

Arc Welding of Dissimilar Metals: FEA and Experiments

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Abstract

Assuming an elliptical disk heat source, several results of theoretical and experimental investigations on heat transfer in copper - low carbon steel welded joints are presented in the first part of the paper. Using thin sheets, temperature variation in the thickness direction is negligible and heat flow is considered two-dimensional. Convection and radiation influence, and thermo-physical properties depending on the temperature are considered in the model. Measurements and visualization of the temperatures distribution have been made during welding using infrared thermography. The proposed theoretical method using finite element analysis was validated for the temperatures prediction in the welded joint. In the second part of the paper, the influence of the welding process on the structural modifications and grains' size in the heat affected zone (HAZ) of both base materials (BM) is described. Discussion on the graphs of temperatures variation vs. microstructural analysis enables conclusions on the potential undesired structural changes and related preventing measures. The asymmetric position of the heat source closer to the material having a higher thermal conductivity is an effective method for controlling the temperature field.

Introduction

The temperature history of the welded joints has a significant influence on the structural changes, as well as on the state of residual stresses and strains. Classical solutions for the transient temperature field such as Rosenthal's dealt with the semi-infinite and infinite bodies subjected to an instant point heat source, line heat source or surface heat source. These solutions can be used to predict the temperature field far from the heat source, but fail to predict the temperatures near the heat source. Goldak et al. have introduced the three-dimensional double ellipsoidal heat source to predict the temperature field of semi-infinite body [1]. For thin plates the

source influence in the thickness direction can be neglected and the source becomes a Gaussian surface-distributed heat source or an elliptical disk heat source [2-4].

Present paper deals with the temperature prediction in dissimilar fusion welded joints made of thin sheets. Measurements and visualization of the temperatures distribution have been made during welding using infrared thermography. The influence of the welding process on the structural modifications and grains' size in the heat affected zone (HAZ) of low carbon steel and copper is also described, together with the possible consequences on the joint properties and behaviour.

Finite element analysis

Several assumptions on the numerical model were:

- isotropy of the base metals;
- material thermal properties depending on the temperature;
- elliptical disk heat source;
- Gaussian distribution of the heat flow density;
- heat loss by convection and radiation;
- neglecting of the thermal source influence in the thickness direction.

The heat transfer in the plates is modelled as 2D heat transfer problem using SHELL element group type (commercial COSMOS 2.5 code). Due to their different thermal properties, both plates were meshed using 4-noded quadrilateral elements, with refined mesh near the weld pool and HAZ [5].

Copper (Cu) and carbon steel (CS) plates of 5x200x300 mm each were used both for simulation and experimental procedures. Heat input corresponding to the heat source power $P=2400\text{W}$ and the welding speed $v=5\text{mm/s}$ was the basic welding condition for simulation and the related experiments.

The heat input is kept constant whilst the welding source moves continuously, heating and melting new regions in front of it, and keeping its influence on the weld pool, as too. In order to simulate the welding process, defining the time function as a sum of triangle functions was necessary (Fig. 1), [6]. The succession of the triangle functions describes the positions of the welding source. Considering the total welding time and the position of the welding source along the joint longitudinal axis, the number of the triangle functions can be calculated. The temperature field is the result of the total thermal effects during the welding process starting from the initial moment $t=0$ until the final moment $t=t_n$.

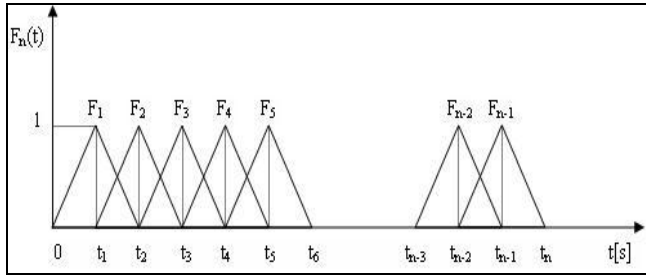


Figure 1: Time functions simulating the thermal effect.

Visualization of the non-stationary (the start of the welding process) and quasi-stationary temperature field in the copper-carbon steel welded joint is presented in the Fig. 2 and Fig. 3, respectively. It can be noticed an emphatic asymmetry of the temperature field (related to the welding direction), as a result of different thermal properties of the base metals. Due to the higher conductivity value, the HAZ in copper is more extended. A slight increase of temperature and a higher elongation of the HAZ (and of the welding pool) can be noticed after reaching the quasi-stationary phase.

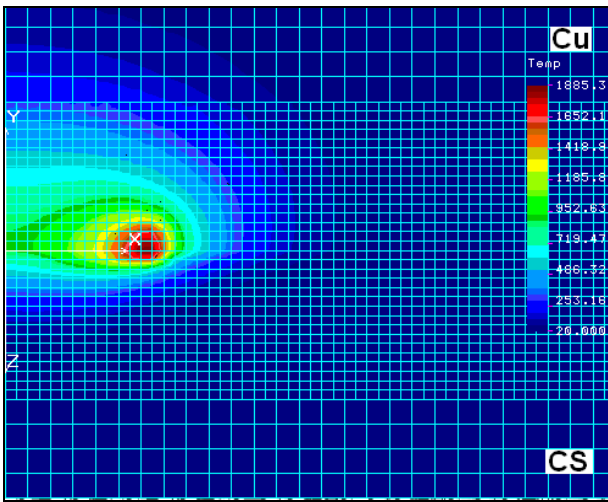


Figure 2: Non-stationary temperature field on carbon steel-copper welding ($t=6s$).

Fig. 4 shows the transversal temperature distribution for non-stationary (at 6s) and quasi-stationary temperature field.

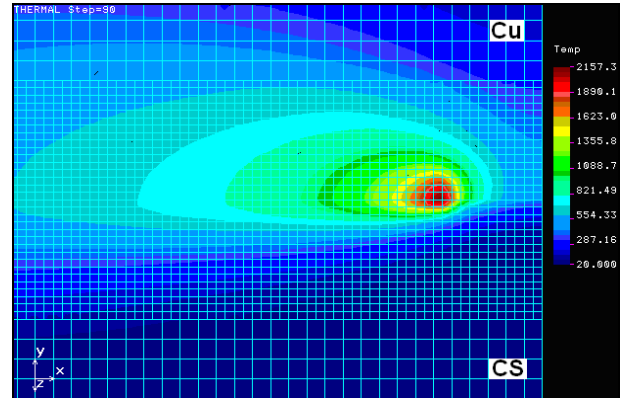


Figure 3: Quasi-stationary temperature field of the carbon steel-copper welded joint (at $t=54s$).

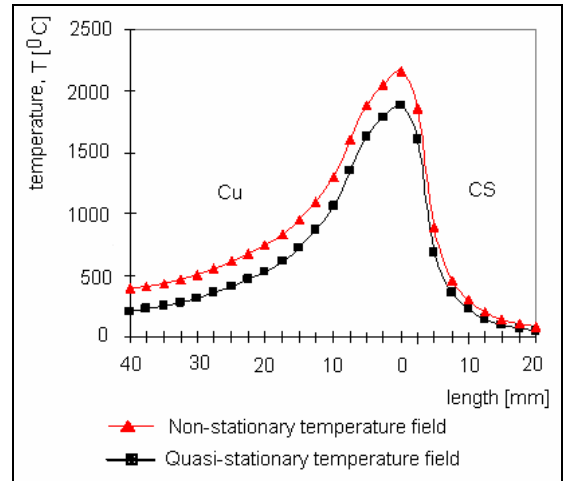


Figure 4: Temperatures distribution in the transverse section of the welded joint ($t=6s$ and $t=54s$).

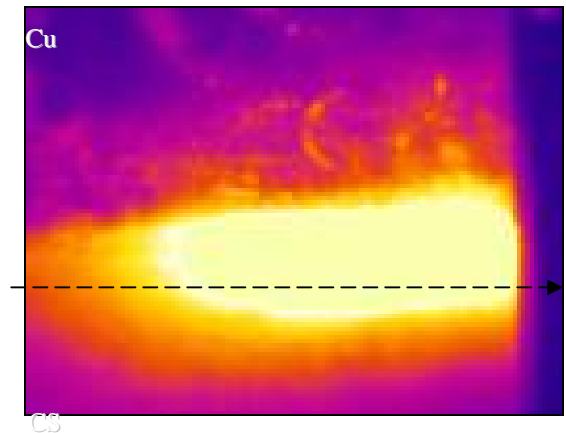
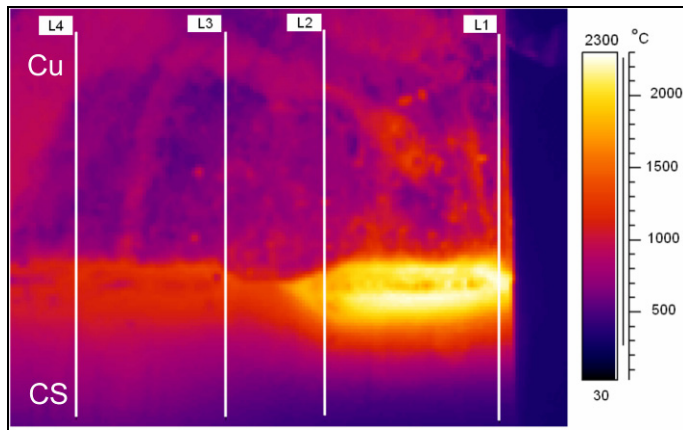


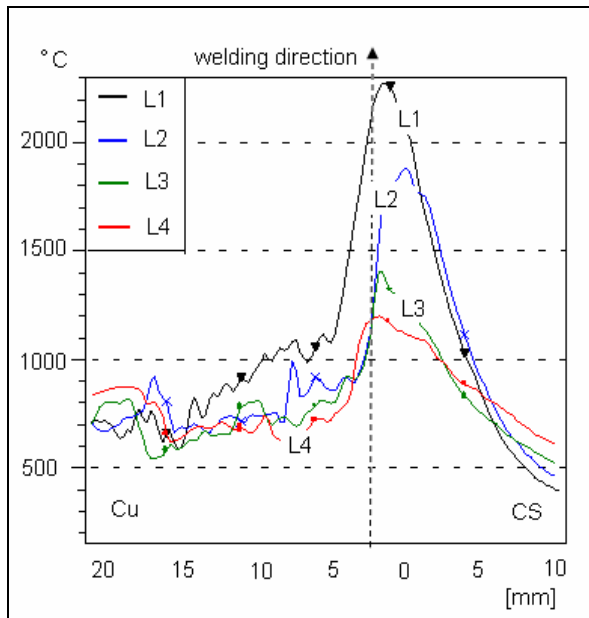
Figure 5: Weld pool visualization and HAZ in Copper-low carbon steel welded joint.

Experiments

Measurements and visualization of the temperature distribution have been made during welding. The experimental welding parameters were similar to the simulation conditions used in finite element analysis. The weld pool visualization and the extension of the HAZ in both materials are presented in Fig. 5, as resulted by using the thermography method. The heat transfer in copper is non-uniform, and this phenomenon could be explained by the anisotropy of this material.



a.



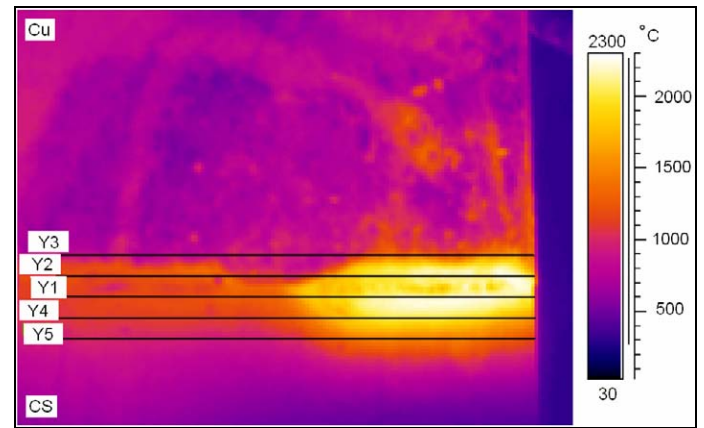
b.

Figure 6: Temperatures distribution transverse to the welded joint: a) the position of the lines; b) the temperature variation.

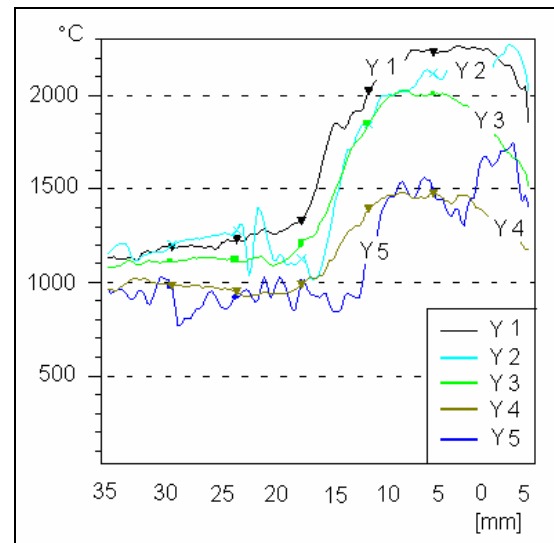
The temperature curves recorded on the transversal lines L2...L4 are presented in the Fig. 6. It can be noticed that the width of the HAZ depends on the thermo-physical properties of each BM. Especially the thermal conductivity is decisive for the extent of the areas heated above certain temperatures.

For this reason, there is an empathic asymmetry of HAZ on the dissimilar metals welding.

Temperature longitudinal variation is shown in Fig. 7 (maximum and minimum temperatures values corresponding to the lines Y1...Y5, symmetrically plotted related to the longitudinal axis of the joint). It can be noticed the non-uniform variation of the temperature in the non-ferrous metal (Y3, Y4). In the Fig. 8 some temperature values are pointed out for different spots in low carbon steel - copper welded joint, allowing a more detailed assessment of the temperature field.



a.



b.

Figure 7: Temperatures distribution along the welded joint: a) the position of the lines; b) the temperature variation.

Hence a smaller conductivity causes heat concentration and less extent of the HAZ such is, for instance, the carbon steel case. For this reason, a smaller conductivity material requires a smaller heat input per unit of weld length, whereas a larger conductivity material requires a larger heat input per unit of weld length.

Numerical and experimental data analysis

The graphs in the Fig. 9 & Fig. 10 are plotted for the temperature variation in front and in the centre of the welding arc, confirming a good agreement between numerical and experimental data. Equation (1) was applied to computing the error:

$$e = \frac{T_{exp} - T_{EF}}{T_{exp}} \cdot 100 [\%] \quad (1)$$

where T_{exp} is the temperature experimental value, and T_{EF} is the model-provided data.

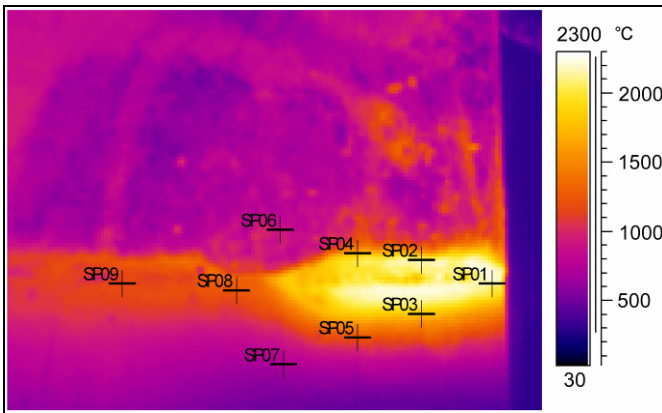


Figure 8: Temperature in different spots of the welded joint:

SP01: 2152°C	SP02: 2187°C	SP03: 1785°C
SP04: 1813°C	SP05: 1227°C	SP06: 939°C
SP07: 730°C	SP08: 1255°C	SP09: 1178°C

Structural modifications in low carbon steel – copper welded joint

When welding copper to low carbon steel, the poor weldability of these metals is related to the occurrence of various flaws, as cracks, and formation of fragile intermediate layers in different carbon steel HAZ sub-zones [7-9].

The weldability of these metals basically depends on their chemical, physical and metallurgical properties. With respect to the atomic characteristics, there is a certain similarity since both copper and carbon steel present the same type of crystal lattice at high temperatures, and their lattice parameters and atomic radius have close values. Also, both iron and copper fail to form fragile intermetallic phases. On the other hand, the different behaviour of the two metals (due to different values of the thermo-physical coefficients, namely the melting temperature, thermal conductivity and expansion coefficient), considerably worsen their welding capability. The chemical alloying elements of the carbon steel affect in a different way the solubility; whilst carbon makes it worse, silicon and manganese improve this property.

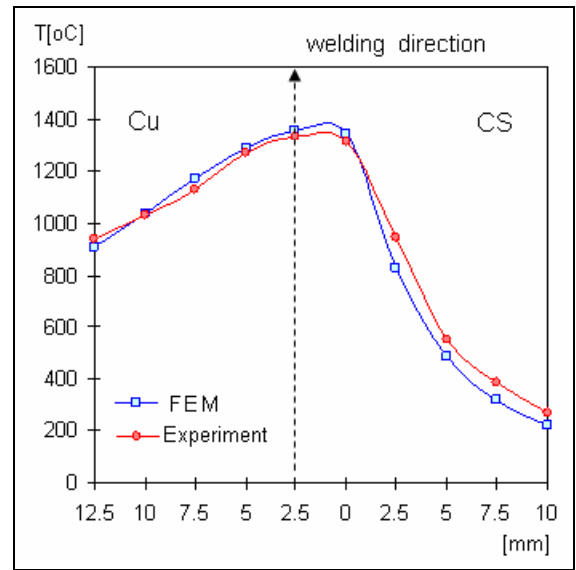


Figure 9: Temperature transverse variation in front of the welding arc.

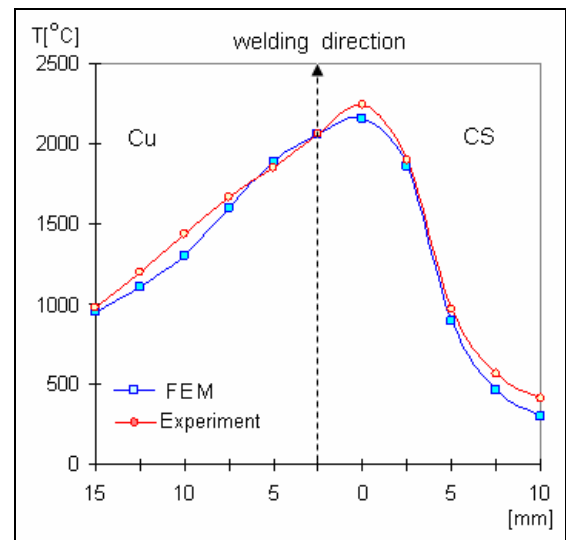


Figure 10: Temperature transverse variation corresponding to the welding arc spot.

The occurrence of cracks in the HAZ of the carbon steel is the main danger when these two metals have to be welded. During the welding process, copper penetrates by the steel crystal grains limits due to the capillarity and diffusion. On the other hand, because of the thermal stresses, the cohesion among the steel crystal grains is poor.

Intermediate fragile layers may occur due to the diffusion of some chemical elements from the carbon steel to the welding pool and backward. Less heating of the carbon steel leads to reducing the duration of the contact time of the steel with the molten metal pool, and consequently to the reduction of the undesired diffusion phenomenon effect.

The investigations revealed the influence of the welding process parameters on the structural modifications (type and granulation), both in the HAZ of the carbon steel, and grains growth in the HAZ of the copper, which further affect the mechanical characteristics of the welded joint. Samples of 8x200x300mm have been TIG welded using the heat input value 10,71KJ/cm, and the L-Ag2P/DIN8513 wire of 3mm diameter as filler metal [10,11]. The initial structure of the carbon steel is ferrite-pearlite, grains size 7-8, whilst in case of copper it is polyhedral with macles, grains size 4-5, as it is shown in Fig. 10. After welding, in case of the carbon steel the structure remains the same, but the grains size decreases from 7-8 to 9 in the grain-refining region, whilst the final structure consists of ferrite, pearlite and bainite in the grain-coarsening region (Fig. 11).

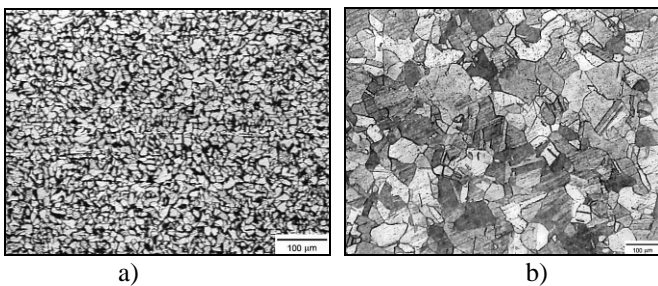


Figure 10: Base metal microstructures:
a) low carbon steel; b) copper.

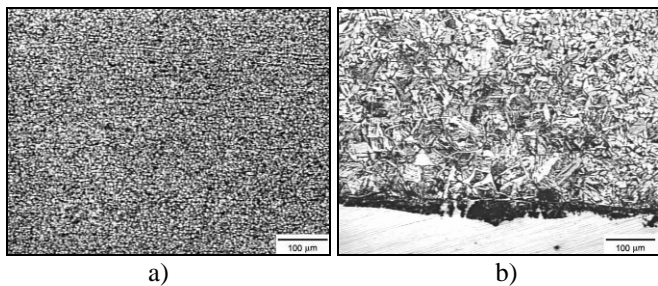


Figure 11: Low carbon steel microstructure:
a) grain-refining region; b) grain-coarsening region.

The most important issue may occur in the transition zone from weld to carbon steel, where bainite is forming and copper islands may appear, reducing the cohesion between the crystal grains. This phenomenon is illustrated in the Fig. 11,b.

The non-ferrous material having a polyhedral structure with macles does not undergo structural modifications in solid state. The effect of the thermal cycle in the HAZ of copper is minimal and the mechanical characteristics are not affected [12]. However, it can be noticed a slight increase of the grain size up to 1-2 granulation (Fig. 12 and 13). A columnar structure is visible in the weld, with relatively long parallel grains, continuously growing from the fusion line until the solidification process is completed (Fig. 13).

The studies show that in the welded joints of low carbon steel and copper, the most important issues caused by the welding process are encountered especially in the transition area from weld to carbon steel. Therefore, in order to perform a qualitative joint, it is recommended a welding technology which affects as less as possible the carbon steel, to minimizing the width of the transition zone and HAZ.

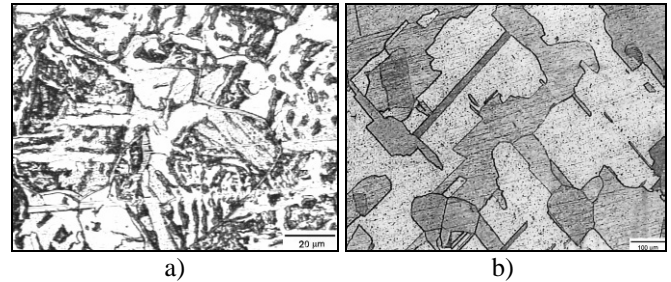


Figure 12: Low carbon steel and copper microstructures:
a) grain-coarsening region of low carbon steel;
b) HAZ of copper.

The research was carried out in the Robotics and Welding Department, Universitatea Dunarea de Jos din Galati, Romania and in two research units of Universidad Politécnica de Madrid, Spain.

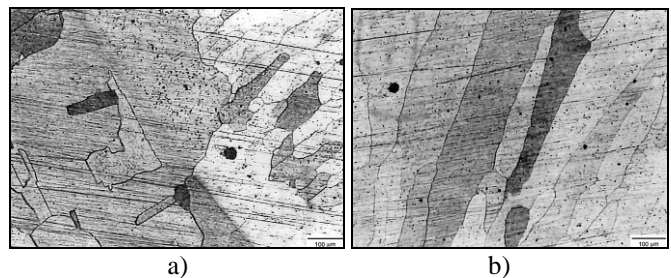


Figure 13: Copper microstructures:
a) transition zone in copper;
b) deposited metal (filler metal: L-Ag2P/DIN8513).

The investigations on the heat processes in the heterogeneous welded joints led to proposing a new welding technological variant, with an asymmetric positioning (closer to the copper) of the heat source moving along the gap. The undesired thermal effects of the welding process on the carbon steel and the related issues will be reduced by applying this technique.

Conclusions

There are several specific conclusions in case of low carbon steel – copper welded joints:

- An asymmetrical temperature field relating to the welding direction is noticed on dissimilar metals welding due to the different thermo-physical properties of the base materials.

- Moving the welding source closer to copper (that has higher thermal conductivity), the HAZ width of the carbon steel decreases and the negative effects induced by the welding process are reduced in this base metal.
- A smaller conductivity material requires a smaller heat input per unit of weld length, whereas a higher conductivity material requires a larger heat input per unit of weld length.
- The grains size increases in the grain-coarsening zone of the carbon steel due to the heat input. On the other hand, increasing the heat input, the bainite formation may occur in this area, strongly affecting the mechanical properties of the welded joint.
- The copper islands visible in the transition area of the low carbon steel to the weld lead to a poorer cohesion among the crystal grains in this area.
- Discussion on the graphs of temperatures variation enables conclusions on the possible undesired structural changes and related preventing measures.
- The asymmetric position of the heat source is an effective method for controlling the temperature field in arc welding of dissimilar plates.

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