractions used in the computations were based on a parametric study of the model. Values of

$f_f = 0.6$  and  $f_r = 1.4$  were found to provide the best correspondence between the measured and calculated thermal history results.

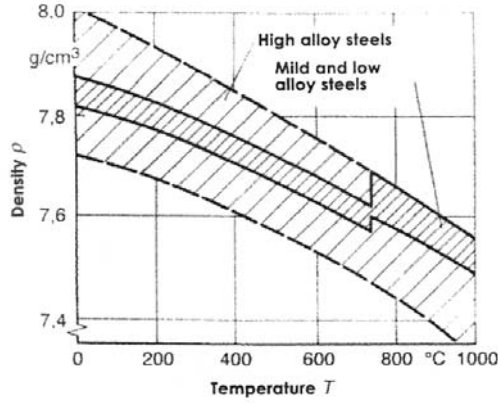


Figure 2.12. Density of some steels as function of temperature; from (Richter, 1973).

The temperature distribution along the width perpendicular to the weld center line at 11.5 seconds after the arc passed was shown in Figure 2.13 (Chakravarti et al, 1984). They was compared to the experimental data from Christensen et al.(1965) and the finite element analysis of the same problem by Krutz and Segerlind (1978) where a disc-shaped heat source (Eq.2.4) was used. They reported that the ellipsoidal model had given better agreement with experiment than the disc.

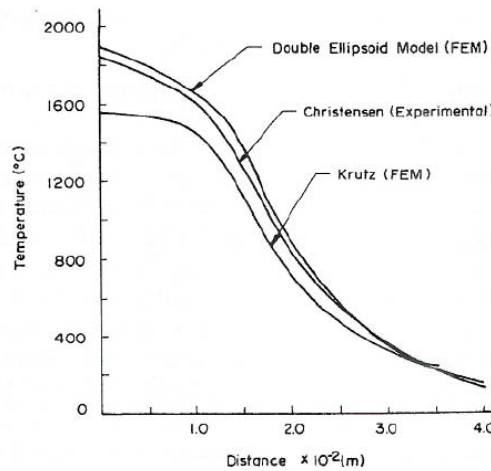


Figure 2.13. Temperature distribution along the top of the workpiece perpendicular to the weld. (Chakravarti et al, 1984).

The fusion and heat affected zone boundary positions were predicted using the *FEM* calculations by Chakravarti et al, (1984) and they reported that these were in good agreement with the experimental data. In addition, they found that, the *FEM* cooling times ( $800^{\circ}\text{C}$  to  $500^{\circ}\text{C}$ ) were much closer to the experimental value than the cooling time calculated by the Rosenthal's analysis. The *FEM* cooling time was slightly larger than the experimental value. This might be due to neglecting the longitudinal heat flow. The radiation-convection was applied to the top surface had little effect on the thermal cycle or the *FZ-HAZ* boundaries.

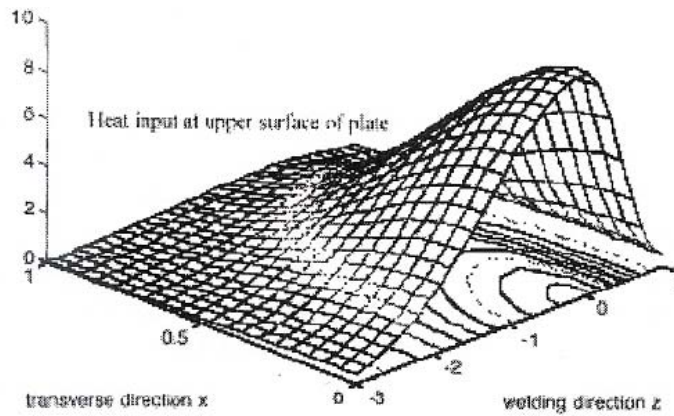


Figure 2.14. Heat input distribution using a double-ellipsoid heat source model, (Lindgren, 2001).

This was to be expected for thick section welds where the heat flow was dominated by conduction. A plot of the heat input at the surface using the double ellipsoid heat source is given in Figure 2.14., from Lindgren (2001).

## 2.2. Welding Simulation and FEA of Welding Operation

A variety of FE software packages used for the simulation of welding have been documented in literature, such as the FE software employed by Vincent et al (1999). They consider a carbon dioxide laser beam delivering thermal loading to a thin disc of French vessel steel to simulate welding and compare ensuring residual stresses obtained either experimentally or using finite element codes referred to as Sysweld (Framatome) and Code\_Aster (EDF). The metallurgical transformations

have been taken into account and the FE results agree with the experimental ones, including temperatures, size of transformed zones, displacements and residual stresses.

Teng and Chang (1998) reported that a thermomechanical model was developed by Friedman (1975) using the FE method to calculate temperatures, stresses and distortions during welding; that elastoplastic FE computer programs were developed by Muraki et al (1975) to monitor welding thermal stresses and metal movement. Residual stresses were estimated by Josefson (1993) in a multi-pass weld and in a spot-welded box beam with SOLVIA and ABAQUS, which were commercially available FE codes for non-linear analyses; and that temperatures and stresses were analysed by Karlsson (1989) and Karlsson and Josefson (1990) in single-pass girth butt welding of carbon-manganese pipe using the FE codes ADINAT and ADINA.

Murthy et al (1996) proposed a detailed methodology for the analysis of residual stresses due to welding and quenching processes. Their thermal and thermo-elasto-plastic formulations take into consideration non-linearities due to the variation of material properties and heat transfer coefficients with temperature as well as the inclusion of a radiation boundary condition and solid phase transformation effects. Temperature and stress distributions obtained numerically are validated against published data for butt welding of plates, circumferential welding of pipes, multi-pass welding of plates and quenching. They also highlighted certain limitations on the usability of some commercial FE codes, in particular thermal effect concerns due to phase transformation and transformation plasticity, the latter being the microscopic plastic flow that occurs during phase transformations.

Mackerle (2001) has written a bibliography of the finite element and boundary element methods published in 1998, 1999 and the first quarter of 2000. The bibliography provides a list of 207 references on the analysis and modelling of residual stresses; general solution techniques as well as problem-specific applications are included.

### 2.2.1. Thermal and Mechanical Finite Element Analysis

Murthy et al (1996) have carried out a numerical analysis on the welding of two 25mm-thick butt welded plates of material IS 2062 using their FE software in this work. The heat flux has been modelled with a trapezoidal variation representing the approach of the welding torch, followed by a constant heat input and then the gradual withdrawal of the heat source. The material properties in the analysis are taken as temperature dependent. The transient thermo-elasto-plastic analysis has been conducted for the second pass only, since it is assumed that the overlapping of the weld passes relieves stresses at temperatures higher than the transformation temperature. The temperature contours and residual stresses have been verified against experimental data obtained from MIG welding in two passes. They have also numerically analysed a butt welding of two 13.2mm-thick stainless steel 316L plates subject to submerged arc welding. The heat input is simulated with a simple trapezoidal model, and the ensuring temperatures and stresses agree with published results for a double ellipsoidal heat input model in this work. Single-pass butt-welded cylindrical pipe and a multi-pass welded thick plates have also been included in the FE study. The pipe made up of carbon-manganese steel was analysed axisymmetrically. Material dilatations have been calculated in proportion to the time-temperature-transformation-diagram fractions of various material phases formed during cooling from austenitizing temperature. The results were compared to published residual hoop stress values. The multi-pass 50mm-thick welded plates have been analysed with the use of simplified models, reducing the CPU time and indicating that the maximum tensile residual stress appears near the finishing bead, leading to the conclusion that it is sufficient to consider the last few welding passes to obtain the same results.

Brickstad and Josefson (1998) simulated the residual stresses due to welding using ABAQUS to perform the finite element analysis. Their analysis consisted of two main parts, the thermal and the structural. They assumed rotational symmetry of the modelled multi-pass butt-welded stainless steel pipes. Hence the analysis was two-dimensional and axisymmetric. The thermal analysis models the heat input from

the welding torch into the weld elements causing the weld to melt. Heat losses allow the weld region to solidify. The temperature contours obtained from this part of the analysis were used in the sequential, structural analysis to derive the stresses generated as the material heats up and cools down again. The behaviour of the material involved non-linearity and therefore residual stresses remain in the welded pipe after cooling. Brickstad and Josefson assumed the von Mises yield criterion and associated flow rule together with kinematic hardening. The coefficient of thermal expansion was given a constant value corresponding to the mean temperature between 20°C and 600°C. All the other material properties were temperature dependent and they were tabulated against temperature ranging between 20 and 2000°C. The element type used in the structural analysis was CAX8, which was an 8-node biquadratic axisymmetric stress/displacement quadrilateral. Large deformations had been assumed in the structural analysis although it was reported that, in comparison, small deformations only give a small difference in residual stress results.

Teng and Chang (1998) examined a three-dimensional FE model, analysing the temperature and stresses in circumferential single-pass welded pipes and discussed the influences of pipe wall thickness on the welding residual stresses. They showed that their study could be used to help resolve problems such as intergranular stress corrosion cracking, which has been observed in the weld fusion lines or nearby, on the inside surfaces of the pipes of boiling water reactors.

The work carried out by Tso-Liang Teng, Chin-Ping Fung, Peng-Hsiang Chang and Wei-Chun Yang (2001) have described the thermal elasto-plastic analysis using finite element techniques to investigate the thermomechanical behaviour and evaluate the residual stresses and angular distortions of the T-joint in fillet welds. Furthermore, their work have employed the technique of element birth and death to simulate the weld filler variation with time in T-joint fillet welds. They also discussed the effects of flange thickness, and restraint condition of welding on the residual stresses and distortions.

Wen and Ferrugia (2001) have modelled residual stresses in steel pipes and pipe joints using ABAQUS. Both pipe seam and pipe girth weldings are considered and the temperature dependency of material properties is taken into account.

Pasquale et al (2001) employed SYSWELD to simulate dissimilar girth welds made of an austenitic steel, a ferritic steel and a nickel weld metal. Their work includes three-dimensional and axisymmetric FE analyses which are in agreement with their X-ray diffraction measurement of residual stresses. FE transient temperature distributions and axial and circumferential residual stresses are discussed for a variable weld fabrication conditions and different boundary conditions.

X.K. Zhu and Y.J. Chao (2002) investigated the effect of each temperature-dependent material property on the transient temperature, residual stress and distortion in computational simulation of welding process. Welding of an aluminum plate using three sets of material properties, namely, properties that are functions of temperature, room temperature values, and average values over the entire temperature history in welding, are considered in the simulation.

Serdar Karaoğlu and Çiçek Karaoğlu (2002) calculated the stress concentration factor (SCF) of T-butt weldments by finite element method. The influence of weld toe transition radius on SCF has been analyzed under both tension and pure bending loading. They showed that it is possible to ease the stress concentration of T-butt welded joint effectively by increasing the weld toe transition radius.

Fanous et al (2002) have introduced a new technique for metal deposition using element movement, which takes less time during simulation in comparison with previous techniques such as “element birth”. In their analysis, they accounted for change of phase and variation of properties with temperature.

Lindgren et al (2002) presented a thermo-mechanical analysis in butt-welding of a copper canister for spent nuclear fuel. They investigated a plane copper end during electron beam welding to a copper canister. The FE method gives the transient and residual stress, temperature and strain field for the weldment. They thought that the most important entity is the accumulated plastic strain, as high values of this entity would indicate an increased risk for creep fracture. From their FE analysis, the maximum plastic strain (plastic+creep) accumulated in the (possibly brittle) heat affected zone is approximately 7%, which is well below the reported ductility for the type of copper under investigation.

Serkan Benli (2004) investigated the residual stresses that taken place in a butt welding with finite element method. The results obtained from 2 dimensional analysis with ANSYS software package program. The temperature profiles and distortion patterns which they obtained by finite element modelling matched well with the experiments.

Fuad M. Khoshnaw and Idrees A. Hamakhan (2006) carried out the mechanical properties of welded austenitic stainless steel plates type AISI 316L using stress strain microprobe in welded region, and heat affected zone. Automated metal inert gas welding process has been used. Different heat inputs have been selected in order to describe the effect of metallurgical aspects on mechanical properties like ultimate tensile strength, yield strength, and hardness. According to their study, for all heat inputs which they used the mechanical properties of welded region and HAZ are better than the base metal.

M. Sunar , B.S. Yilbas and K. Boran (2006) examined a cantilever assembly subjected to heating at its fixed end, which resembles the welding of a sheet metal is considered. Temperature and stress fields are computed during the heating process. A control volume approach is introduced for the numerical solution of heat transfer equations while the finite element method is adopted for stress field predictions. It is found that the temperature distribution in the transverse direction does not vary considerably, but varies significantly in the longitudinal direction. The temporal change of temperature gradient induces stresses in the substrate material. However, the maximum magnitude of the von Mises stress is less than the yield strength of the substrate material.

M.M. Mahapatra, G.L. Datta, B. Pradhan and N.R. Mandal (2006) modelled top and bottom reinforcement to minimize angular distortions in single-pass submerged arc welded (SAW) butt joints by using a reusable flux-filled backing strip and proper SAW process parameters without resorting to costly distortion mitigation techniques. The process was also modeled by using three-dimensional finite element analysis by incorporating the top and bottom reinforcements into the modeling. The modeling methodology adopted can be used for predicting the angular distortions in SAW square butts with top and bottom reinforcements.

Z.B. Dong and Y.H. Wei (2006) simulated the dynamic thermal distributions and strain evolutions multipass welding after taking into consideration of the fluid flow in the weld pool, the latent heat, taking into account the effect of the deformation in weld pool, change of initial temperature and solidification shrinkage. At the same time, the driving forces to weld solidification cracks of each weld pass are obtained successfully according to simulated thermal cycle (temperature against time) and mechanical strain cycle (mechanical strain against time). The results showed that the patterns of distribution of the driving force are similar to those of surface fusion welding. The driving force of first weld pass is larger than following weld passes and the driving force decreases gradually in company with welding processing. Sequent welding processes affect the mechanical strain distributions of previous weld pass, of which the tensile mechanical strain changes to compressive strain. In addition, the driving forces are analyzed and weld solidification cracks are predicted during multipass welding.

### 3. MATERIAL AND METHOD

#### 3.1. Welding Method

##### 3.1.1. Gas Metal Arc Welding Process (GMAW)

The gas metal arc welding (GMAW) is increasingly employed for fabrication in many industries. This process is versatile, since it can be applied for all position welding; it can easily be integrated into the robotized production centers. Gas Metal Arc welding is an arc welding process that uses an arc between a continuously-fed filler metal electrode and the weld pool. The process is used with shielding from an externally supplied gas and without the application of a pressure. It is also known as MIG welding or MAG welding where MIG (Metal Inert Gas) welding refers to the use of an inert gas while MAG (Metal Active Gas) welding involves the use of an active gas (i.e. carbon dioxide and oxygen). The process is illustrated in Figure 3.1. A variant of the GMAW process uses a tubular electrode filled with metallic powders to make up the bulk of the core materials (metal core electrode).

Such electrodes may or may not require a shield gas to protect the molten weld pool from contamination. All commercially important metals such as carbon steel, high-strength low alloy steel, stainless steel, aluminium, copper, titanium, and nickel alloys can be welded in all position with GMAW process by choosing appropriate shielding gas, electrode, and welding variables.

Metal transfer in GMAW refers to the process of transferring material of the welding wire in the form of molten liquid droplets to the work-piece. Metal transfer plays an important role in determining the process stability and weld quality.

Depending on the welding conditions, metal transfer can take place in three principal modes: globular, spray, and short – circuiting. Globular transfer, where the droplet diameter is larger than the wire diameter, occurs at relatively low currents. Since it is often accompanied by extensive spatters, globular transfer is typically used in welding parts which has relatively loose quality requirements.

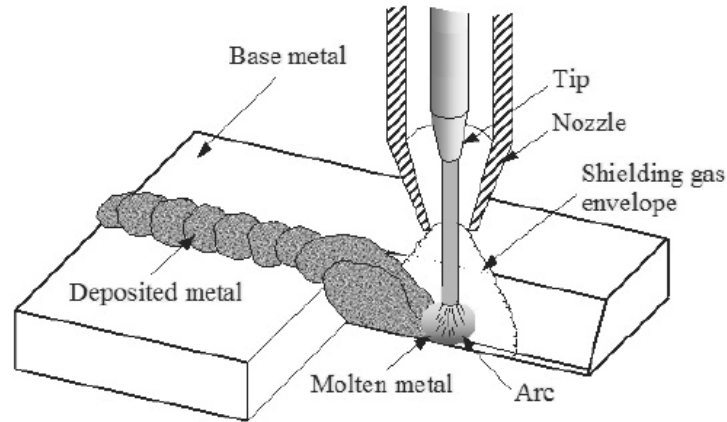


Figure 3.1. GMAW Process (Weglowski, 2008).

Spray transfer, where the droplet diameter is smaller than the wire diameter, occurs at medium and high currents. It is a highly stable and efficient process, and is widely used in welding thick steel plates and aluminium parts. Short – circuiting transfer is a special transfer mode where the molten droplet on the wire tip makes direct contact with the work-piece or the surface of the weld pool. It is characterized by repeated, intermittent arc extinguishment and re-ignition. It requires low heat input and hence is commonly used in welding thin sheets (Weglowski, 2008).

GMAW process offers flexibility and versatility, is readily automated, requires less manipulate skill than SMAW, and enables high deposition rates (5-20 kg per hour) and efficiencies (80-90 %). The greatest shortcoming of the process is that the power supplies typically required are expensive.

### 3.1.2. Welding Machine

In this thesis results of thermal–stress analysis obtained from FE compared with the results obtained from experimental measurements. The main objective of the experimental work is to describe the structural response of welded T-Joint under different set of welding parameters. For the welding operations Gedik Fronuis Vario Star 404-2 is used. The technical specifications of the machine are given in Table 3.1.

Table 3.1. Technical Specifications of Welding Machine

|                                                                                   |                             |          |                   |
|-----------------------------------------------------------------------------------|-----------------------------|----------|-------------------|
|  | Mains voltage (V)           |          | 380               |
|                                                                                   | Power (KVA)                 |          | 11.1              |
|                                                                                   | Power factor                |          | 0.7               |
|                                                                                   | Welding current             | 60% (A)  | 400               |
|                                                                                   |                             | 100% (A) | 280               |
|                                                                                   | Adjustment range (A)        |          | 40 – 400          |
|                                                                                   | Open circuit voltage (V)    |          | 18 – 55           |
|                                                                                   | Means of cooling            |          | F                 |
|                                                                                   | Protection Class            |          | IP 21             |
|                                                                                   | Dimensions (l x w x h) (mm) |          | 1075 x 480 x 1235 |
|                                                                                   | Weight (kg)                 |          | 177               |

### 3.1.3. Workpiece Material

The accurate modelling of temperature dependent material properties is a key parameter to the accuracy of computational weld mechanics and has been a challenging job due to scarcity of material data at elevated temperature. In the past, several research efforts have been dedicated to the investigation of material properties and their effect on the structural response under transient thermal loading during welding. Microstructure evolution and its effects on thermal and mechanical properties are the hard core issues in material modelling. In the computational weld mechanics microstructure evolution is addressed either by direct calculations from thermal history, various phase fraction, properties each constituent and deformation history or indirectly by considering the microstructural dependency on the thermal and mechanical history. Although the indirect approach is relatively crude but is widely used in the welding simulation due to its relative ease.

This work is related to the mechanical effects of welding and is based on the comparative studies to investigate structural response for different structural boundary conditions, welding parameters and procedures without going into the details of metallurgical investigations therefore indirect approach is adopted to account for the effect of microstructure evolution.

### 3.1.3.1. Weld Joint Configurations

The type of joint, or the joint geometry, is predominantly determined by the geometric requirements or restrictions of the structure and the type of loading. Together, joint configuration and the number and placement of weld joints determines ease of manufacture, cost, and structural integrity including robustness against weld-induced distortion.

The fundamental types of welds are shown in Figure 3.2 and include groove welds, fillet welds, plug welds, and surfacing welds. Groove, fillet, and plug welds are used for joining structural elements. Surfacing welds are used for applying material to a workpiece by welding for the purpose of providing protection from wear or corrosion, or, perhaps, restoring dimensions lost through wear or corrosion.

The five basic joint designs for producing structures are (1) butt joints, (2) corner joints, (3) edge joints, (4) lap joints, and (5) tee (or T) joints, as shown in Figure 3.3. The plug weld is a special weld used to attach one workpiece to another locally through penetrations in the surface.

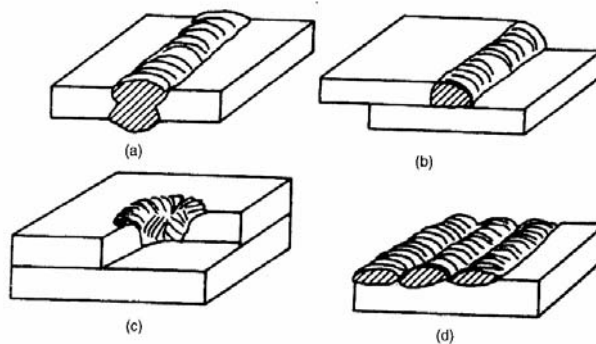


Figure 3.2 Fundamental types of welds, including (a) butt, (b) fillet, (c) plug, and (d) Surfacing (Teng, 2001)

While structural, plug welds generally do not provide the same degree of structural integrity as the other five weld joint types shown in Figure 3.3.

Butt welds or joints are also called square butts or straight butts when they are produced from joint elements prepared (before welding) with square or straight,  $90^\circ$  abutting edges. Such joints do not require filler metal, as they abut tightly, and are

usually welded by an autogenous process such as GTAW, PAW, LBW, or EBW. For such welds, good fit-up, without gaps typically exceeding about 1,5mm, is required, thereby placing additional constraints on preparation methods (usually machining versus sawing or thermal cutting). However, butt joints can have other preparations (by thermal or abrasive water-jet cutting, machining, or grinding) that can include single or double V's, single or double bevels, single or double J's, or single or double U's. These all require filler metal and so are performed by consumable electrode arc welding processes such as SMAW, FCAW, GMAW, or SAW. Likewise, corner joints can use no preparation, as in a single or double fillet, or have various preparations including a single V or a single V and a fillet.

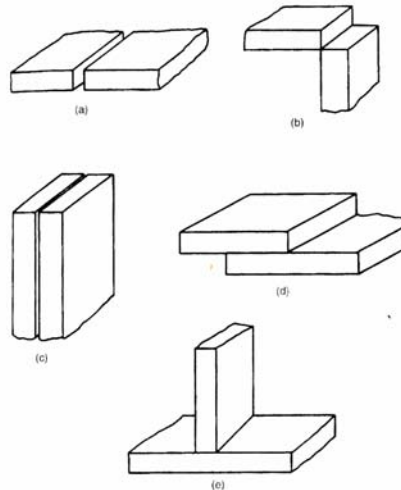


Figure 3.3. The five basic weld joint designs used in structural fabrication: (a) butt joint, (b) corner joint, (c) edge joint, (d) lap joint, (e) tee joint (Teng, 2001).

Edgewelds can have no preparation, in which case they are called square edge welds, or a single V preparation. Lap or overlap joints can have single or double fillets, virtually always without any preparation. Finally, tee (T) joints can be made using double double fillets, single or double bevels, or double J's.

The square-groove is simple to prepare, economical to use, and provides satisfactory strength, but is limited by joint thickness. For thick joints, the edge of each member of the joint must be prepared to a particular geometry to provide accessibility for welding (torch tip and electrode or filler wire manipulation) and to

ensure the desired weld soundness and strength. For economy, the opening or gap at the root of the joint and the included angle of the groove should be selected to require the least weld metal necessary to give needed Access and meet strength requirements. The J- and U- groove geometry minimizes weld metal requirements compared to V's, but adds to the preparation costs. Single-bevel and J-groove welds are more difficult to weld than V or U-groove welds because one edge of the groove is vertical

The design of a joint for welding, as in other processes, should be selected primarily on the basis of load-carrying requirements. However, especially in welding, variables in the design and layout of joints can substantially affect the costs associated with welding, as well as the ability to carry loads safely, inherent susceptibility to the formation of certain defects, susceptibility to distortion, ability or facility to inspect quality, and other key properties (e.g. corrosion resistance, leak tightness, or hermeticity). (Teng, 2001).

T-Joint fillet welds are widely used employed in ships, bridge structures and supporting frames for pressure vessels and piping. Due to localized heating by the welding process and subsequent rapid cooling, residual stresses and distortions can occur near the T-Joint. High residual stresses in regions near the weld may promote brittle fracture, fatigue, or stress corrosion. T-Joint fillet weld is used in this study to analyse thermomechanical behaviour of the welding material.

### **3.1.3.2. Material Model**

SYSWELD allows the simulation of welding processes with all commercial aluminum alloys and steels. More exotic alloys, such as alloys existing in aerospace engineering, can also be processed. Aluminum alloys exist as self-hardening aluminum wrought materials (for example AlMgMn), the strength of which can be improved by means of cold forming, and thermosetting wrought alloys (for example AlMgSi). Steel materials include general structural steels, higher resistance and low corrosion structural steels appropriate for welding, case hardening and tempering steels, high temperature steels, corrosion-resistant steels and model steel.

This thesis describes the thermal and mechanical analysis using finite element techniques to analyse the thermomechanical behaviour and evaluate the residual stresses and angular distortions of the T-Joint welding. Figure 3.4 depicts two plate fillet weld.

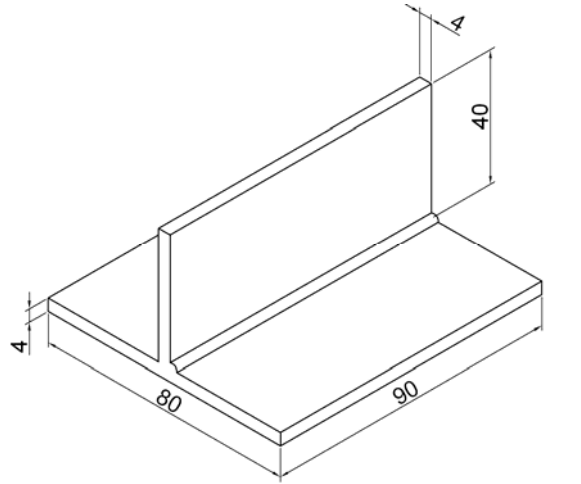


Figure 3.4. Isometric view of T-Joint welding.

The plate material is S355J2G3 and properties of this material is dependent on the temperature history.

In welding computations thermal material properties are strongly nonlinear and depend on temperature and phases. Melting temperature of S355J2G3 steel is 1505°C. The composition of the steel is shown in Table 3.2. Figure 3.5 and 3.6 shows the thermal conductivity and density of workpiece material depending on the temperature.

Table 3.2. Composition of the Workpiece Material (Boutout.2004).

| % C  | % Mn | % Si | % S   | % P   |
|------|------|------|-------|-------|
| 0.20 | 1.60 | 0.55 | 0.035 | 0.035 |

The density and thermal conductivity has to be entered for alpha phases (ferrite/pearlite, bainite and martensite) and austenite. The phase dependent properties are mixed based on the computed phase proportions.

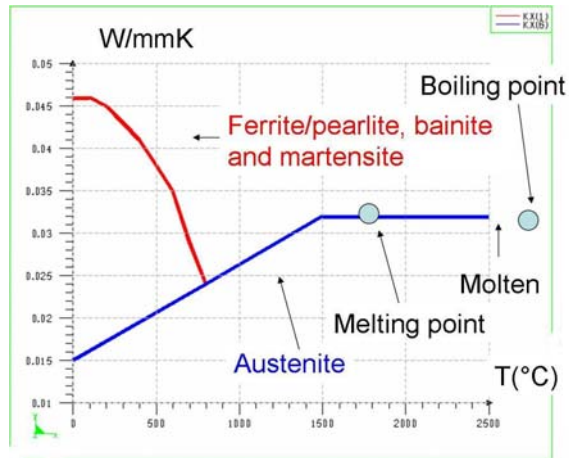


Figure 3.5. Thermal conductivity of steel (Boutout, 2004).

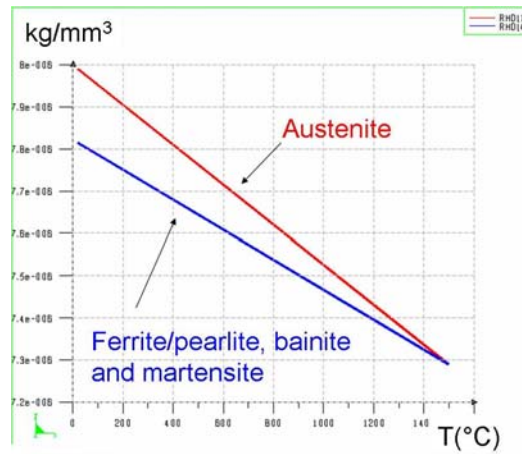


Figure 3.6. Density of steel (Boutout, 2004).

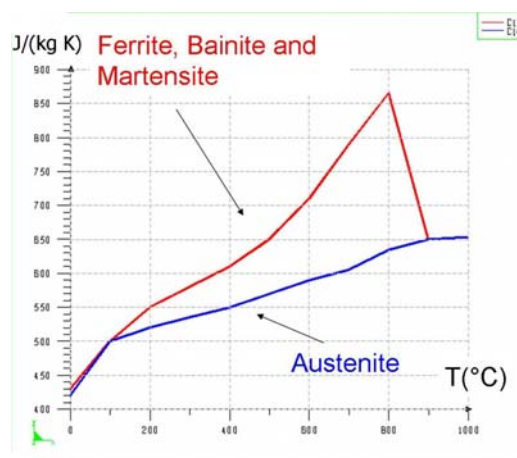


Figure 3.7. Specific Heat of steel (Boutout, 2004).

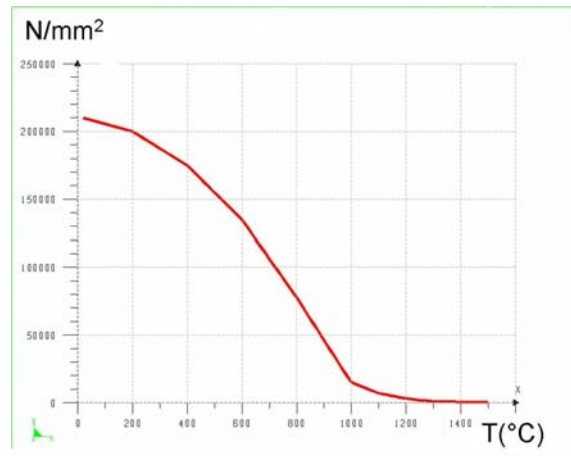


Figure 3.8. Modulus of Elasticity of steel (Boutout, 2004).

Starting from 1200-1300°C, it is assumed that the material starts to behave ‘viscous’. Thus, the removal of material history can be set to a value between 1200°C and 1500°C. The modulus of elasticity should be never less than 1000N/mm<sup>2</sup>. Figure 3.8 shows the modulus of elasticity of the workpiece material.

Poisson coefficient of the steel is constant and it is not a function of temperature. Its value is 0.3.

Mechanical properties of workpiece material are shown in the following figures.

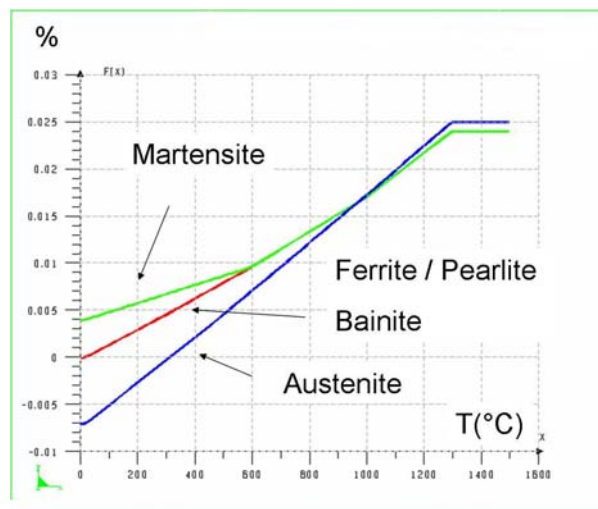


Figure 3.9. Thermal strain of steel (Boutout, 2004).

The yield stress depends on temperature and phases. It should be not less than 5N / mm.

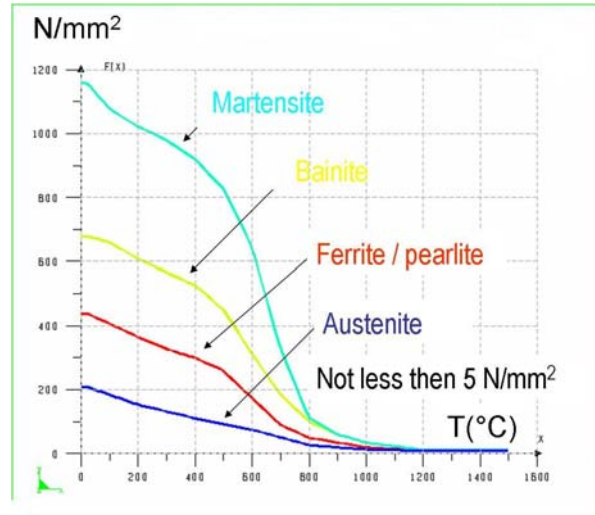


Figure 3.10. Yield stress of steel (Boutout, 2004).

### 3.2. Welding Simulation Method

The objective of this thesis is to develop a three dimensional finite element model by using SYSWELD package program for the analysis of the T-Joint to evaluate the effect of welding parameters on temperature distribution, residual stresses and distortions.

#### 3.2.1. FE Modelling of Arc Welding

A detailed modelling of complete welding phenomena with all its physics is certainly a very difficult job because of the involvement of various fields such a heat flow in multiple phases, complicated weld pool dynamics, microstructures evolution and overall structural response. Diferent fields and their couplings are shown in Figure 3.11 and are described in Table 3.3. It is indeed very cumbersome to account for all the couplings exist between these fields. In computational weld mechanics a number of simplifications are used and most of these couplings are ignored based on

their weak nature. Detailed weld pool phenomena may, however, be regarded as a separate research field due to the level of refinement and as a temperature field and weld bead geometry can not be predicted and subsequently accounted for in a macroscopic context. However, if geometrical changes close to the weld are of primary interest, modelling of fluid flow will be essential.

Neglecting the physics of weld pool due to its insignificant effect on macroscopic effect of welding, all the bidirectional couplings associated with fluid flow in the weld pool (except dependence of heat transfer on fluid flow) are ignored. Similarly, some other weak couplings such as microstructure stress dependency (coupling 4) and heat generation due to deformation (coupling 10) are also ignored.

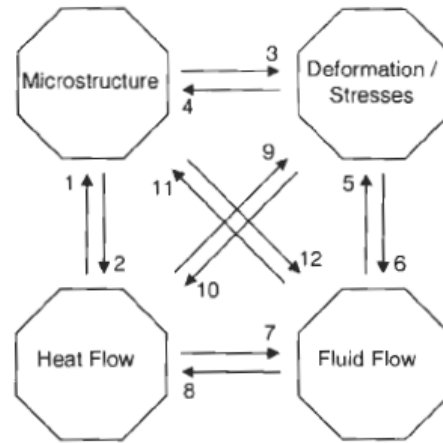


Figure 3.11. Coupling between different fields (Siddique, 2005).

Since the effect of mechanical deformation on heat flow has been ignored, the fully coupled (bidirectional) thermo-mechanical phenomenon of welding can be safely broken down into unidirectional coupled analysis. According to this simplified approach a fully coupled thermo-metallurgical analysis is performed first which is followed by a structural analysis.

During the thermal analysis microstructure evolution can be modeled through either more sophisticated direct calculation procedure or by relatively simpler but common method of indirect incorporation of microstructure aspects into the material model.

Table 3.3. Description of couplings in welding analysis (Siddique, 2005).

| Coupling | Description                                                                            | Nature |
|----------|----------------------------------------------------------------------------------------|--------|
| 1        | Microstructure depend on temperature                                                   | Strong |
| 2a       | Phase changes release latent heat                                                      | Medium |
| 2b       | Thermal conductivity and heat capacity depend on microstructure                        | Medium |
| 3a       | Plastic strain associated with phase change                                            | Strong |
| 3b       | Thermal expansion depends on microstructure                                            | Strong |
| 3c       | Elastic/Plastic material behavior depends on microstructure                            | Strong |
| 4        | Stress state affects phase changes                                                     | Weak   |
| 5        | Structural deformations affect flow pattern                                            | Weak   |
| 6        | Fluid pressure causes deformation                                                      | Weak   |
| 7        | Temperature affects fluid velocity                                                     | Weak   |
| 8        | Fluid flow governs heat transfer                                                       | Strong |
| 9        | Temperature changes produce deformation                                                | Strong |
| 10       | Mechanical deformation generate heat (due to elastic, plastic and thermal strain rate) | Weak   |
| 11       | Flow pattern alters material behavior                                                  | Weak   |
| 12       | Material behavior affect flow pattern                                                  | Weak   |

During the structure analysis, temperature and microstructure dependence of stresses and deformations are accommodated by invoking the results of thermal-metallurgical analysis into the structural (thermal-stress) analysis. The final form of field couplings, used in this thesis, is shown in Figure 3.12.

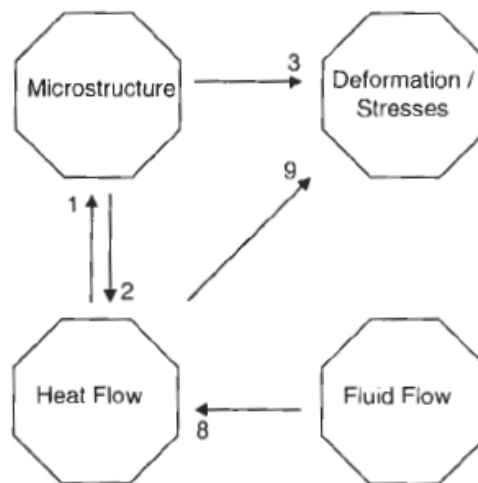


Figure 3.12. Selective coupling between different fields (Siddique, 2005).

### 3.2.2. Heat Source Modelling

The residual stresses and deformations in welded structures are believed to be due to highly non-uniform temperature field applied during welding. It is a widely recognized fact that both the residual stresses and welding deformations are highly sensitive to transient temperature distribution, which itself is a function of the total heat applied and heat distribution pattern within the domain. Thus for the determination of realistic temperature profile in the target application, a very careful and accurate modelling of heat source is required. If the prime objective is to study the mechanical effects of welding, then the only critical requirement in modelling of heat source is the estimation of weld pool and HAZ (heat affected zone) dimensions. During the several developments in modelling of heat sources have been reported in the previous work chapter, the most widely acceptable model for simulation of arc welding process called “double ellipsoidal heat source model” is used in this thesis.

The origin of the coordinate system is located at the center of the moving arc. On the outer boundary of the source, heat input reduces 5% of the peak value. Some very useful recommendations regarding the use of this model are given below:

- Good agreement between actual and computed weld pool size is obtained if the selected ellipsoidal parameters are about 10% smaller than the actual weld pool size.
- The mesh must be sufficiently fine to model the heat source with adequate accuracy. Specially, the Gaussian ellipsoidal model requires approximately four quadratic elements along each axis to capture the inflection of the Gaussian distribution. (This suggestion is probably for two dimensional models.)
- For plane strain formulations approximately ten to twenty time steps are needed for the ellipsoidal heat source to cross the reference plane. For the in-plane and three dimensional model, the heat source may move approximately one half to the weld pool length in one step (Goldak, 2005).

### 3.2.3. Sysweld Software

The welding process has always played a major role in industrial production, especially in the automotive, maritime and aerospace industries. Despite many advantages, welding has some process-specific disadvantages: thermal expansion and shrinkage, microstructural transformations, stresses and component distortions develop. All, of which, need to be controlled. For simulation purposes, it is desirable that distortion and stresses of the component are calculated prior to, during and following the welding process, and that these factors are reduced by varying welding parameters, welding processes, sequence, position of welding seams, clamping conditions and the behavior of the microstructure. Distortion, residual stresses and plastic history of welded components can be calculated with the simulation software SYSWELD, taking into account all relevant physical phenomena. Therefore, the designer can specifically influence optimization of the welding process and component distortion. In case of large automotive and maritime structures, transient simulations are today used either for the computation of local models for the local – global approach, or the macro-weld deposit method. The various welding assembly simulation methods are presented and discussed in more detail in the paper ‘Welding Assembly with SYSWELD’, with respect to result quality, feasible part size and cost.

#### 3.2.3.1. Geometry and Mesh

Simulation of stresses and distortion of practical components by means of finite elements initially requires that the component is meshed with finite elements, on the basis of the component geometry generated in a CAD system. The welding seam itself and the immediate environment is meshed with solid elements in order to achieve adequate representation of physical phenomena, the more distant environment can also be meshed with shell elements especially in case of thin-walled components. This facilitates the creation of complex models. Model types can basically be categorized as thin-walled (example: vehicle outer body parts made of steel) and thick-walled components (example: vehicle inner chassis components).

However, prior to starting meshing, it is often necessary to adjust the CAD model. Surfaces which are not used have to be removed and surfaces which are not connected have to be trimmed back. Edges of adjacent surfaces should be joined together. Geometry interfaces for CAD systems are integrated in SYSWELD / GEOMESH, which provides powerful tools for geometry processing of CAD models, and surface and volume (solid) meshing. Optionally, FEM meshes can be created using any other mesh generator of choice.

### 3.2.3.2. Heat Transfer from the Torch to the Work Piece

The term ‘simulation of welding processes’ has to be interpreted with great care. On the one hand, the term can mean thermodynamic simulation of the shape of the molten and ‘mushy’ zone (the solidus area) and on the other hand, thermomechanical simulation of stress and distortion, which is also called ‘heat effects of welding’. Calculation of the shape of the solidus area can be regarded as an independent and separate task. Simulation of stresses and distortion requires that the thermal energy supplied in practice is effectively introduced into the component. This can be carried out by means of a moving solidus area in the component, or by means of an analytically specified heat source. Transfer of the solidus area into the thermomechanical simulation is referred to as the ‘equivalent heat source method’. SYSWELD facilitates the transfer of externally calculated solidus areas to act as the heat source.

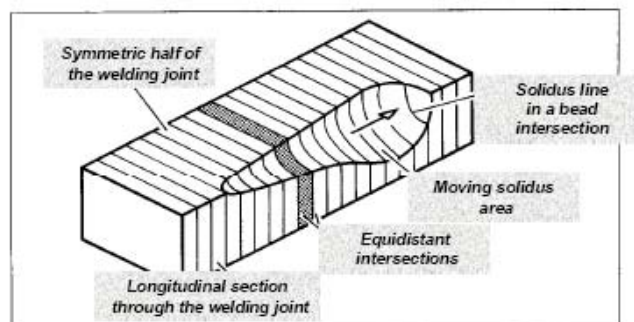


Figure 3.13. Solidus area of the moving molten pool (‘equivalent heat source’) (Boutout, 2004).

If a solidus area does not exist, then an analytically specified volumetric heat source is used. The parameters of the heat sources are adjusted in a way that the result is approximately the shape of the molten zone. For each welding process a specific type of heat source is most effective. A heat source in the shape of a double ellipsoid is appropriate for the simulation of GMAW welding processes, whereas a cone-shaped source is more appropriate for laser beam and electron beam welding processes.

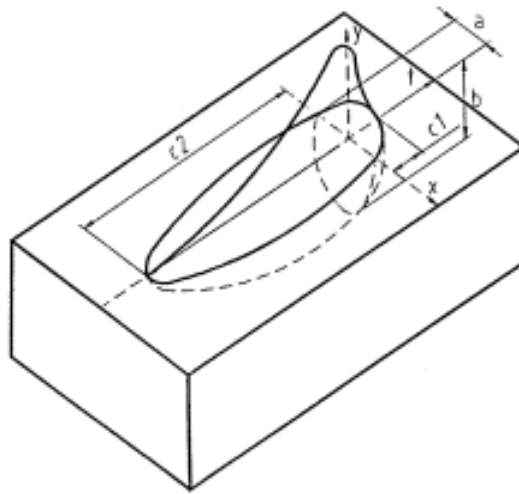


Figure 3.14. Double ellipsoidal volumetric heat source (Boutout, 2004).

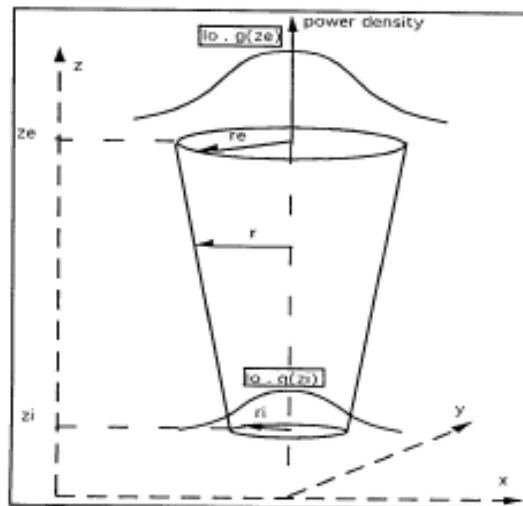


Figure 3.15. Cone-shaped volumetric heat source with Gaussian distributed thermal energy density (Boutout, 2004).

With SYSWELD, the user has a broad range of pre-defined heat sources at his disposal, which covers all current welding processes. A heat source fitting tool greatly simplifies the calibration of the heat source on the real geometry.



Figure 3.16. Heat source fitting tool.

### 3.2.3.3. Changes in the Microstructure

Apart from the ever present non-linear thermal conduction phenomena, microstructural changes frequently occur during welding processes. They decisively influence the formation of stresses and distortion. Microstructural changes are accompanied by volume changes and, generally, microstructures with completely different mechanical properties can develop. When welding case hardening and tempering steel, for example, austenite develops in the heat affected zone and in the molten zone during heating, which turns into martensite (high cooling rate), bainite (medium cooling rate) or ferrite and perlite (low cooling rate). Martensite is a very hard microstructure with a high yield point and low notch impact reaction, similar to ceramic. Ferrite and perlite is a softer microstructure with a low yield point and high

notch impact reaction. As a consequence, microstructure changes have to be taken into consideration when welded designs are evaluated. With SYSWELD, all microstructural transformations which are relevant to the automotive and maritime industries can be simulated and, therefore, SYSWELD allows optimal evaluation of a weld design.

During welding, different microstructures are formed depending on the carbon content and added alloy elements based on different austenitizing stages and cooling rates. All these phenomena have to be taken into consideration for the simulation of welding processes and thus are consequently included in SYSWELD. The degree of austenitizing has to be taken into consideration in the heat affected zone. Within the molten area range, the early microstructure history does not have to be taken into consideration in the calculation of phase transformations during cooling. In this case, the structure is assumed to be perfectly austenitic.

With SYSWELD, it is possible to calculate thermal as well as transformation stresses in accordance with the process.

The thermal, microstructural and structural material properties of a welded material are quite complex and depend on temperature and phases. SYSWELD features a comprehensive material database including major steels and aluminum alloys. In this study S355J2G3 steel is used for analyse thermomechanical behaviour of welded material.

#### **3.2.3.4. The Welding Advisor**

The Welding Advisor is a graphical user interface that allows an intuitive and process-driven methodology to set-up simulations. Once a dedicated project is defined and stored, parts, process and material parameters can be exchanged with a few mouse-clicks within the project and within minutes a computation of a variant can be started. Delivered with the software is an illustrated Advisor Primer that shows, step by step, how to perform an industrial welding study. Set-up of computations with the Advisor is therefore efficient.

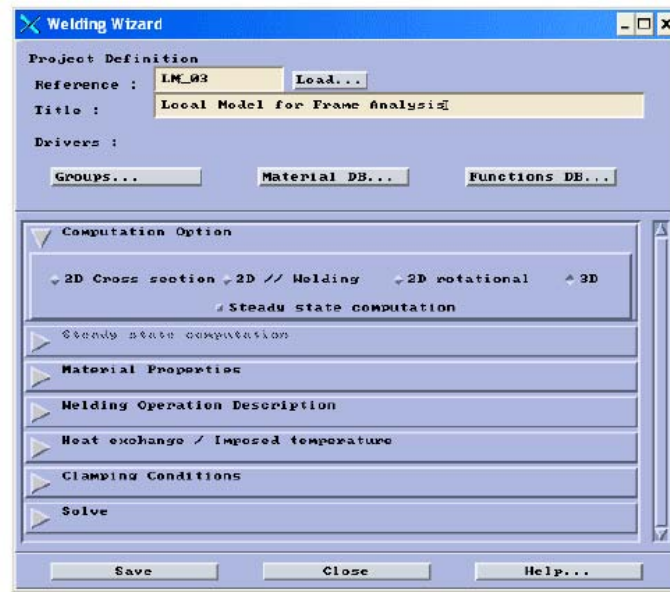


Figure 3.17. Intuitive and straight forward set up of a welding simulation with the Welding Wizard

### 3.2.3.5. Automatic Solver

The SYSWELD solver provides an automatic solution for welding problems, covering all related complex mathematics and material physics. Depending on temperature, phases and proportion of chemical elements, thermal, microstructural and mechanical results are computed, including:

- Latent heat effects of phase transformation and melting/solidification
- Changes in microstructure
- Isotropic, kinematic and mixed hardening including phase transformations
- Visco-plasticity including phase transformations
- Transformation plasticity
- Nonlinear mixture rules for the yield stress of phases
- Phase dependent strain hardening
- Restoring of strain hardening during diffusion controlled phase transformations
- Removal of mechanical history when melting

- Automatic activation of mechanical history during solidification
- Material properties depending on temperature, phases and proportion of chemical elements

and all features dedicated to the methodology of finite elements. It is important to notice that the user does not need to be familiar with the mathematics involved in this solver in order to perform welding computations. The only work needed to perform a computation is to load the project and to start the solver.

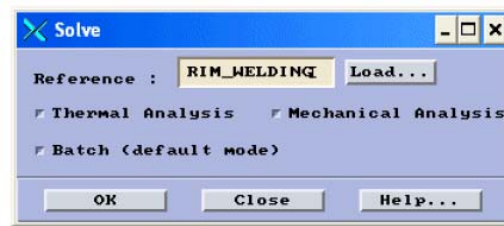


Figure 3.18. Launching a computation – the only work necessary is to load the project name

#### 3.2.3.6. Multi-Physics Post-Processor

The multi-physics post-processing capabilities provide instantaneous process information for the evolution of

- Temperature field
- Heating and cooling rates
- Changes in the microstructure (phase transformations (steel), change in material status (aluminum alloys))
- Distortion
- Stresses
- Yield stress (as a result of the changes in the microstructure)
- Plastic strains

SYSWELD provides a variety of techniques for reviewing process results including

- Contour plots
- Iso-lines and iso-surfaces
- Vector-display
- X-Y diagrams

- Symbol plots
- Numerical presentation
- Cutting planes
- Animations

Of specific interest is the capability to review movies on the evolution of loads and results, step by step, for all important loads and results on the surface or through the structure. The simultaneous display of the evolution of loads and results gives a deep understanding of the process and the computed results. The loads in a welding simulation are thermal strains and changes in the microstructure. Summary of SYSWELD program properties:

- All physical effects related to welding and heat treatment processes can be simulated in SYSWELD.
- The computations can be performed with shell only, solid only or mixed shell-solid Finite Element models, using linear or quadratic shape functions.
- Meshes can be created starting from the CAD model, using SYSWELD / GEOMESH meshing capabilities or using any mesh generator of choice. The FE mesh necessary for welding analysis will be different to that used for general stress analysis.
- Computations can be done for two-dimensional plane and axial-symmetric cross-sections, and for three dimensional structures of arbitrary shape.
- Thermal, microstructural and structural results can be computed step by step or in steady state. For the analysis of large maritime and automotive structures, special computation methods are available which are discussed in paper (II): ‘Distortion Control for Large Maritime and Automotive Structures’.
- The thermal and structural models include changes in the microstructure.
- Specific material law formulations take into consideration the removal of mechanical history when melting, handling of weld material which is yet to be deposited (activation and deactivation of elements), activation of mechanical history during solidification, thermal-elastic-plastic material behavior and hardening including phase transformations, visco-plastic material behavior including phase transformations, transformation plasticity, individual properties of phases (steel) or

material status (aluminum alloys), nonlinear mixture rules of properties of phases and restoring of strain hardening during phase transformation and the influence of the size of the austenite grains formed.

- Extremely high heating and cooling rates – which cause extremely high gradients of thermal, microstructural and mechanical properties - can occur in a welding process. These gradients have to be numerically controlled by the program with a reasonable time expenditure. Apart from robust solvers and dedicated numerical algorithms, special element formulations have therefore been developed in SYSWELD for simulation of welding and heat treatment processes.
- SYSWELD is extremely rapid and convergent. Dedicated algorithms and material laws that have been tuned throughout the last 25 years enable to apply the maximum time step possible from a physical point of view, providing convergence in only a few iterations within a time step.
- Specific capabilities have been developed to review computed results. Thermal and microstructural loads (temperature fields, phases and thermal strains) are stored together with the mechanical results at the same time steps. Therefore, thermal and microstructural loads and mechanical results can be compared and analyzed in an objective manner. The displacement field is stored in an extra file for each computed time step, which allows instant creation of displacement evolution movies. If the results at each gauss point (stresses, strains, etc.) were stored at each computed time step, the result file would be in most cases too large. Consequently, results at gauss points are only stored at selected time steps. In case these results are needed later for other time steps, they can be easily created with a restoring operation based on the stored displacement file. This restoring operation is fast and does not require the inversion of the stiffness matrix, which is the most time consuming operation for larger structures.
- Results are available at gauss points, nodes (extrapolated from gauss points and averaged) and element nodes (extrapolated from gauss points but not averaged). Results computed at gauss points can be transferred to nodes using all common averaging and extrapolation methods.

- Computed results can be transferred between meshes of different density – in full compliance with the material law - in order to provide results on a mesh suitable for post-computations such as general stress or durability analysis.
- The number of nodes and elements is not limited.

#### 4. RESULTS AND DISCUSSION

Highly non-uniform temperature applied during welding is a well established cause of residual stresses and distortions in welded structures. The temperature profile and thus residual stresses depend largely on the welding parameters and geometrical size of the structure to be welded. Welding parameters such as welding current, welding speed and geometrical parameters have significant effect on residual stresses and distortions in welding.

To analyze the effect of each parameter explicitly only one parameter is changed at one time. All of cases 4 mm thickness of welding materials are used. T-Joint geometry and single-pass welding is employed. Temperature dependent material properties and dimensions of this material are described previously. Three dimensional FE models used in this analysis.

##### 4.1. Experimental Measurements

Different finite element studies performed with SYSWELD program in this thesis and their main objective is to describe structural response of welded T-joint under varying set of parameters. Therefore, an experimental approach, which can sufficiently describe the general behaviour, is considered sufficient to validate results.

For the effects of heat input and effects of the welding speed results, presented in this study are found in reasonable good agreement with the experimental measurements. These results are shown in Table 4.1.

Table 4.1. Experimental Measurements of Welding Processes

| Heat Input | Welding Speed | Angular Distortion |
|------------|---------------|--------------------|
| 4000W      | 10 mm/s       | 1,31               |
| 4250W      | 10 mm/s       | 1,35               |
| 4500W      | 10 mm/s       | 1,39               |
| 4500W      | 12.5 mm/s     | 1,35               |

### 4.2. Effects of Welding Heat Input

In order to evaluate the effect of heat input welding parameters are kept unchanged while heat input value is changed. Figure 4.1, 4.2 and 4.3 show the temperature contours in the sheet metal for 7.5 seconds heating duration in various heat inputs with 10 mm / s welding speed.

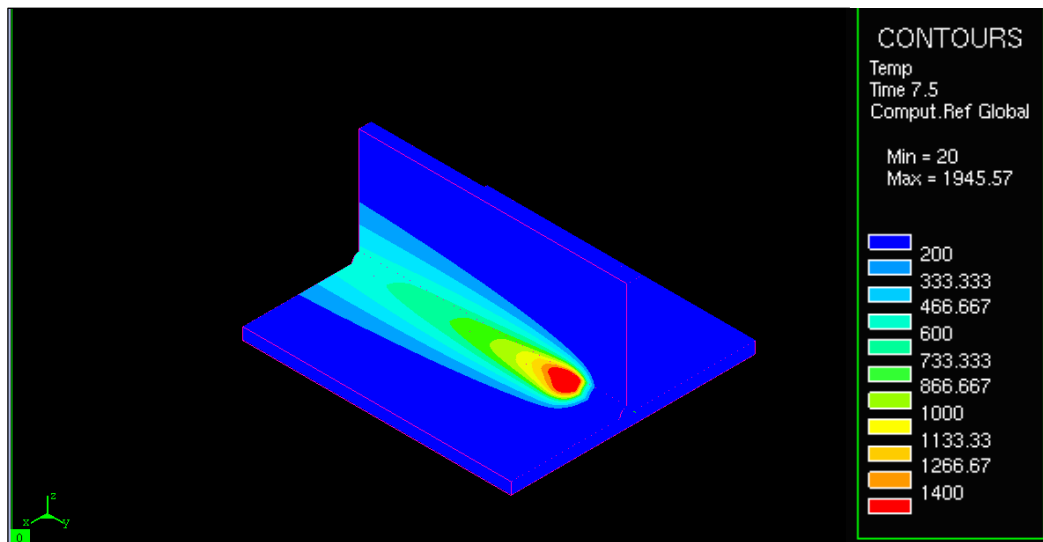


Figure 4.1. Temperature contours in °C for 7,5 s heating duration with 4500 W heat input.

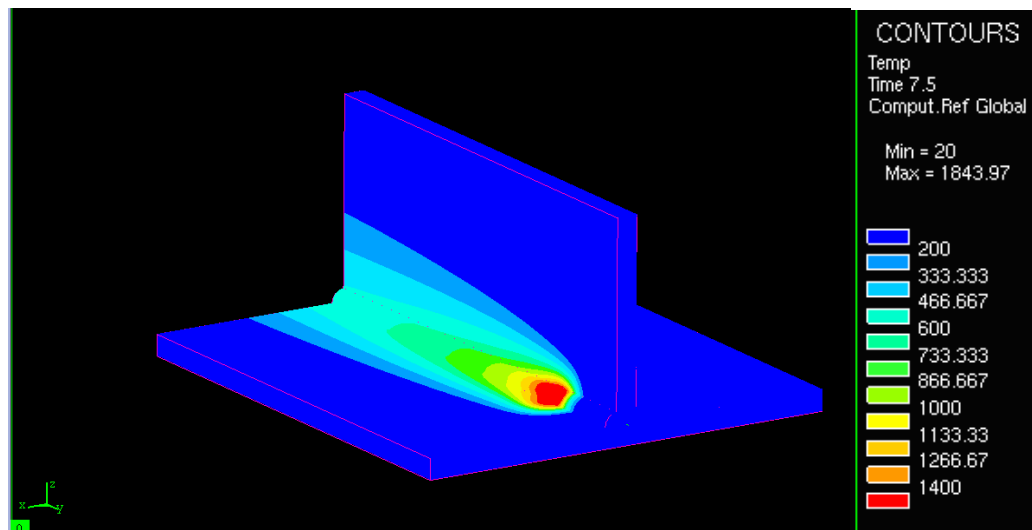


Figure 4.2. Temperature contours in °C for 7,5 s heating duration with 4250 W heat input.

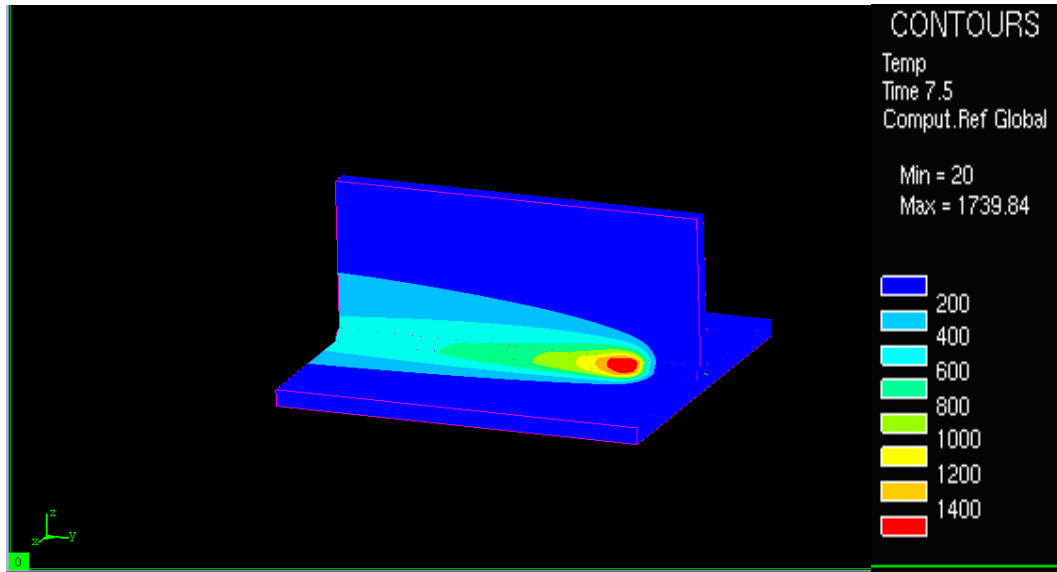


Figure 4.3. Temperature contours in °C for 7,5 s heating duration with 4000 W heat input.

These figures show the predicted temperature distribution of the specimen during welding process for three different heat input values. Peak temperature and the width of the heat affected area, which directly effect distortion, are increased by increasing the amount of heat input. According to results of the temperature distribution, when the heat input value is increased to 4500 W from 4000 W, the peak temperature increases about 12%.

Figure 4.4. shows the temperature distributions at 45 mm from the edge along the X direction in 4500W heat input and 10mm/s welding speed condition with different welding time.

These temperature distributions are taken with different welding times. As shown on the figure the peak temperature is decreasing while the welding time is increasing. Because when the heat source is passed away from the point in the weld center line, it is starting to be cooling. Therefore for a point in the weld center line and next to this point perpendicular to the weld direction, temperatures of them are decreasing in both with welding time and distance from the weld center line.

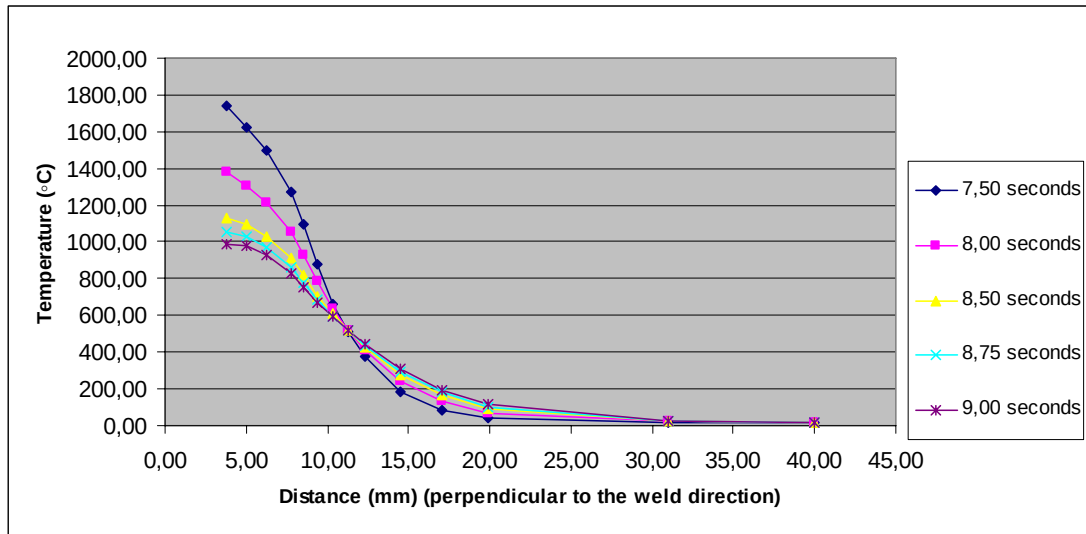


Figure 4.4. Temperature distributions perpendicular to the weld direction

As shown on the above figure, the temperature is higher than 750 – 800 °C up to 10 mm away from the center line. The temperature in this zone is high enough to cause phase change in the microstructure of steels. The local change in the temperature also causes formation of residual stresses. Therefore, in any welding process, it is very important to keep temperature rise in a narrow area to minimize inhomogeneous plastic deformation, residual stresses and microstructural changes in welded joints.

#### 4.2.1. Microstructural Change During Welding Process

For the simulation of hardenable steel welding processes, microstructural changes include heating and cooling. If the temperature exceeds a certain value during heating, then the microstructure starts to transfer to austenite. The lattice changes from body-centered cubic into face-centered cubic, the specific volume is smaller and carbon from dissolved carbides dissolves in the austenite structure. The start temperature and the degree of austenitizing depends on the respective heating speed and the top temperatures reached and the residence time above the austenitizing temperature. During the cooling process, austenite starts to transform back into a body-centered cubic lattice once the structure cools below the

austenitizing temperature. For high speed transformations, the dissolved carbon is caught in the metallic matrix, and the body-centered cubic lattice formed undergoes a maximum ‘inner stress’. The material developed is referred to as martensite (very hard). Formation of martensite is referred to as a ‘trapping process’. In case of a lower cooling rate, carbon can more or less diffuse, which leads to the formation of carbides. Intermediate stages, also referred to as bainite (hard) or ferrite (less hard), can develop by means of diffusion. Formation of bainite and ferrite / perlite is referred to as a ‘diffusion controlled process’.

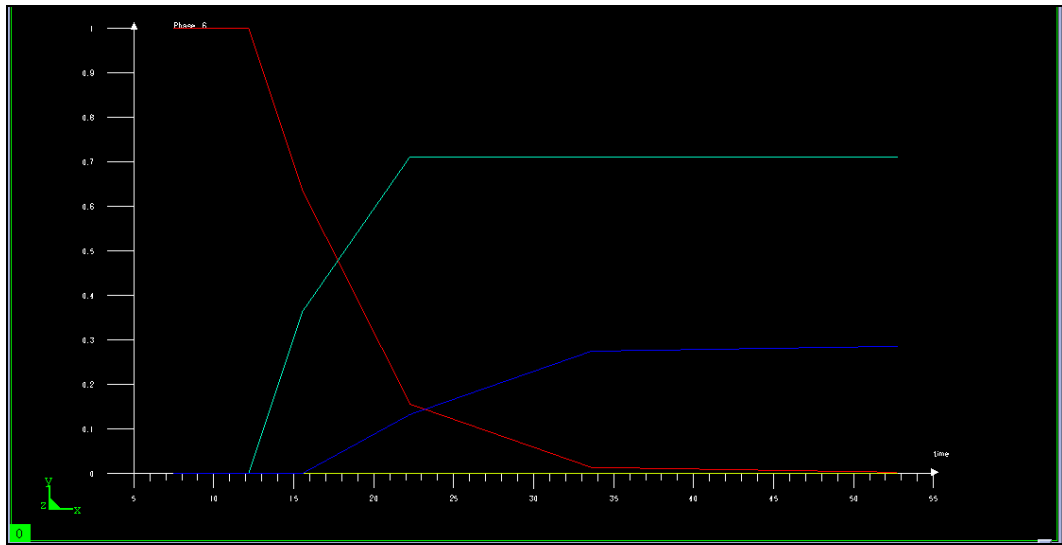


Figure 4.5. Phase Proportions at 5mm away from the weld central line

Figure 4.5, 4.6 and 4.7 shows the phase proportions at various points away from the weld center line according to 55 seconds from the beginning of welding operation (0 sec.). Red line represents austenite phase, blue line represents martensite phase, cyan line represents bainite phase and yellow line represents initial material. These results are obtained from 4500W heat input and 10mm/s welding speed condition.

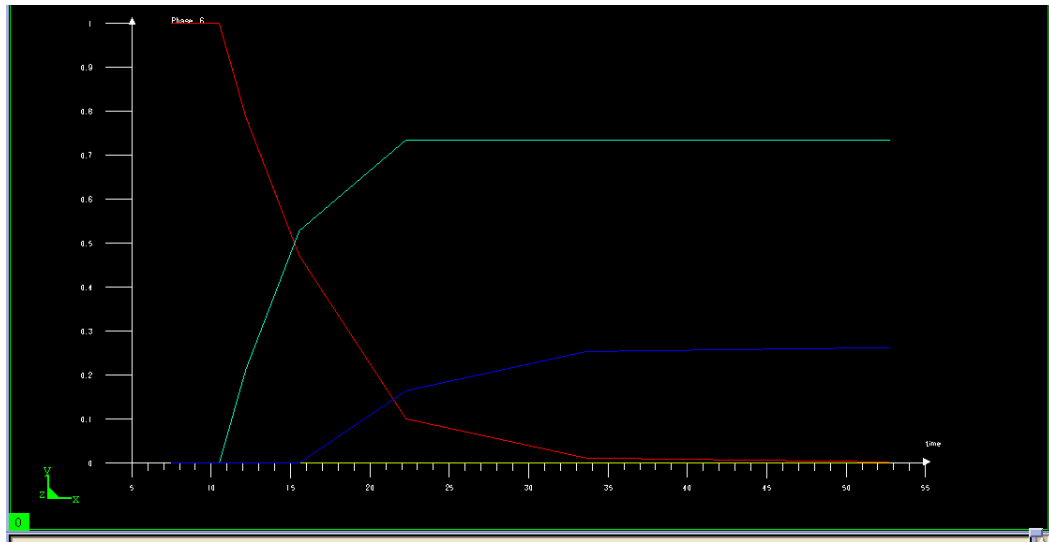


Figure 4.6. Phase Proportions at 8mm away from the weld central line

Figure 4.5 and 4.6 shows the phase proportions of 5mm and 8 mm away from the weld center line. As shown in the figures, it is the austenite phases until the 15 mm, then the phase is changing to the bainite form.

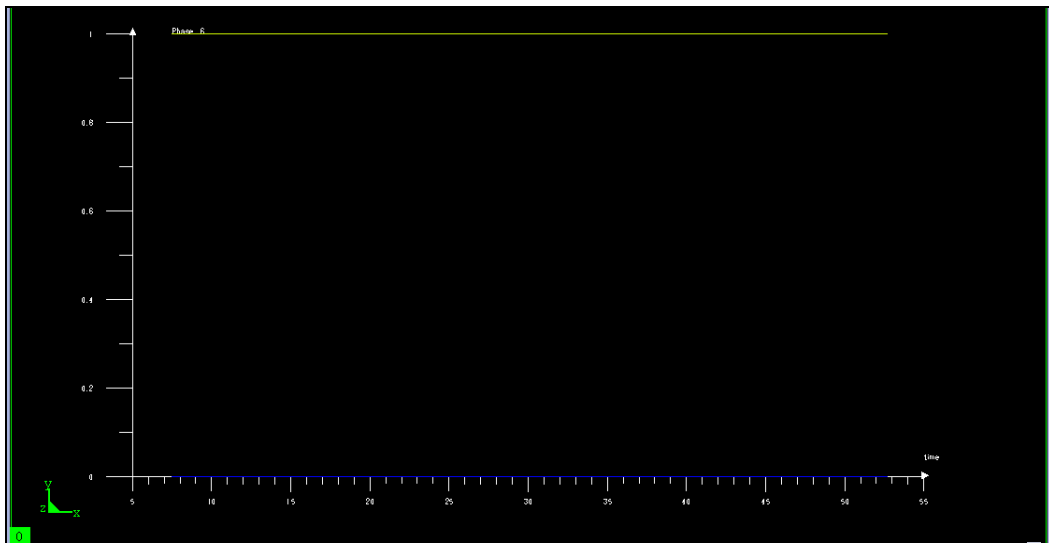


Figure 4.7 Phase Proportions at 15mm away from the weld central line

#### 4.2.2. Residual Stresses and Distortions Patterns in the Welding

Thermal stresses are caused during welding due to thermal expansion and shrinkage. Melting and solidification, as well as addition of material has to be taken

into consideration. Structural transformations cause additional transformation stresses, which in case of thermal stresses interfere with each other in optional time intervals. A combination of both phenomena results in a state of stress and distortion of the component. Interference of both phenomena for example (contraction strains in case of cooling plus transformation strains) result in a complicated, multi-axis state of stress in a hardened welding seam.

Apart from classical thermal phenomena, the mechanical analysis of steel materials is basically influenced by two microstructure phenomena:

- Volume changes, which accompany microstructure transformations of hardenable steels
- Specific material behavior dependent on existing phases (general material states)

A hardenable steel (for example structural steel, carburizing and heat-treatable steel, high-temperature steel, several corrosion-resistant steels, model steel) has a body-centered cubic structure at room temperature. In case of austenitizing (the steel exceeds a certain temperature), the steel transforms into a face-centered cubic lattice and, during cooling, back into a body-centered cubic lattice.

The face-centered cubic lattices and the body-centered cubic lattices have different specific volumes, which can be measured with a dilatometer test. The volume changes, resulting from the transformation of the body-centered cubic lattice, have a decisive influence on component distortion and on the development of the stresses due to the fact that they cause transformation stresses, which interfere with the thermal stresses (time dependent).

Residual stresses and distortions in welding have been investigated by many researchers using different techniques and parameters. Some of them used ABAQUS or ANSYS for the two dimensional analysis of residual stresses by keeping the coefficient of thermal expansion in a constant value corresponding to the mean temperature between 20°C and 600°C (Brickstad and Josefson (1998), Benli (2004)). On the other hand, three dimensional Finite Element Model has also been used to investigate the effect of workpiece thickness on the residual stresses (Teng, 1998).

On the contrary of the works mentioned in the previous paragraph, this work aimed to analyse the effect of welding parameters on the residual stresses and distortions. Also, in this analysis all of the material properties including thermal expansion are temperature dependent so results of analysis is closer to the actual results.

Following figures show the amount of deformation and residual stresses in the welding operation with various heat inputs and unchanged other welding parameters.

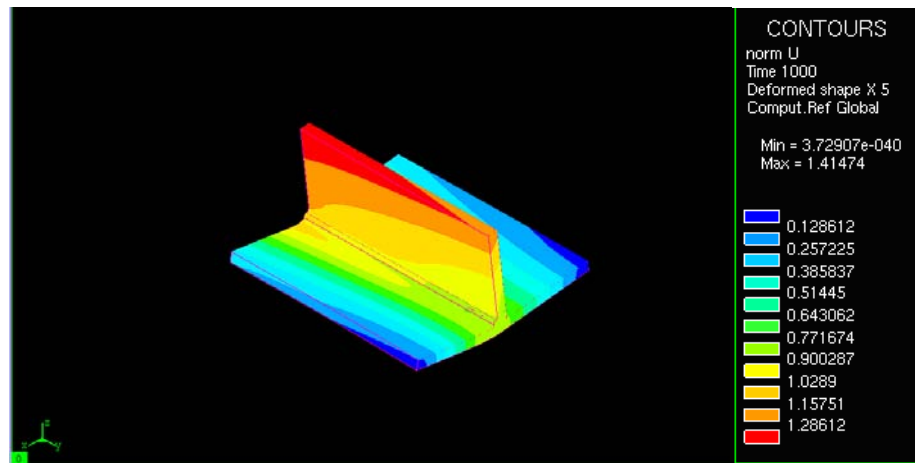


Figure 4.8. Distortion of T-Joint Weld with 4500 W heat input.

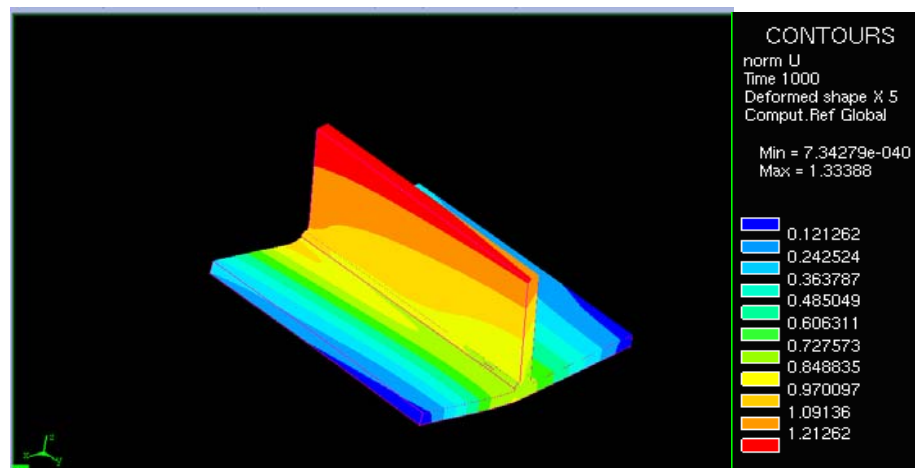


Figure 4.9. Distortion of T-Joint Weld with 4250 W heat input.

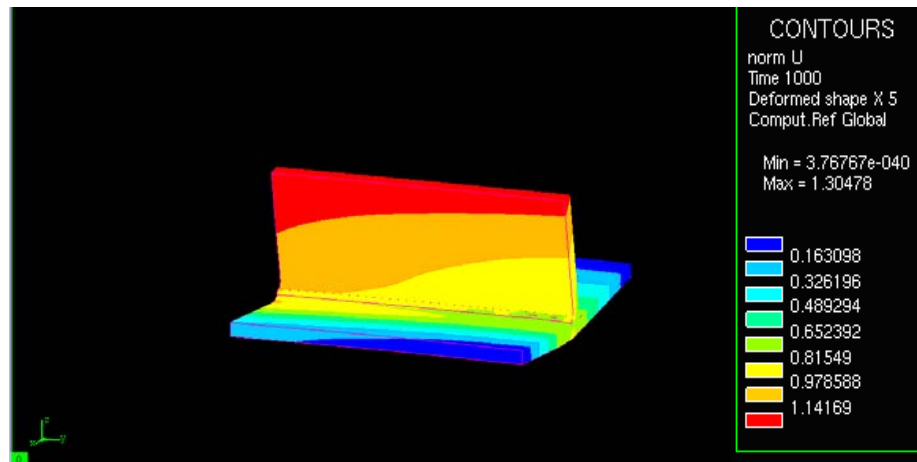


Figure 4.10. Distortion of T-Joint Weld with 4000 W heat input.

According to results of the distortion simulations, when the heat input value is increased to 4500 W from 4000 W, the amount of distortion increases about 8%. This results of distortion simulations obtained from FE compared with the results obtained from experimental measurements.

Figure 4.11, 4.12 and 4.13 show the residual stress simulation results of the different heat input values of T-Joint welded structure.

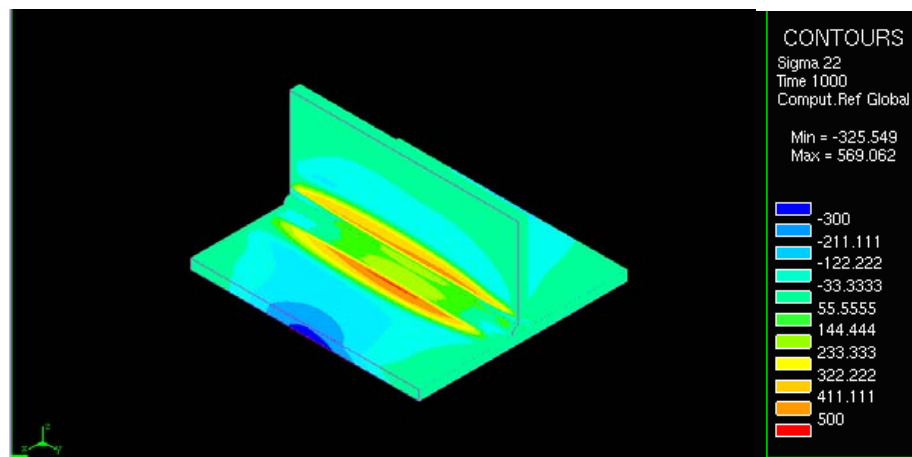


Figure 4.11. Stress Distrubition of T-Joint Weld with 4500W heat input

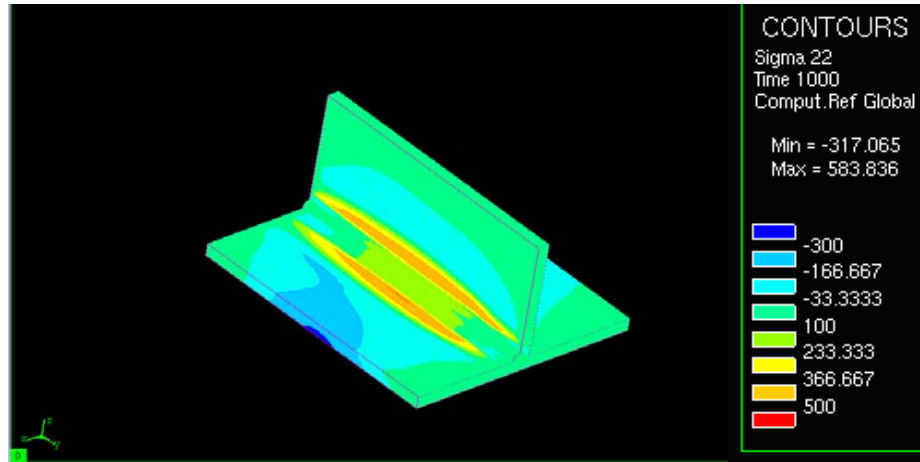


Figure 4.12. Stress Distrubition of T-Joint Weld with 4250W heat input

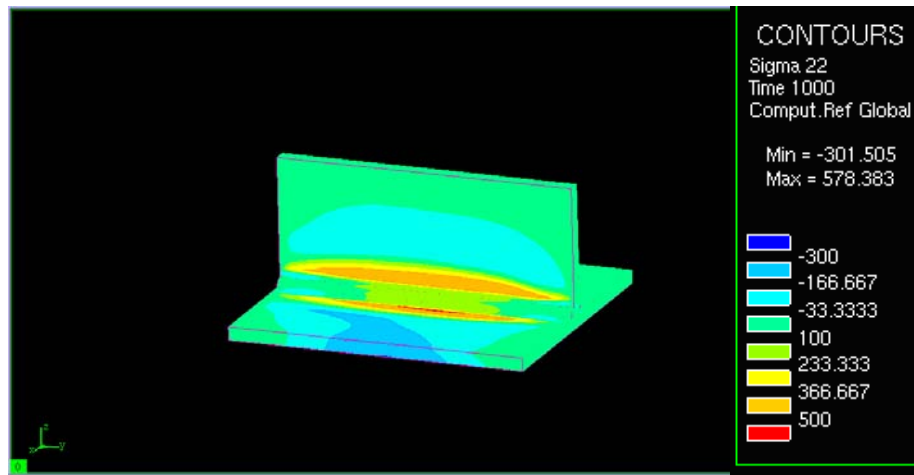


Figure 4.13. Stress Distrubition of T-Joint Weld with 4000W heat input

Different values of heat input were used to assess the effect of heat input magnitude on the results for distortions. It was concluded from the results that, in general, the heat input amount has significant effect on the final distortions. It is shown from this analysis the amount of deformation increases with increasing heat input value. This is the case as indicated by Siddique (2005).

#### 4.3. Effects of Welding Speed

Different welding speeds 10 mm/s and 12.5 mm/s are used while keeping all the other parameters unchanged to assess the effect of welding speed on the welding

deformation. Figure 4.14 and 4.15 show the amount of deformation for 10 mm/s and 12.5 mm/s with 4500 W heat input value, respectively.

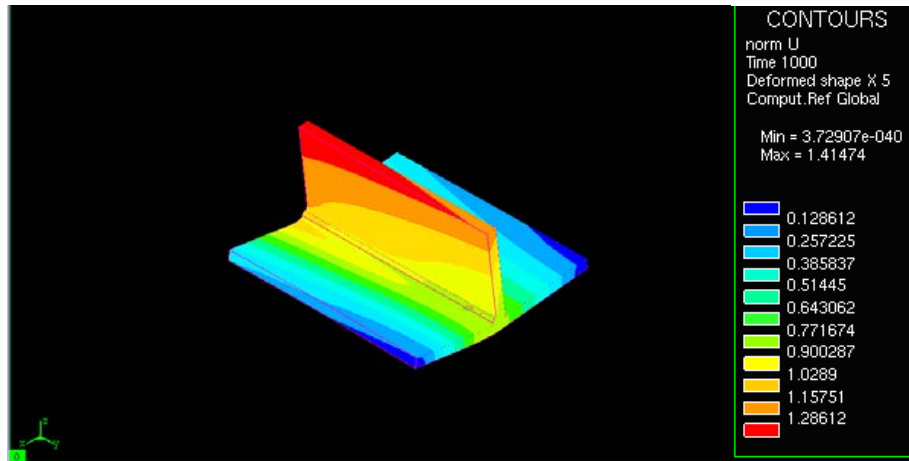


Figure 4.14. Distortion of T-Joint Weld with 10 mm/s welding speed

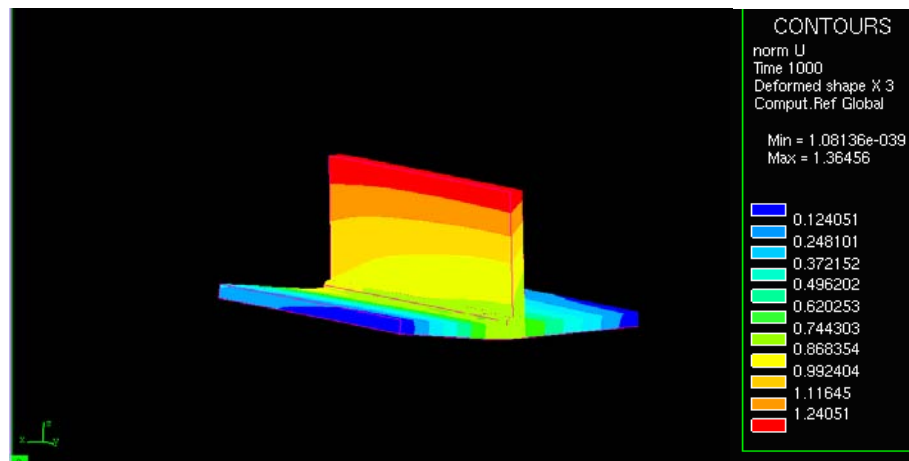


Figure 4.15. Distortion of T-Joint Weld with 12,5mm / s welding speed

According to results of the distortion simulations, when the welding speed is increased to 12,5 mm/s from 10 mm/s, the amount of distortion decreases about 4%. This results of distortion simulations obtained from FE compared with the results obtained from experimental measurements.

Figure 4.16 and 4.17 show the residual stress distribution for different welding speeds.

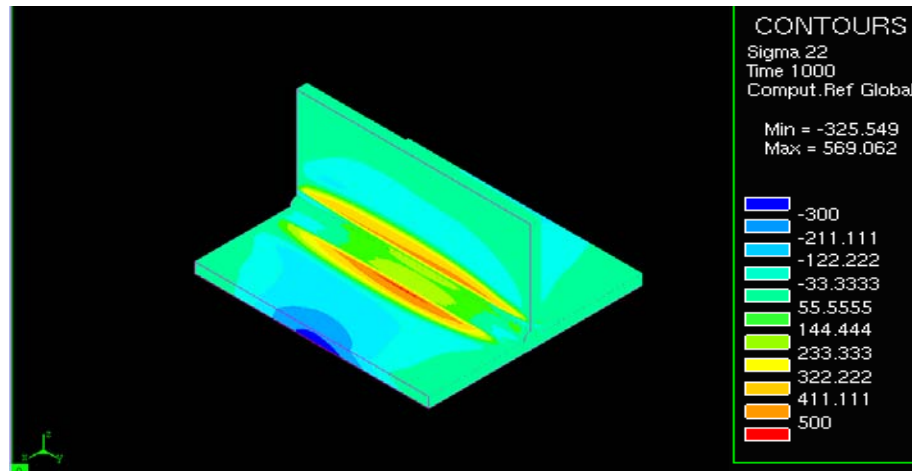


Figure 4.16. Stress Distrubition of T-Joint Weld with 10 mm / s welding speed.

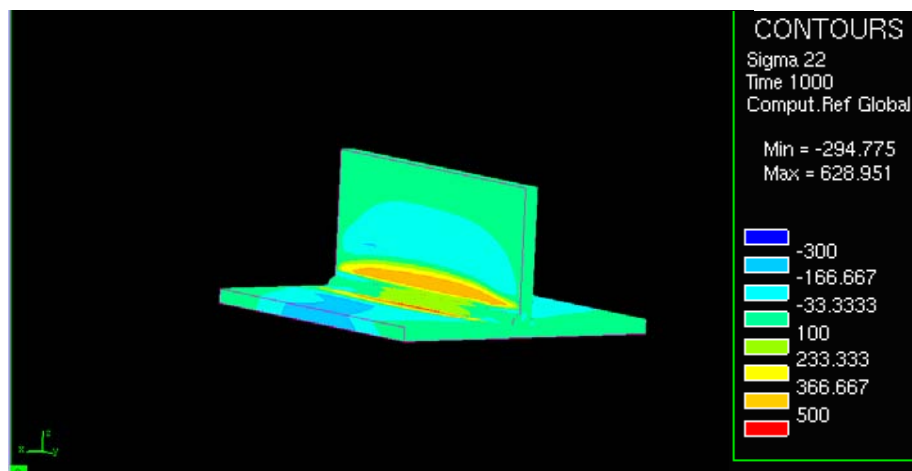


Figure 4.17. Stress Distrubition of T-Joint Weld with 12,5 mm / s welding speed.

Different values of welding speeds were used to assess the effect of welding speed on the results for distortions. It is shown from this analysis the amount of deformation increases with decreasing welding speed.

#### 4.4. Effects of Clamp Condition

The use of welding fixtures is widely recommended for dimensional stability of structural components during welding. Although fixtures used in the welding process control welding deformations but result in higher stresses. Hence the

mechanical constraints in the form of welding fixtures play a crucial role in the final geometrical shape and state of residual stress of the welded structures.

In structural analysis, boundary conditions vary from case to case, as shown in Figure 4.18 all the edges are constrained for all axes in this study.

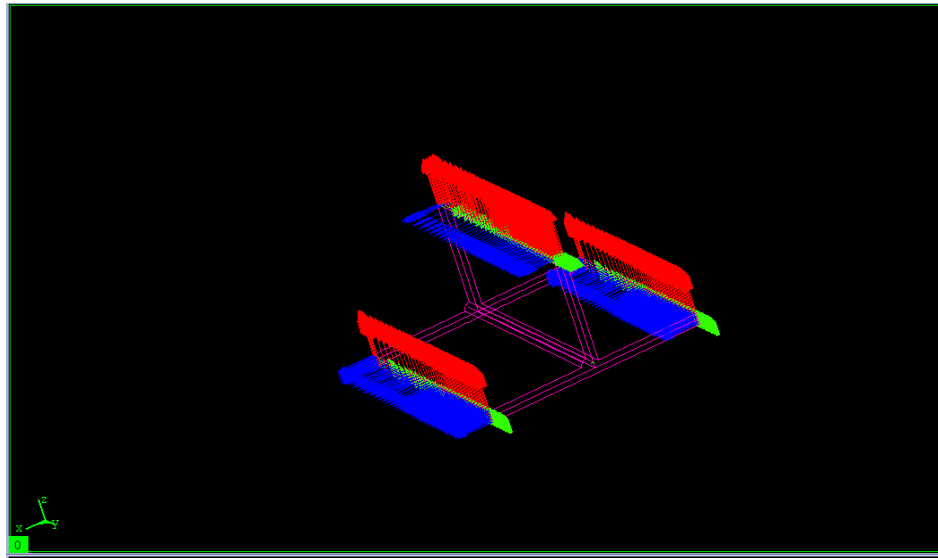


Figure 4.18. Schematic of structural boundary conditions for 4500 W heat input and 10 mm / s welding speed.

As shown in Figure 4.19 and 4.20 constraints during welding reduce deformations significantly but induce higher as welded stresses. This analysis have done with 4500 W heat input and 10 mm / s welding speed.

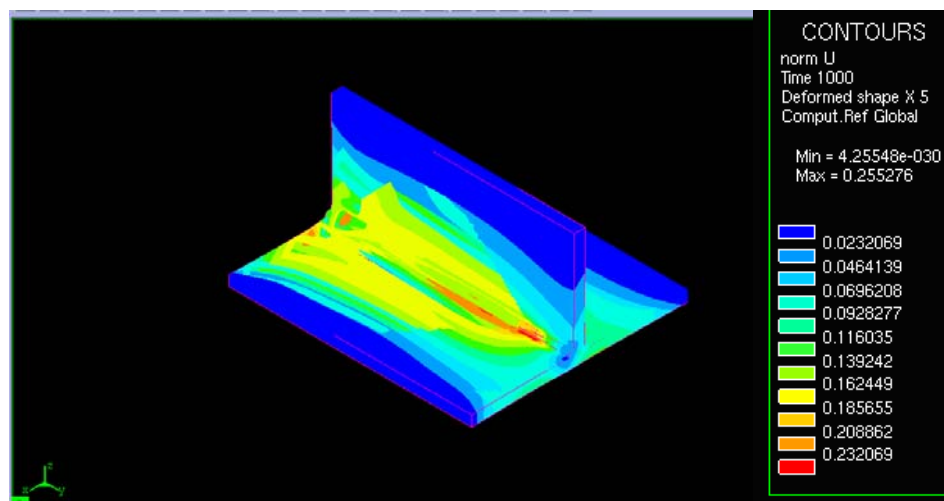


Figure 4.19. Distortion of T-Joint Weld with clamp condition.

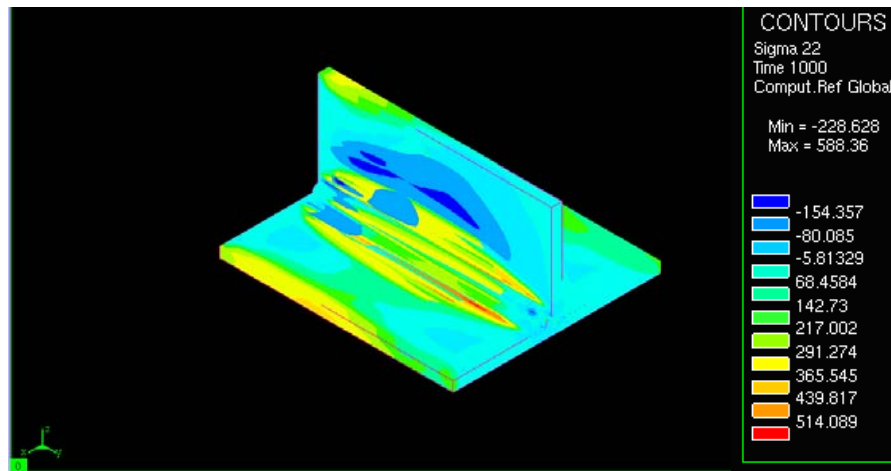


Figure 4.20. Stress Distrubition of T-Joint Weld with clamp condition

Fixtures used in the welding process control welding deformations, because they balance stress distrubition which is obtained from welding process. According to results of the distortion simulations, when using welding fixtures, amount of distortion decreases 83%.

## 5. CONCLUSION

The development of post-weld residual stresses and distortions in a welded structure and microstructural changes are based intrinsically on the thermal cycle from the welding processes. The thermal cycle also provides information on heat-affected zone geometry. Therefore, controlling the thermal cycle is critical to good quality welding. Computer-based simulative welding models that can be predict process outcomes without the need for costly pre-production trials or experimentation will increasingly become essential tools for welding engineers.

The physical model that considers the phase change, thermal properties varying with temperature and heat loss to the environment for convection / radiation demonstrated to be able of identifying the global thermal and fusion efficiency at each instant of the process.

To investigate the effects of welding parameters on transient temperature, residual stresses and distortions in simulation of T-Joint welding process 3D nonlinear thermo-mechanical analyses are performed using FEA method.

The objective of this thesis is to develop a three dimensional finite element model with using SYSWELD package program for the analysis of the T-Joint to evaluate the effect of welding parameters on temperature distribution, residual stresses and distortions. Pasquale(2001) employed SYSWELD for simulation of a welding process but Wen (2001) modelled the welding using ABAQUS. Benli (2004) obtained the results of simulation with ANSYS program. Researchers can use ANSYS and ABAQUS package programs for all finite element problems. However SYSWELD package program is focus on only welding operations. According to this, all of welding operations such as joint type, heat source type can be modelled with this program and the results obtained more accurately.

Based on the results, following are some important conclusions:

- The distortion patterns obtained through finite element modelling matched well with the experimentally observed patterns.

- The angular distortion is less when constraints are applied to the workpiece material.
- For the same heat input the angular distortions of 12.5 mm / s welding speed is lower than 10 mm / s welding speed.
- The effect of increasing heat input is similar to decreasing welding speed. It has been found that heat input has positive effect on the magnitude of the residual stresses and distortions.
- The residual stress is getting higher when constraints are applied to the workpiece material.

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