ISSN 1019-1011

Ç.Ü.MÜH.MİM.FAK.DERGİSİ **Haziran-Aralık** **2009** **Ç.Ü.J.FAC.ENG.ARCH.**
CİLT.24 *SAYI.1-2* *June-December* *VOL.24* *NO.1-2*

ANALYSIS OF DISTORTIONS IN T-JOINT FILLET WELDS

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ABSTRACT : *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 distortion before welding has been an important subject for researchers. In this investigation, SYSWELD finite element package program was used in modelling.*

T – BAĞLANTILI KAYNAKLARDA ÇARPILMA ANALİZİ

ÖZET : *Kaynak işlemindeki ısı kaynağına, malzemenin ısıl 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 çarpılmaların dağılımı ve miktarının önceden tahmin edilebilmesi araştırmacılar için önemli bir konu olmuştur. Bu çalışmada, SYSWELD sonlu eleman paket programı modellemede kullanılmıştır*

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 (1).

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 distrubition patterns and hence residual stresses and distortions. A large number of models have been reported in the published literature to predict temperature distrubitions, 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 proporties.

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 (2).

This study performs thermal elasto-plastic analysis using finite element (FE) techniques to analyse the thermomechanical behaviour and evaluate angular distortions of the T-Joint fillet welds.

In FE simulation of welding which may include validation of material properties, FE model, analysis technique, temperature distrubition and deformation need to be implemented. For this simulation SYSWELD software package program was used.

2. WELDING METHOD

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 canters. 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 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 (3).

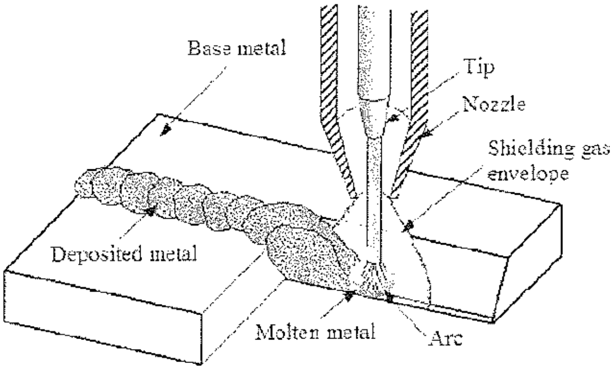


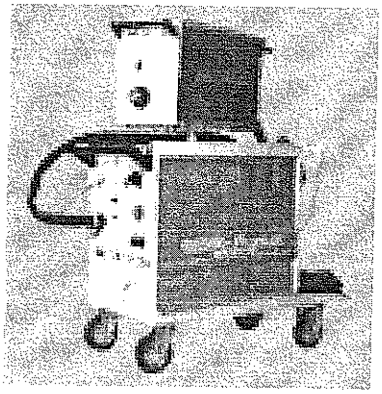
Figure 1. GMAW Process (3).

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.

2.1. Welding Machine

In this investigation 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 . For the welding operations Gedik Fronuis Vario Star 404-2 is used. The techical specifications of the machine are given in Table 1.

Table 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

2.2. 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 investigation is related to the mechanical effects of the material after welding process.

2.2.1. 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 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. The plug weld is a special weld used to attach one workpiece to another locally through penetrations in the surface.

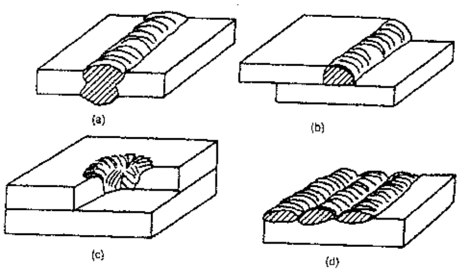


Figure 2. Fundamental types of welds, including (a) butt, (b) fillet, (c) plug, and (d) Surfacing (4)

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.

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° 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.

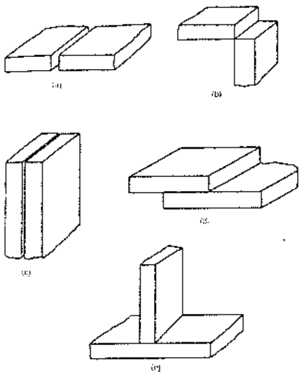


Figure 3. The five basic weld joint designs used in structural fabrication: (a) butt joint, (b) corner joint, (c) edge joint, (d) lap joint, (e) tee joint (4).

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 resistanee, leak tightness, or hermeticity).

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.

2.2.2. 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 investigation describes the thermal and mechanical analysis using finite element techniques to analyse the thermomechanical behaviour and evaluate the distortions of the T-Joint welding. Figure 4 depicts two plate fillet weld.

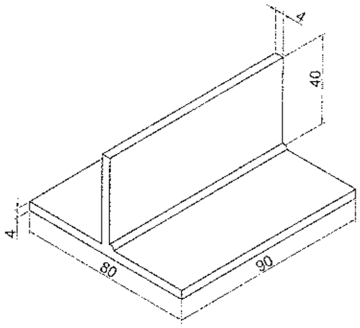


Figure 4. Isometric view of T-Joint welding.

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 2. Figure 5. and 6. shows the thermal conductivity and density of workpiece material depending on the temperature.

Table 2. Composition of the Workpiece Material

% 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.

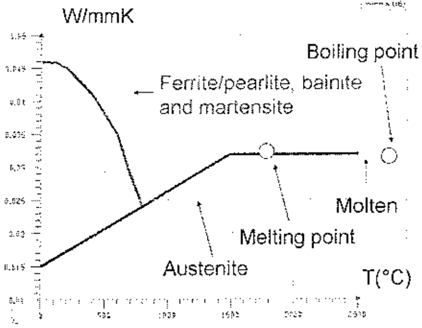


Figure 5. Thermal conductivity of steel (5).

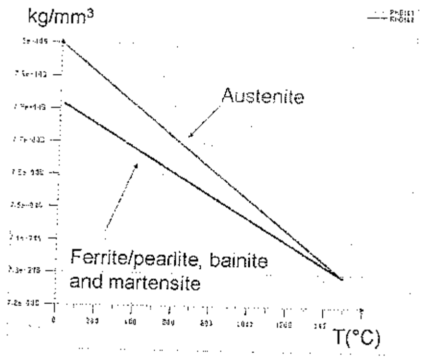


Figure 6. Density of steel (5).

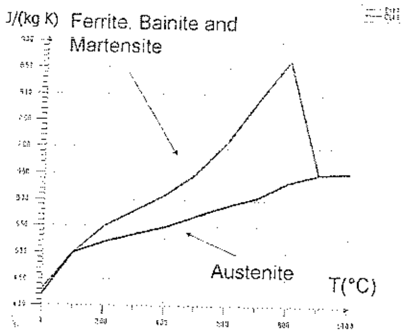


Figure 7. Specific Heat of steel (5).

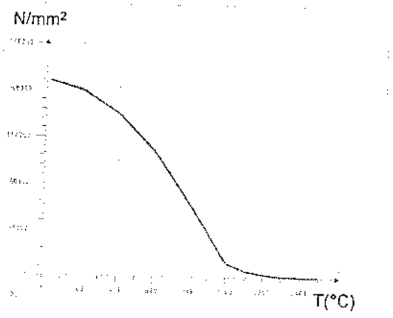


Figure 8. Modulus of Elasticity of steel (5).

Starting from 1200-1300°C, it is assumed that the material starts to behave 'viscose'. 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 then 1000N/mm^2. Figure 8. shows the modulus of elasticity of the workpiece material.

Poison coefficient of the steel is constant and it is not a function of temperature. It's value is 0.3.

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

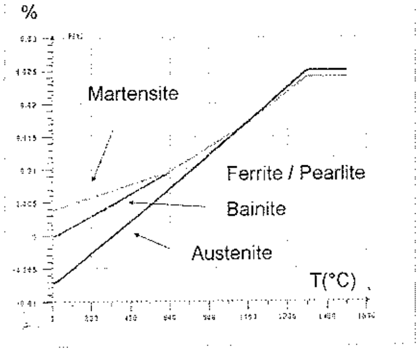


Figure 9. Thermal strain of steel (5).

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

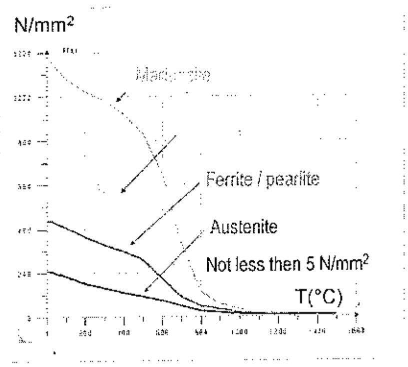


Figure 10. Yield stress of steel (5).

3. WELDING SIMULATION METHOD

The objective of this investigation is to develop a three dimensional finite element model by using SYSWELD package program for the analysis of the T-Joint to evaluate temperature distribution and distortions.

3.1. 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 Figure11. and are described in Table 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 week nature. Detailed weld pool phenomena may, however, be regarded as a seperate 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.

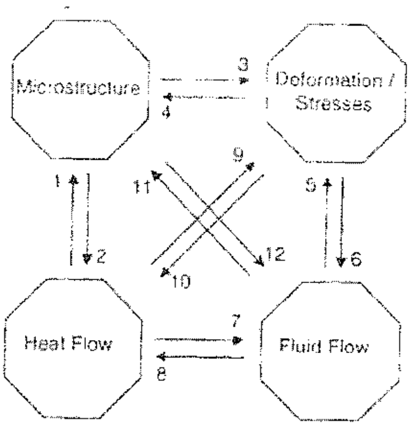


Figure 11. Coupling between different fields (6).

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. Description of couplings in welding analysis (6).

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	Stres 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 study, is shown in Figure 12.

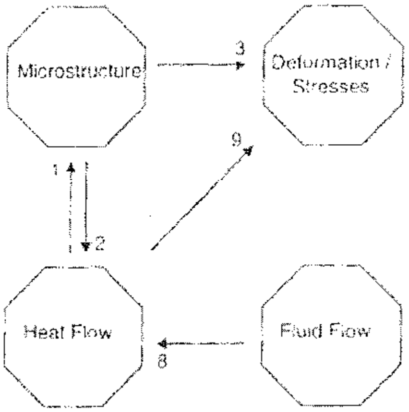


Figure 12. Selective coupling between different fields

3.2. 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 distrubition 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 the most widely acceptable model for simulation of arc welding process called "double ellipsoidal heat source model" is used in this investigation.

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 distrubition. (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 (7).

3.3. 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.

4. RESULTS AND DISCUSSION

Highly non-uniform temperature applied during welding is a well established cause of 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. 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. Figure 13. shows the temperature contours in the sheet metal for 7.5 seconds heating duration in various heat inputs with 10 mm / s welding speed.

Figure 14. show the temperature distributions at 45 mm from the edge along the X direction 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.

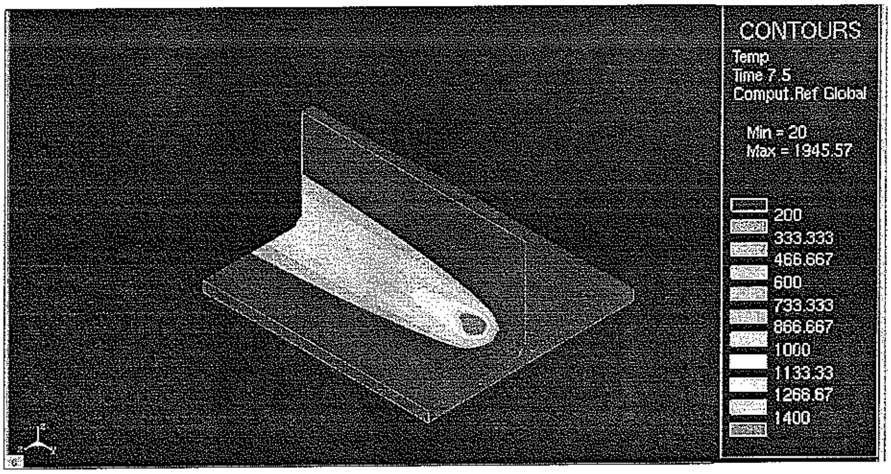


Figure 13. Temperature contours in ◦C for 7,5 s heating duration with 4500 W heat input.

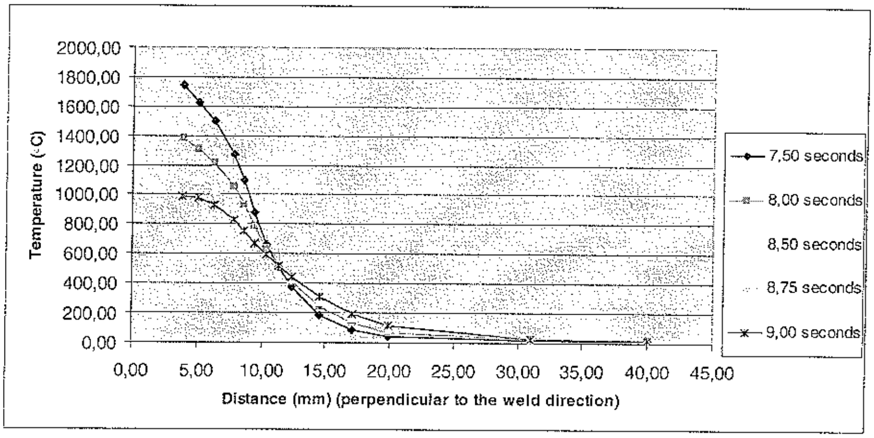


Figure 14. Temperature distrubitions perpendicular to the weld direction

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.

This work aimed to analyse the welding process with Finite Element Method and compare its results with experimental study. 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.

Figure 15. show the amount of deformation in the welding operation according to analyse results.

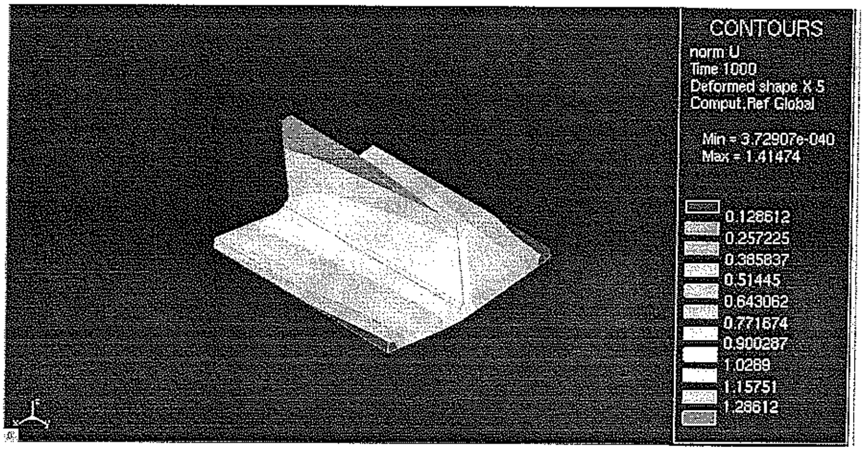


Figure 15. Distortion of T-Joint Weld with 4500 W heat input.

Finite element study performed with SYSWELD program in this investigation and their main objective is to describe structural response of welded T-joint after welding process. Therefore, an experimental approach, which can sufficiently describe the general behaviour, is considered sufficient to validate results. According to the experimental work for 4500W heat input and 10mm/s welding speed condition the amount of angular distortion is 1.31. Therefore the analyse of welding distortion with Finite Element Method in this study are found in reasonable good agreement with the experimantal measurement.

5. CONCLUSION

The development of 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 proporites 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 distortions in simulation of T-Joint welding process 3D nonlinear thermo-mechanical analyses are performed using FEA method.

The objective of this investigation is to develop a three dimensional finite element model with using SYSWELD package program for the analysis of the T-Joint to evaluate the temperature distribution and distortions. All of welding operations such as joint type, heat source type can be modelled with SYSWELD package program and the results obtained more accurately.

Based on the results; the distortion patterns obtained through finite element modelling matched well with the experimantally observed patterns.

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