THEORETICAL ANALYSIS OF TEMPERATURE DISTRIBUTION IN FRICTION STIR WELDING

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ABSTRACT

Friction stir welding (FSW) is a relatively new welding process that may have significant advantages compared to the fusion processes as follow: joining of conventionally non-fusion weldable alloys, reduced distortion and improved mechanical properties of weldable alloys joints due to the pure solid-state joining of metals. In this paper, a two-dimensional model based on finite element analysis is used to study the thermal history and thermomechanical process in the butt-welding of aluminum alloys. The model incorporates the mechanical reaction of the tool and thermomechanical process of the welded material. The heat source incorporated in the model involves the friction between the material and the probe and the shoulder. The calculation result also shows that preheat to the workpiece before process is beneficial to FSW. The effects of welding parameters such as preheating (100, 200) ˚C, rotational speed (960, 1200) rpm and linear speed (110, 155, 195) mm/min on the distribution of temperature of Al Alloy will be studied.

الخلاصة

اللحام بالاحتكاك والدعج هي إحدى طرق اللحام الحديثة وتعتبر من طرق لحام الحالة الصلبة للمعادن حيث تستخدم بشكل واسع لسبائك الألمنيوم المعروفة بصعوبة لحامها أو كثرة مشاكل لحامها بالطرق الاعتيادية.

هذا البحث يمثل دراسة نظرية لتوزيع الحرارة لصفيحة منوعه من لسبيكة ألمنيوم (1435) ذات أبعاد (200ملم و 80 ملم و 4 ملم). حيث تمت دراسة تأثير متغيرات اللحام مثل التسخين المسبق (والتي تمثل التسخين قبل عملية اللحام)(100,200)م، السرعة الدورانية (والتي تمثل سرعة أداة اللحام)(1200,960)دوره\دقيقه، والسرعة الخطية (التي تمثل سرعة اللحام)(110,155,195)مم\دقيقه على توزيع درجات الحرارة للسبيكة.تمت الدراسة النظرية من خلال استخدام موديل رياضي عددي خلال برنامج الانسس لاستخراج نتائج توزيع الحرارة والحصول على اقصى درجات حرارة يصلها المعدن نظرياً ومقارنتها النتائج.

Keywords: Friction stir welding; Finite element method; Thermomechanical process; Temperature distribution.

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INTRODACTION

Friction stir welding (FSW) is a recently emerged solid-state joining technology patented by The Welding Institute (TWI) in 1991 [Thomas, et. al 1991]. The process is illustrated in Fig.1, where a rotating cylindrical shouldered tool plunges into the butted plates and locally plasticizes the joint region during its movement along the joint line that causes a join between the work pieces.

In this process, the heat is originally derived from the friction between the welding tool (including the shoulder and the probe) and the welded material, which causes the welded material to soften at a temperature less than its melting point. The softened material underneath the shoulder is further subjected to extrusion by the tool rotational and transverse movements. It is expected that this process will inherently produce a weld with less residual stress and distortion as compared to the fusion welding methods, since no melting of the material occurs during the welding [Thomas, et. al 1991].

Despite significant advances in the application of FSW as a relatively new welding technique for welding aluminum alloys, the fundamental knowledge of such thermal impact and thermomechanical processes are still not completely understood [Thomas, et. al 1991].

published a three-dimensional heat transfer model in 1998, in their paper, a constant heat generation input from the tool shoulder/workpiece interface was assumed, a trial-and-error procedure was used to adjust the heat input until the all the calculated temperatures matches with the measured ones [Chao and Qi.1998]. Developed a process model for FSW, the heat input from the tool shoulder is assumed to be the frictional heat, and the coefficient of friction or the calculated temperature during the welding is adjusted to keep the calculated temperature from exceeding the material melting point [Frigaard, et. al 1998 and Frigaard, et. al 2001]. The Rosenthal equation for modeling heat-transfer for thin plates has also been applied in modeling the heat transfer in FSW [Gould and Feng 1998 and Russell and Shercliff 1999]. The heat transfer for overlap friction stir welding with the finite element method; a moving heat source is used [Zahedul, et. al 2001]. Applied the CFD method in modeling the heat and material flow process for FSW, where the material is assumed to be a kind of non-Newtonian fluid in their modeling [Bendzsak et. al 2000 and Smith, et. al 2000]. In the above-mentioned models, the heat input from the tool shoulder is the only heat input, the heat generated at the tool pin workpiece interface has not been included. Heat generated by the pin was estimated to be only 2% of the total heat generation during the FSW [Russell and Shercliff 1999]; however, this ration was estimated to be up to 20% by some researchers [Kohn 2002], In order to model the heat transfer process accurately, it is necessary to include the heat generated by the tool pin in the modeling. The heat transfer process during the tool penetration period cannot be modeled if the heat input from the pin is not included. Moreover, the initial field is very important in a transient heat transfer model, especially for modeling the preheat effects of laser-assisted preheated FSW [Song and Kovacevic 2002]. For this purpose, the heat transfer during the tool penetration period cannot be neglected. During the FSW process the tool penetrates into the workpiece, then moves along the joint line at a constant speed (see Fig. 2). The material in front of the rotating tool pin is plastically deformed and stirred back to the trail edge of the tool pin in the welding. This continuous “stir” process makes it difficult to model the heat input from the pin. First, the material plastic flow process is very complicated, making it almost impossible to determine the temperature distribution of the relocated material that is stirred from the front edge to the aft edge of the tool pin. Secondly, the tool pin is non-consumable in the welding, and modeling a moving tool pin in the workpiece is also not easy. The heat input from the tool pin is simplified as a moving heat source [Song and R. Kovacevic 2004]; however, this assumption is not helpful in modeling the coupled heat transfer for both the tool and the workpiece. In this paper, a moving coordinate has been introduced to model the transient two-dimensional heat transfer process for FSW. The coordinate is chosen stationary with the moving tool. Therefore, the difficulty of modeling the complicated stir process can be greatly reduced, thus making this model more accurate.

THERMAL MODELING OF FRICTION STIR WELDING(CFD ANALYSIS):

In this paper, the application of computational fluid dynamics (CFD) method in modeling the heat transfer during FSW process has been used.

The following assumptions are introduced to simplify the model:

1. FSW produces high temperature metal flow.
2. It is a transient analysis model.
3. In thermal modeling, the main heat input comes from the tool shoulder/workpiece interface; therefore heat generation at the tool pin/workpiece interface is negligible.
4. Homogeneous material.
5. Constant properties.
6. Isotropic material.
7. Two dimensional heat transfer model due to a thin plate.
8. The radiation heat loss can be neglected.[Song and R. Kovacevic 2003].
9. Constant heat input from the tool shoulder / workpiece interface was assumed.

Mathematical model

The FSW process is divided into the following three periods: the penetration period, the weld period, and the tool pulling out period [Song and R. Kovacevic 2002], as shown in Fig. 3 The following assumptions are introduced in the model:

1. The heat generated at the tool shoulder/workpiece interface is frictional heat;
2. The tool pin is a cylinder; the thread of the pin can be neglected;
3. No heat flows into the workpiece if the local temperature reaches the material melting temperature.

➢ Heat Transfer Equation for the Workpiece:

The heat transfer equation for the workpiece in a moving coordinate system with a positive X-direction moving tool can be written as [Song and R. Kovacevic 2003]:

$$\rho c \,\partial T/_{\partial t} = K\left(\partial^2 T/_{\partial^2 x} + \partial^2 T/_{\partial^2 y}\right) + v_w \rho c \,\partial T/_{\partial x} \quad ..(1)$$

Where (T) is the temperature, (c) is the specific heat, (ρ) is the density, (k) is the thermal conductivity and (v_w) is the welding speed.

➢ Heat Generation:

In FSW, there are two main heat inputs: heat generated at the tool pin/workpiece interface and heat generated at the tool shoulder/workpiece interface.

➢ Heat Generated at The Tool Shoulder / Workpiece Interface:

The heat generated at the tool shoulder / workpiece interface is assumed frictional heat. The local friction force at every point can be calculated from:

$$Ff=\mu Fn \quad \ldots (2)$$

Where:

($F f$) : Friction force.

(Fn) : Normal force applied to the workpiece.

(μ) : Coefficient of friction.

Therefore, heat generation rate can be calculated as:

$$q=Ff*v \quad \ldots (3)$$

Where (q) is heat generation rate and (v) is the linear speed. Because $v=R\omega$ and $\omega=2\pi\, n$ therefore:

$q=2\pi\mu FnRn$ … (4)

Where (R) is the distance from the calculated point to the axis of the rotating tool and (n) is the number of rotation [Mohanad 2007].

The coefficient of friction is believed to vary during FSW, but the details of the variation of the friction coefficient are not clear so far. In this modeling constant coefficient of friction is assumed.

Boundary Conditions and Initial Condition for CFD Modeling:

1. Plate surface:

$q = h\,(T - T\infty)$ for $r > R_{sh}$ and

$q=qi$ (Heat input) for $r < R_{sh}$

2. For incoming side and out coming side of plate :

$V_x = V$ (Welding speed)

$V_y = 0$

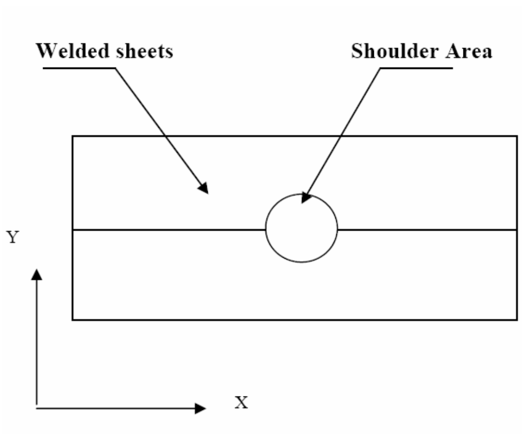
$q = h\,(T - T\infty)$

3. For two vertical sides:

$V_x=V$, $V_y = 0$

$q = h\,(T - T\infty)$

4. Initial Temperature = T_i



Boundary Restriction:

The heat generation input condition is applied only to the points within the tool shoulder covered surface, i.e. when $r < R_{sh}$, while the convection boundary condition is applied to all other points in the plate surface i.e. $r > R_{sh}$.

Finite element model

The general purpose finite element code ANSYS is used for solving the energy equations and carrying out analysis. In this study a, 2-D transient model based on a finite element proposed to study the thermal history in the welded plates. Ansys/FLOTRAN as a finite element software used to carry out the numerical simulation.

In the present study, it is assumed a reference framework fixed to the welding tool, in such a way that, the plate moves towards it with different welding speed.

In the finite element modeling the convection heat transfer coefficient at the welded plates used is (30 $W/m^2.C$), which is typical for natural convection between aluminum and air[Song and R. Kovacevic 2002].

A right-handed X-Y coordinate system was used throughout. The X-axis is parallel to the welding direction. The mesh used is also illustrated in Fig. 3; FLUID 141 two-dimensional element type was used with refined element around the welding tool shoulder.

REESULTS AND DISCUSSION

Curves Discussion

In general, the figures represent the relationship between the temperature and time, from Fig. 4, it was concluded that the revolution speed and linear speed and preheating process had a strong effect on the temperature distribution along the welded plates.

Also, it was noticed that in each curve the peak temperature at A ((20 mm) from the edge of the plate), B ((20 mm) from the edge of the plate), and C (in the center of the plate) is affected by the location of welding tool which turning in its limited speed.

The temperature at point (A) begins about (100 or 200) depend on preheating, then increased when the welding tool being in the points of testing, after that the temperatures begins to decrease gradually while the welding tool leave the testing point.

From the increase and decrease of temperature at the testing points it was noticed that the welded plates takes more time to dissipate heat that for its gain.

The temperature at this point decreases continuously until the end of welding process.

This is coincide with point (B) which reach about (300 ºC) where it's temperature increased as the temperature of point (A) reach about (293 ºC) decreased because welding tool passing through point (B) while it leaves point (A).

The highest temperature at point (B) was recorded as the welding tool reaches the point, while it begins to decrease when the welding tool leave it.

The process of increasing and decreasing the temperature is also true for point (C), but at this point the decreasing of temperature becomes lower than the previous points because the welding process was on its end according to the position of the testing point.

In all figures, it was noticed that the temperature of point (C) reach about (314 ºC) was higher than that of point (B) which reach about (300 ºC), while the temperature of point (B) was higher than that of point (A), this is because of the nature of the process, which begins at point (A) (the beginning of heat input), so that point (A) was the lowest one. While point (B) was higher than (A) because of heat build in the welded plates. Also, the temperature of point (C) was higher than the temperature of point (B) for the same reason.

The heat building process at point (B) and (C) was very effective factor on the welding process which gives more homogenous, smooth and clean welding.

This is very clear when comparing the welding at points A, B, and C with theoretical analyses as shown in Fig. (5) to (7) when rotation speed 1200 RPM, translational speed of 110 mm/min, preheating 100 ºC.

Discussion of the parameters effect on the welding.

1. The preheating effect.

Case one:

With working conditions as follows:-

Preheating 100 **ºC**
Revolution speed 1200 RPM
Linear velocity 155 mm/min
Fig. (8 - 10) represent the temperature distribution for point A, B, and C respectively.
Case two:
With working conditions as follows:-
Preheating 200 **ºC**
Revolution speed 1200 RPM
Linear velocity 155 mm/min
Fig. (11 - 13) represent the temperature distribution for point A, B, and C respectively.

According to the two cases above it was noticed that the increasing of the preheating with constant revolution speed and linear velocity, the temperature of testing points increased.

Fig. 14 represent the curves of temperature distribution in point (B) with various preheating and constant revolution speed and linear speed.

The effective of preheating on the peak temperature tested point can be show in Fig. (15).

The revolution speeds effect.

Case one:
With working conditions as follows:-
Preheating 100 **ºC**
Revolution speed 960 RPM
Linear velocity 155 mm/min
Figures (16- 18) represent the temperature distribution for point A, B, and C respectively.

Case two:
With working conditions as follows:-
Preheating 100 **ºC**

Revolution speed 1200 RPM
Linear velocity 155 mm/min
Figures (8-10) represent the temperature distribution for point A, B, and C respectively.

In the welding process, the heat come from the friction between the specimen and the tool shoulder as well as from the stir and plastic deformation of the specimen. The rotation speed of the tool shoulder may change all these factors. The influence of the tool shoulder rotation speed on the temperature field is shown in Fig. 20. From Fig. 20, it is clear that the rotational speed has an effect on the peak temperature.

According to the two cases above it was noticed that the increasing of the revolution speed with constant preheating and linear velocity, the temperature of testing points (A, B, C) increased. This is because (a high rotational speed, the relative velocity between the tool and workpiece is high and consequently, the heat generation rate and the temperature are also high).

Fig. 19 represents the curves of temperature distribution at point (B) with various revolution speed and constant preheating and linear speed.

The effect of revolution speeds on the peak temperature tested point can be show in Fig. 20.

The linear speed effect.

Case one:

With working conditions as follows:-
Preheating 100 **ºC**
Revolution speed 1200 RPM
Linear velocity 195 mm/min
Figures (21-23) represent the temperature distribution for point A, B, and C respectively.

Case two:

With working conditions as follows:-
Preheating 100 **ºC**
Revolution speed 1200 RPM
Linear velocity 155 mm/min
Figures (8-10) represent the temperature distribution for point A, B, and C respectively.

Case three:

With working conditions as follows:-
Preheating 100 **ºC**
Revolution speed 1200RPM
Linear velocity 110 mm/min
Figures (5 - 7) represent the temperature distribution for point A, B, and C respectively.

According to the three cases above it was noticed that the linear speed had a reverse effect on the temperature distribution, so that with increasing the linear speed the temperature become lower and this is because of the fact that at high welding speed (linear speed), the heat input per unit length decreases and heat is dissipated over a large volume of the workpiece. So the points that tested had not enough time to increase the temperature.

Fig. 24 represents the curves of temperature distribution in point (B) with various welding speed and constant preheating and revolution speed.

Fig. 25 shows the effective of linear speed on the peak temperature of welded plate.

CONCLUSIONS

1- A preheat is beneficial to increase the temperature of the workpiece in front of the tool pin, making the material easy to be welded, while protecting the tool from being worn out.

2- It be select optimum welding parameters to obtain good weld, there is no necessary to use high values of revolution speed or linear Speed with preheating process.

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NOMENCLATURES

ρ : Density (Kg/m^3).

μ : Coefficient of friction.

Cp : The specific heat (J/Kg.K)

Ff : Friction force.

Fn : Normal force.

k : Heat conductivity (w/m.k)

R_p : Radius of pin (mm).

R_{sh} : Radius of shoulder (mm).

T : Temperature (K or °C).

t : Welding time (sec).

T_i : Initial or preheat temperature of the workpiece (°C).

T_m : Melting temperature (K or °C).

V : Welding speed (mm/sec).

W : Rotational speed (rev/min).

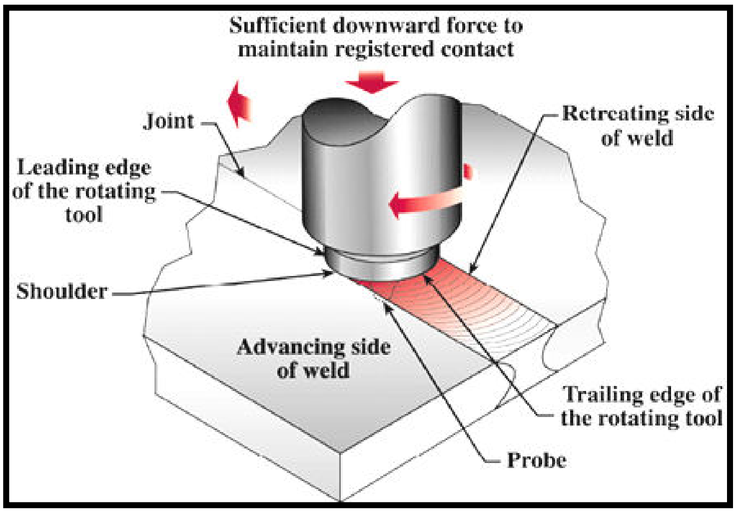

Figure. 1: Schematic representation of FSW of a butt joint.

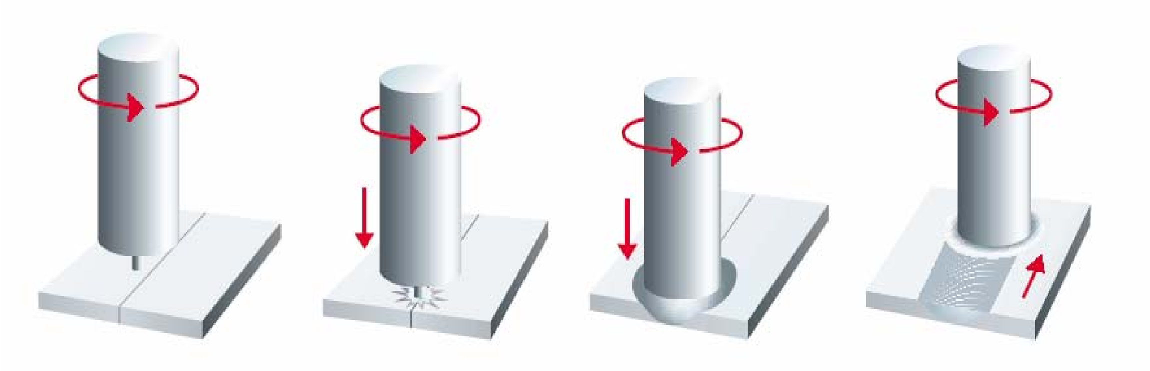

Figure. 2 Schematic diagram of FSW.

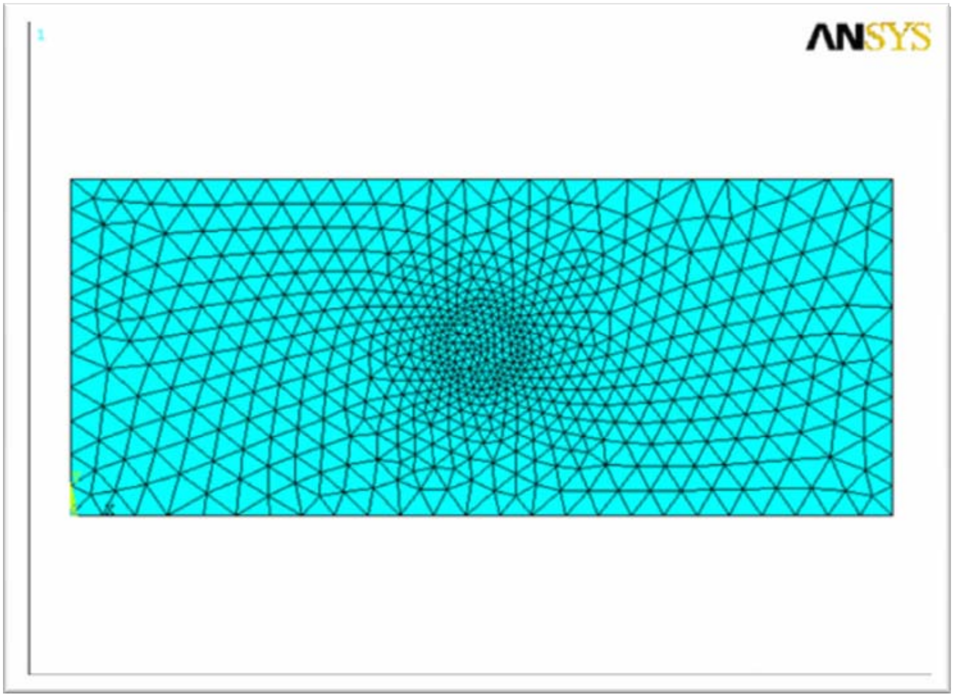

Figure. 3:2-D mesh of modeled welded plates.

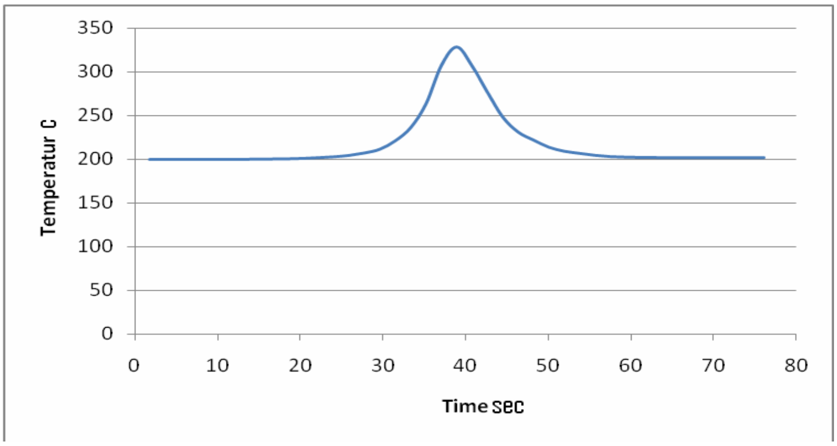

Figure. 4: Temperature distribution in points (B). 1200 RPM, 155 mm/min, preheating 200 ºC.

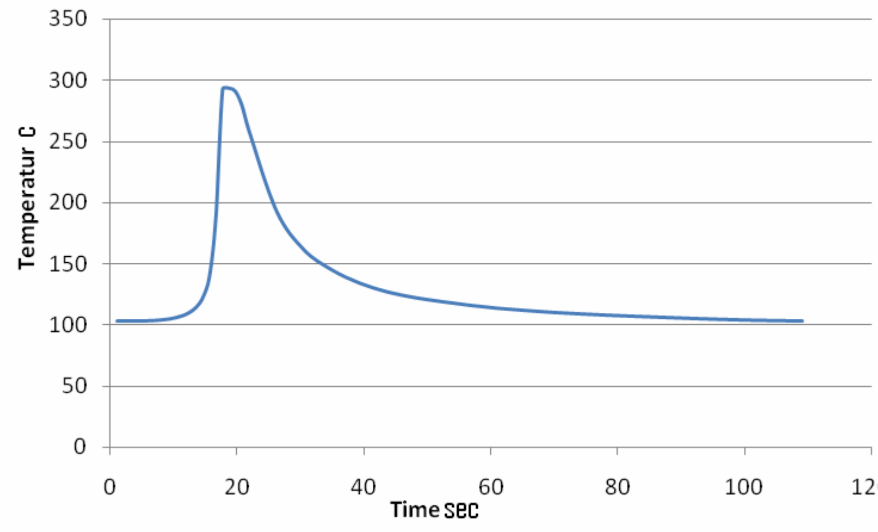

Figure. 5: Temperature distribution at point (A). 1200 RPM, 110 mm/min, preheating 100 C.

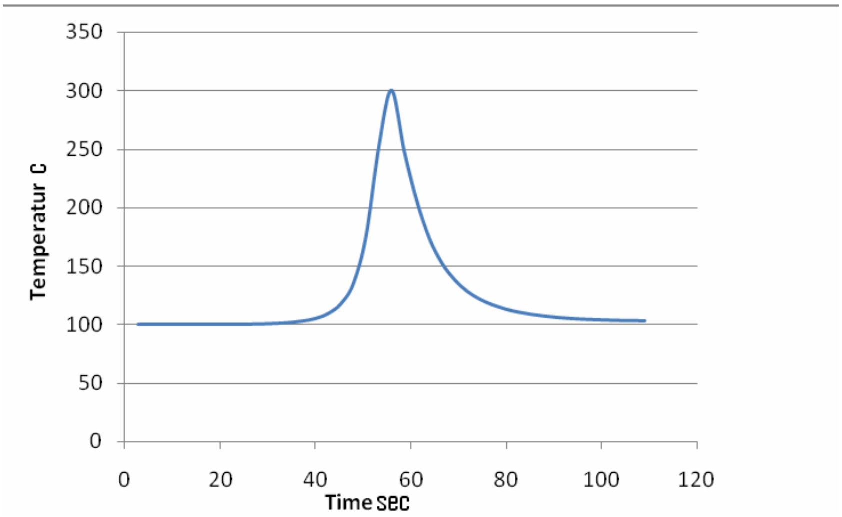

Figure. 6 : Temperature distribution in points (B). 1200 RPM, 110 mm/min, preheating 100 ºC.

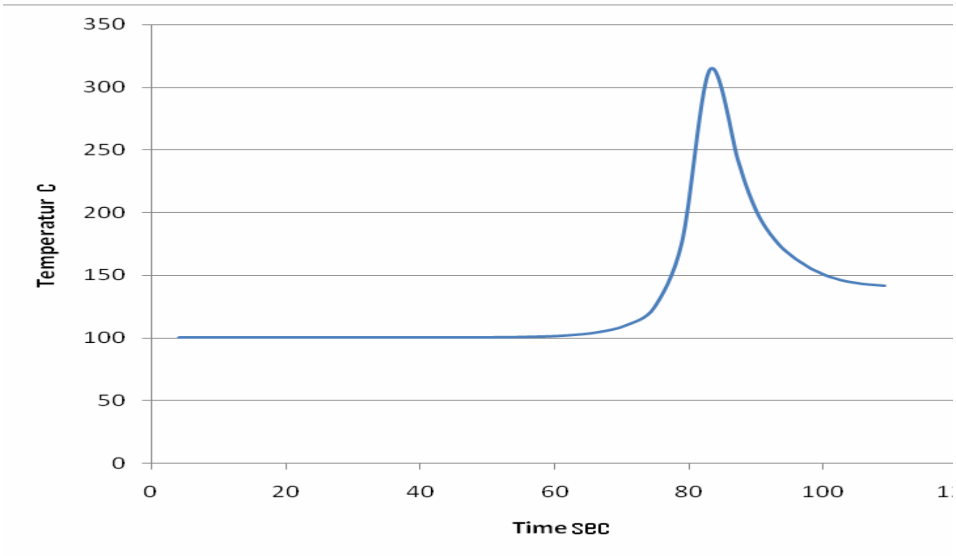

Figure. 7: Temperature distribution in points (C). 1200 RPM, 110 mm/min, preheating 100 ºC.

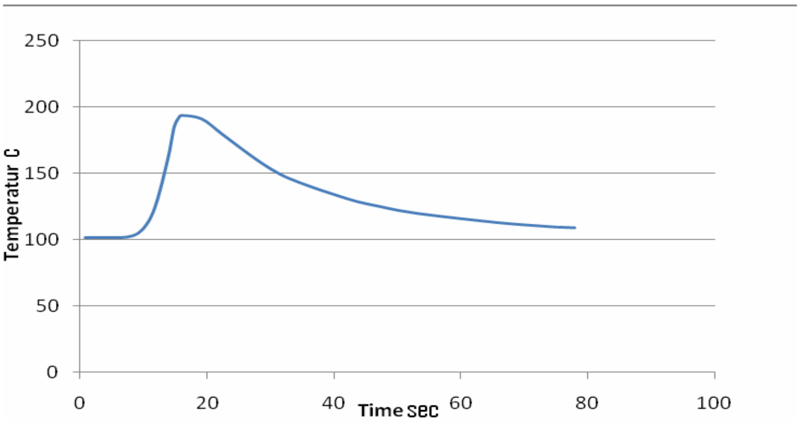

Figure. 8: Temperature distribution in points (A). 1200 RPM, 155 mm/min, preheating 100 ºC.

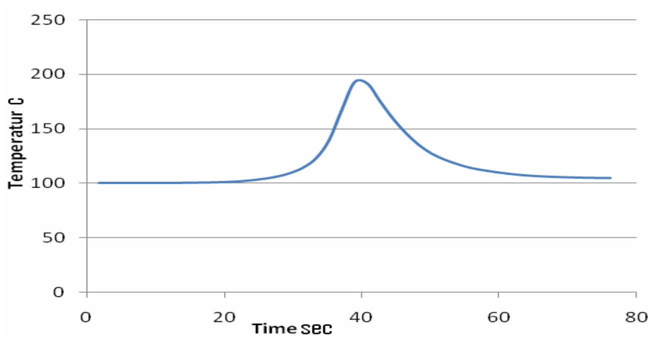

Figure. 9: Temperature distribution in points (B). 1200 RPM, 155 mm/min, preheating 100 ºC.

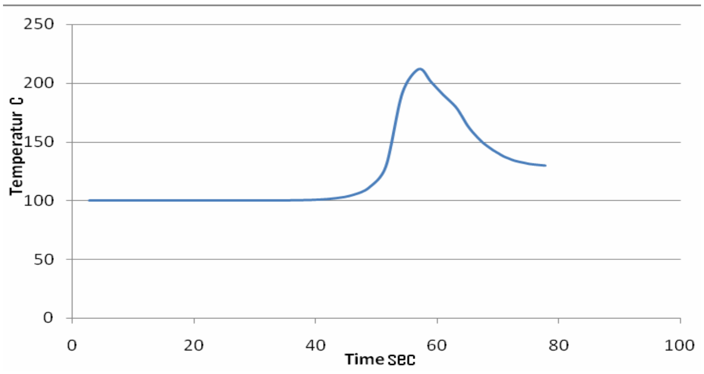

Figure. 10: Temperature distribution in points (C). 1200 RPM, 155 mm/min, preheating 100 ºC.

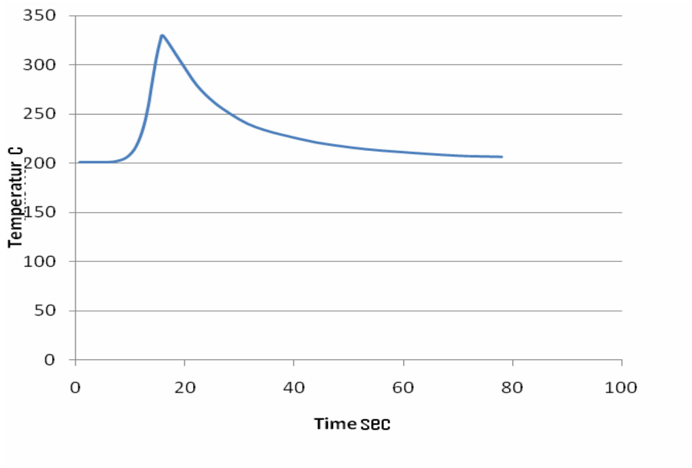

Figure. 11: Temperature distribution in points (A). 1200 RPM, 155 mm/min, preheating 200 ºC.

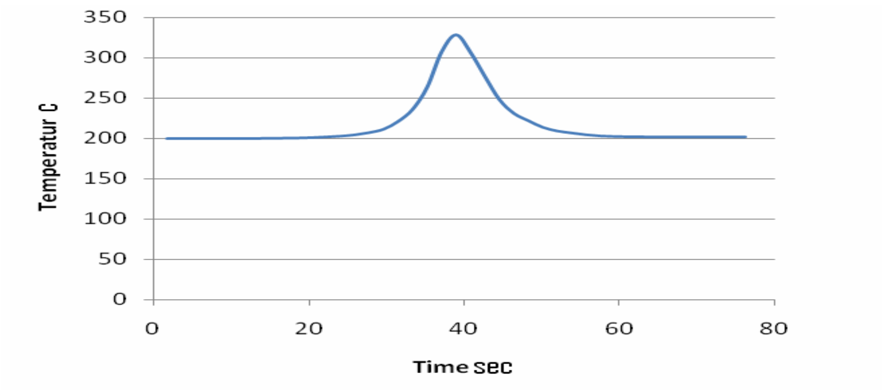

Figure. 12: Temperature distribution in points (B). 1200 RPM, 155 mm/min, preheating 200 ºC.

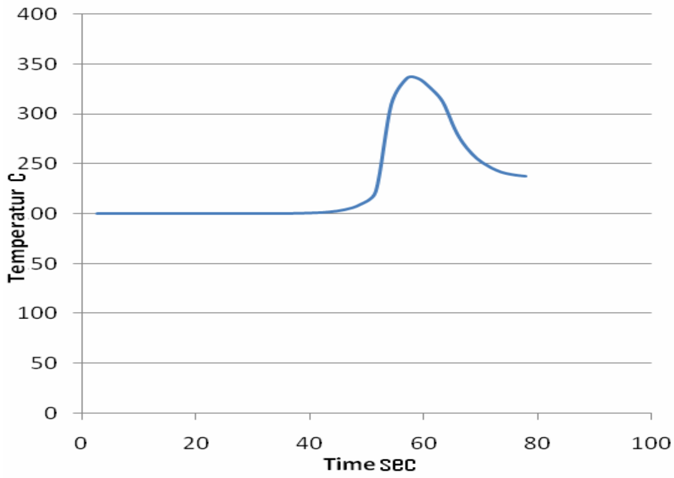

Figure. 13: Temperature distribution in points (c). 1200 RPM, 155 mm/min, preheating 200 ºC.

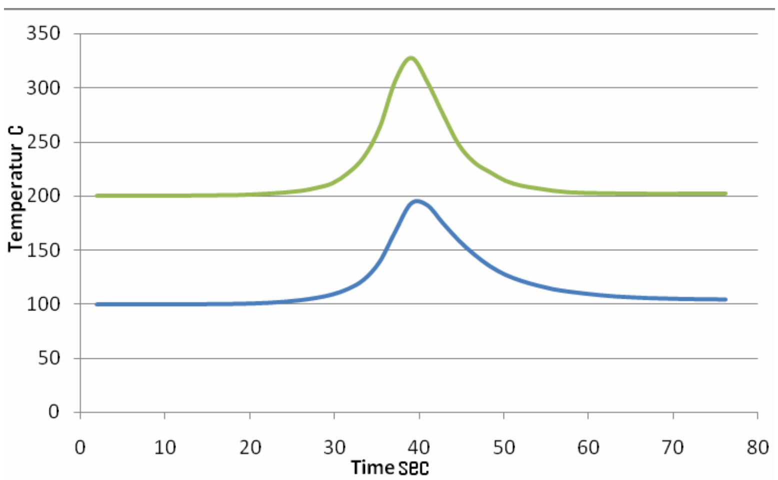

Figure. 14: Temperature distribution in point (B) with variable preheating and constant linear speed and revolution speeds.

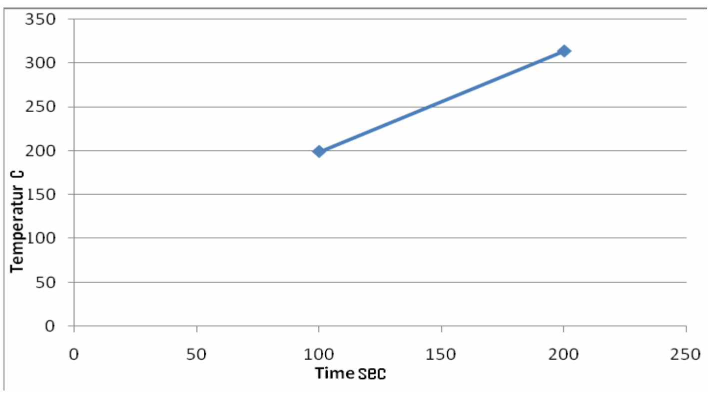

Figure. 15: The effective of preheating on the peak temperature in point (B).

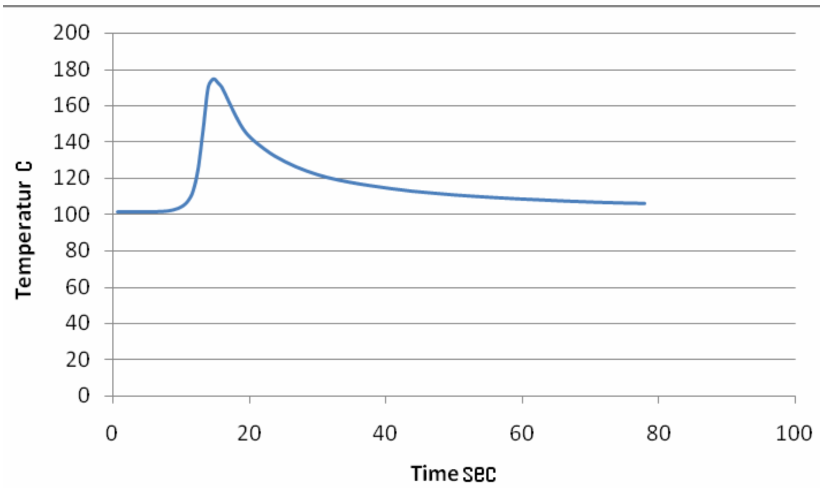

Figure.16: Temperature distribution in points (A). 960 RPM, 155 mm/min, preheating 100 ºC.

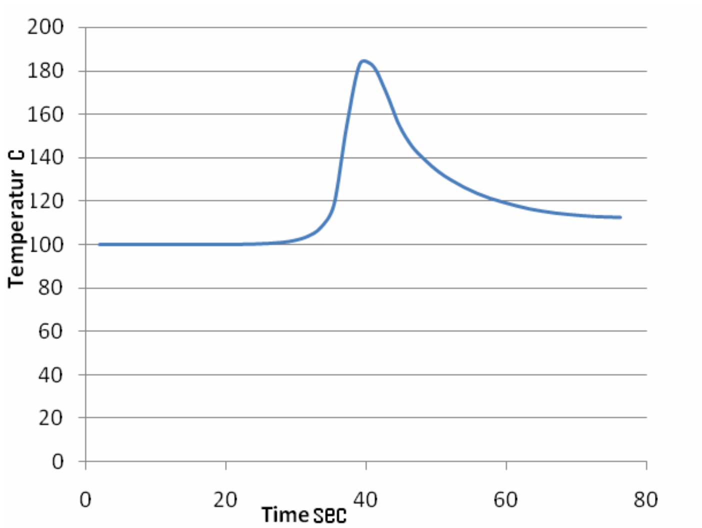

Figure. 17: Temperature distribution in points (B). 960 RPM, 155 mm/min, preheating 100 ºC.

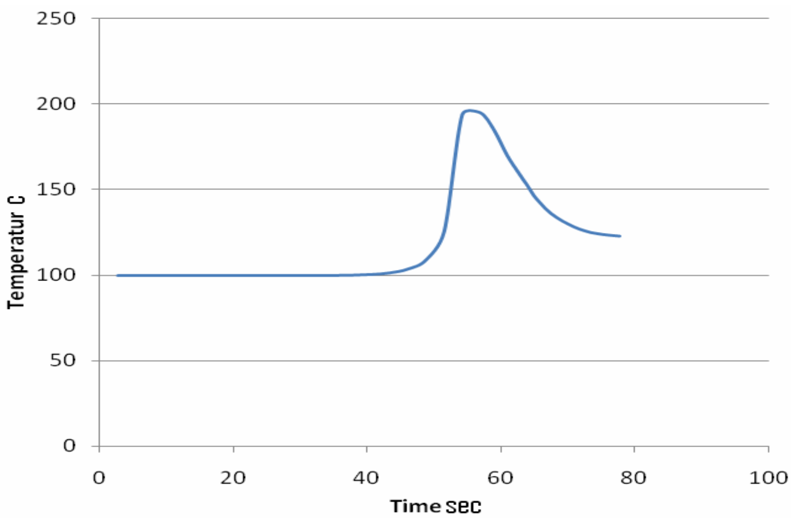

Figure. 18: Temperature distribution in points (A). 960 RPM, 155 mm/min, preheating 100 ºC.

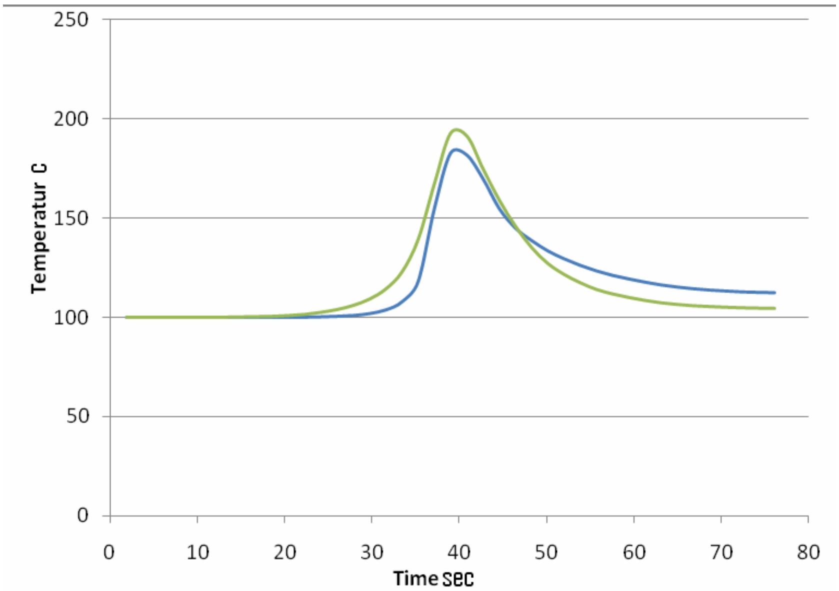

Figure.19: Temperature distribution in point (B) with variable revolution speeds and constant linear speed and preheating.

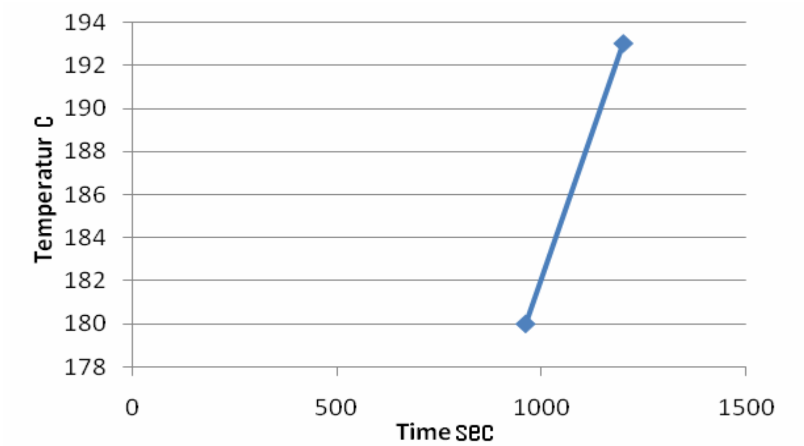

Figure. 20: The effective of revolution speeds on the peak temperature in points (B).

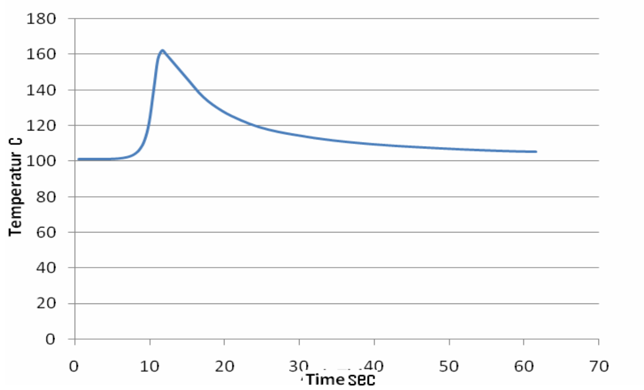

Figure. 21: Temperature distribution in points (A). 1200 RPM, 195 mm/min, preheating 100 ºC.

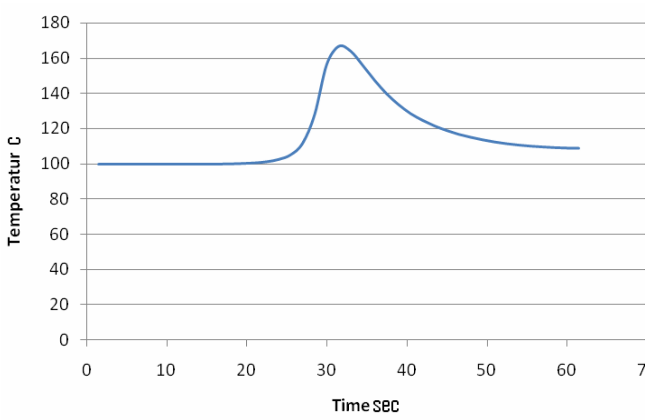

Figure. 22: Temperature distribution in points (B). 1200 RPM, 195 mm/min, preheating 100 ºC.

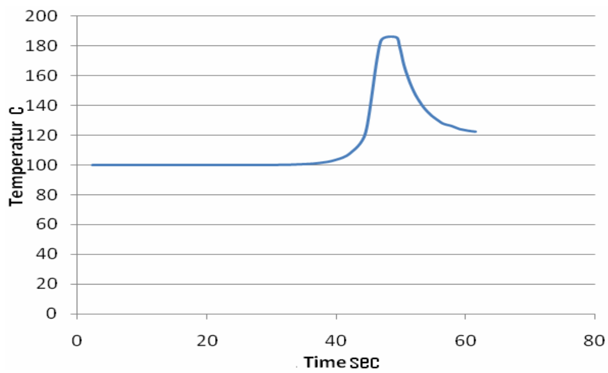

Figure. 23: Temperature distribution in points (C). 1200 RPM, 195 mm/min, preheating 100 ºC.

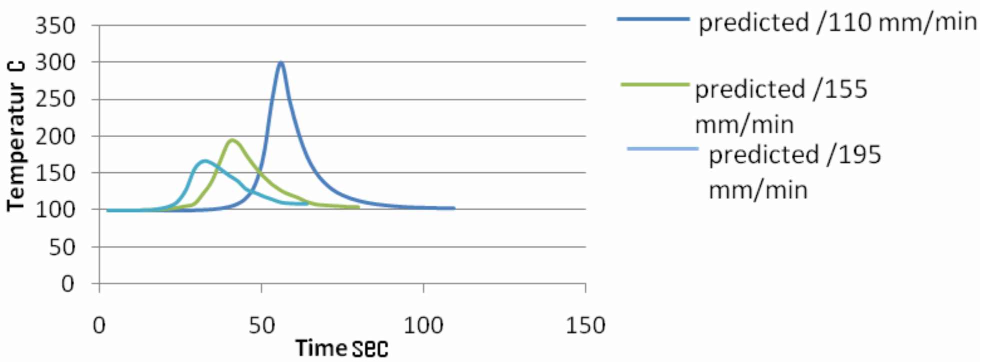

Figure. 24: Temperature distribution at the point (B) with variable welding speed and constant revolution speed (1200rpm) and preheating (100 ºC).

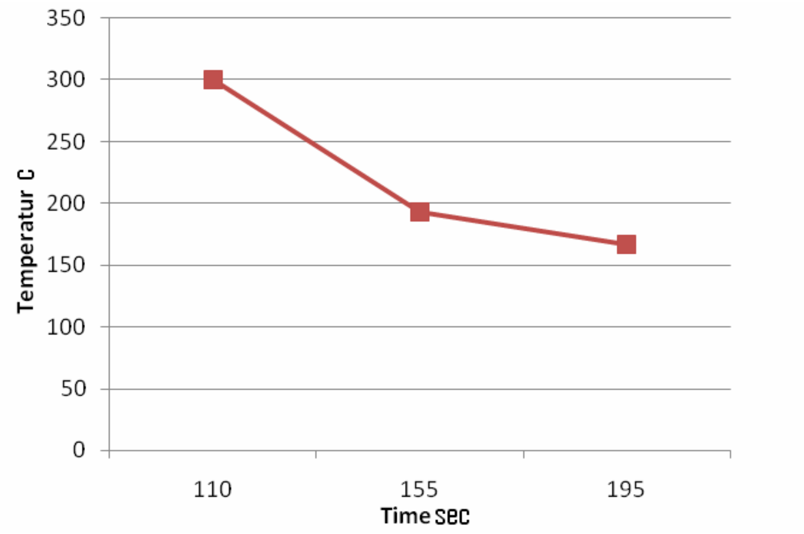

Figure. 25: The effective of linear speed on the peak temperature of welded plate in the point (B).