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NUMERICAL SIMULATION OF THE MATERIAL FLOW INFLUENCE UPON HEAT GENERATION DURING FRICTION STIR WELDING

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Abstract. *Friction stir welding is a solid state welding technique using a welding tool for carrying out material joining. In performing this process, the welding tool is deforming the workpiece material in the welding zone, forcing it to travel, mix and depose as a weld; and in the whole welding cycle, the welding tool is initiating the heat generation. To estimate the generated heat amount is a challenging task requiring a multidisciplinary approach as well as an analysis of many influencing factors. The material flow around the welding tool appears almost throughout the whole cycle of welding, but it is never considered as a factor involving the heat generation process. The paper is giving a view of the possible influence of the material flow on heat generation as well as numerical simulation that includes a procedure for explanation of the material flow around the welding tool. Numerical simulations have given the results which are then compared to each other; the goal is to show the extent to which the material flow influences the generation of heat in the friction stir welding.*

Key Words: *Friction Stir Welding, Heat Generation, Material Flow*

1. INTRODUCTION

Friction stir welding (EN ISO 4063:2009 – 43, usually called "FSW") is a solid state welding technique mostly used for welding of aluminum and aluminum alloys. Its main characteristic (that makes it specific and different from other solid-state friction based welding techniques) is the usage of at least one welding tool that does the welding of two pieces. In the friction stir welding, the welding tool is the third piece in tribo-pair [1, 2] initiating, affecting and performing the welding of other two pieces while other friction welding techniques initialize welding of two pieces using only the friction that appears between these two parts while in relative motion [3].

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The friction stir welding tool is a cylindrical/conical part that rotates around its axis at a prescribed rate and translates along the joint line when inserted between the pieces that are about to be welded. During such a movement, the welding tool is in constant contact with the pieces over its active surfaces [4]: the material of the pieces near the welding tool is stirred, deformed, heated and softened, then partially recrystallized, mixed and deposed behind the welding tool as a monolith structure – weld. Throughout the whole welding cycle the affected material is never led to the melting temperature regardless of the technological parameters of the process or the materials used [5]. The nature of friction and deformation processes that appear during FSW are in a certain way self-controlled processes [5] and in such conditions material influenced by the welding tool is never becoming molten at a recognizable level or in certain droplets [6]. This is the reason why FSW is considered to be a solid state welding.

However, what stands for every welding process also stands for FSW – power (heat) input in the weld is crucial for the quality of weld. The arc welding processes (e.g. MIG, MAG, TIG, etc.) are good examples of welding processes where materials are fully molten (in the zone of welding), mixed and recrystallized, and when solidified create a weld. Heat input is one of the main concerns for them – it has to be sufficient to create a good weld, but minimal to reduce the thermal damage of the material (lower deformations and residual stresses, for example). In these cases, heat input is controlled by the welding parameters – electric current and voltage, since there is a direct connection between them and the power delivered to the weld. The principle is the same for FSW but adapted for the situation: power delivered to the welding tool is connected to the torque and rotation rate of the welding tool, as well with the loads and the welding regimes (welding rate, plunging time, dwelling time, etc.). This mechanical power is delivered from the tool to the material (workpieces) mostly in a form of heat [7] and the rest of it are mechanical losses and deformational work, noise, vibrations, light, etc. The challenges are to estimate how much mechanical power is transformed into heat and afterwards to estimate how much heat has entered the weld.

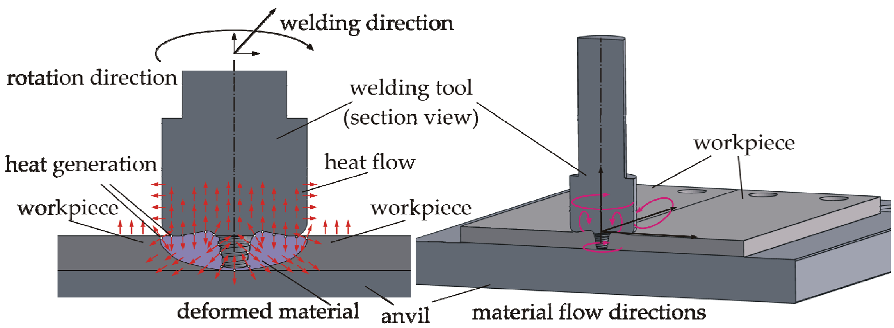

Fig. 1 FSW scheme: heat generation, heat flow and material flow directions [8]

2. HEAT GENERATION

Heat generation in FSW is considered as a process of transformation of mechanical power into heat. The mechanical power is delivered to the welding tool and the welding tool delivers it to the workpieces. Since the welding tool is constantly "machining" the material of workpieces, the mechanical power is used for overcoming the resistances and processes that appear while in contact, namely: friction, adhesion, material deforming, sliding, hardening, etc. This is the main reason why heat generation in FSW is in general considered as a sum of heat generated due to friction and heat generated due to deformation [9, 10, 11]. Estimation of both is still a challenge since heat generation is a case sensitive process depending on many parameters that can be estimated only experimentally [9, 10].

Heat is an unstable type of energy [11] and it is difficult to be measured explicitly due to its short termed existence. A certain indicator of the heat presence is a temperature change in the space close to the heat source; since there is a mathematical dependence between the temperature and the heat it is possible to estimate the extent to which heat has induced a measured temperature change [12, 13]. However, the heat generated during FSW is induced on the contact between the welding tool and the workpieces or in the zone close to it (primary generation) and within the deformed material of workpieces (secondary generation). This makes estimating heat/temperature in the heat generation zone difficult. The validation of the generated heat amount estimated analytically can be done over temperatures: an estimated temperature change (as a heat generation result) can be compared to the temperature change experimentally determined on the spots where it is suitable to measure it [13]. The problem is the need to get detailed knowledge about the heat flow in the system, the thermo-mechanical properties of materials, the boundary conditions, etc.

The existing models for estimating the heat generated during FSW [8, 10, 15-17] use this principle and almost all of them recognize conduction, convection and radiation as the heat flow descriptive models. All of them consider the welding tool as a moving heat source with or without special care paid to the welding tool topology, different engagement of the welding tool during stages of the FSW [4, 5] with numerous assumptions, what combined with the heat flow models provides some results.

However, besides pure conduction, convection and radiation, the heat generated during FSW is also traveling mechanically. Since the stirred particles of the material travel around the welding tool [18, 19], and while travel they deform, reform, speed up or slow down, they give and receive a new amount of mechanical power that transforms into heat. In a specific manner, heat is traveling with the particles.

The material transfer around the welding tool is called material flow. There are many investigations of this process. However, none of them connects material flow with the heat generation process.

3. Material Flow

The material flow impact around the welding tool is important for the development of the FSW from its invention. It is obvious that the deformed material has to be movable until it mixes properly and deposes behind the tool as weld. The welding tool development has also had a goal to provide for an adequate material flow which would finally result in a qualitative weld. That is the main reason why welding tools have threads, flutes, nonsymmetrical shapes, etc [20]. Moreover, early research projects have shown that the proper material flow leads to a good microstructure of the weld and a larger or smaller welding nugget.

Preliminary investigations of the material flow [18] involve marker technique or "stop action" technique (also known as "frozen pin" technique) [18]. The marker technique uses insertion of a specific material that does not mix with workpieces and can be used to describe the material flow while the "stop action" is based on an intentional stopping of the welding tool and retracting from the weld; this results in a realistic shape of the material flow patterns in workpieces at the moment when the tool is stopped. Both the techniques are purely experimental and give significant understanding of the material flow around the welding tool, the flow patterns, influence of the threads and direction of rotation, etc. The most important conclusions can be summed up as:

1. Material is traveling around the welding tool 3-dimensionally: it rotates around the welding tool and translates upwards/downwards along the rotation axis of the welding tool.
2. It is not uncommon that some of the deformed material circles around the welding tool more than once before it stops and deposes as weld.
3. While "flowing", the deformed material keeps the form of small chunks – it never becomes 100% plastic nor elastic.
4. Deformed material has some properties of a highly viscous realistic fluid.

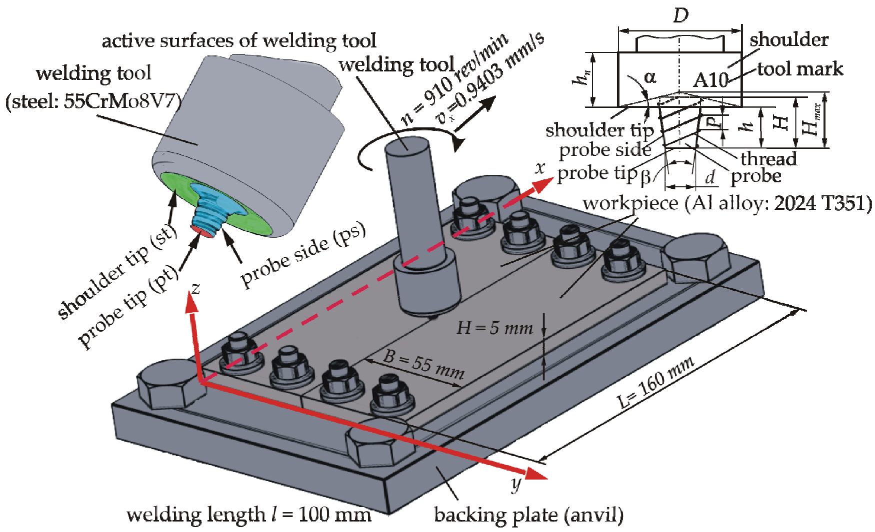

Fig. 2 Details of numerical simulation and experimental investigation

Newer investigations of the material flow involve simulation software capable of processing demanding calculations of the fluid flow patterns that are used to simulate deformed material [21]. The results have shown good agreement with experimental results, but they are limitedly usable due to the longtime lasting calculations on present day's computers (talking about the months of computer work).

4. Estimation of Amount of the Generated Heat during FSW with the Material Flow Implementation

The estimation of amount of the heat generated during FSW [5, 8] with the material flow implementation around the welding tool, besides the analytical model for estimating the generated heat amount, requires numerical simulation of the material flow. The algorithm used for numerical simulation of the material flow is called "node replacement and substitution"

[5, 8] and relies on several experimental results and previous simulations as well as on a quasi stochastic nature of the material flow. The goal of implementation of such algorithm in the analytical model for estimating the generated heat amount during FSW is an increase of the model precision without any significant increase of the calculation time.

Fig. 2 gives necessary details for the simulation – materials used for welding, welding tool material, dimensions, welding rate, rotation rate, etc. The same parameters are used for experimental investigation and the results from the experimental investigations are used as an input for the numerical simulation [5, 8].

4.1. Numerical simulation of the material flow

In order to estimate temperature/generated heat, it is necessary to solve the heat equation [13]. It has to be numerical due to the complexity of the problem. The observed space consisting of welding tool, workpieces, anvil, etc. has to be discrete (Fig. 3, primary discretization) as well as the time.

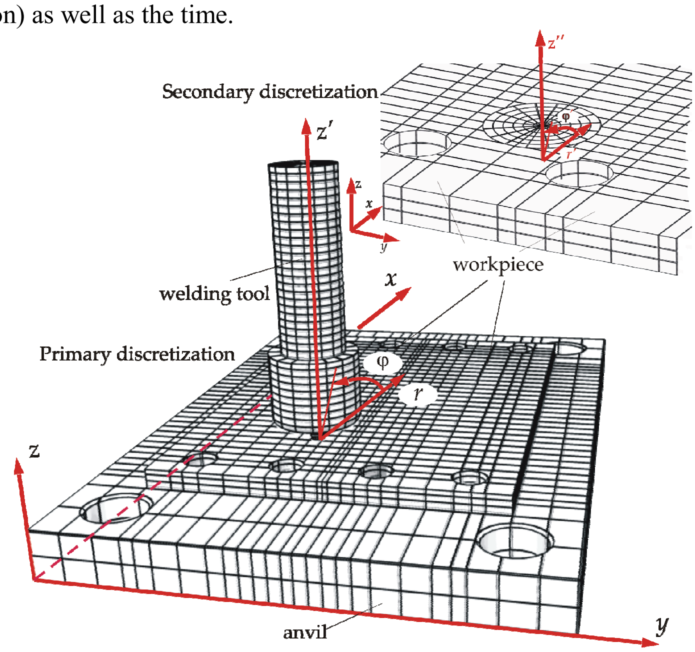

Fig. 3 Primary and secondary discretization of the space

The material flow around the welding tool happens in a zone near the welding tool. This zone has to be discretized in such a way that the material flow can be realistically shown in discretized time and space. Fig. 3 gives an example of how the material flow zone can be discretized.

Primary discretization is global and time independent which is not the case with the secondary discretization. The welding tool is traveling along the joint line and the zone of material flow is traveling with the welding tool. This requires that after every discrete transversal movement of the welding tool the material flow zone is rediscretized. The non-deformed material of workpieces captured with the discretized zone of material flow is entering the flow while the deformed material left behind the zone enters a steady state condition and has no direct influence of welding tool. This is secondary discretization of the space (Fig. 3).

Secondary discretization of the space is done in polar-cylindrical coordinates with coned sides of the cylinders (Fig. 4a). The explanation of such unusual discretization should be found in following statements:

- The shape of the deformed material zone is similar to a curve sided cone without top. Discretization of such a body is the simplest when done by using multiple cones (as radial discretization borders) having the same axis and basis, but different cone angles. Circular discretization is classic discretization of circles and axial discretization (along *z* axis) is linear (Fig. 4a).
- Due to previous research projects [13, 17, 18, 20], it can be assumed that the workpiece material is "flowing" around the welding tool in circles, traveling from upper to lower zones and back, as well as radially traveling to or from the welding tool axis.

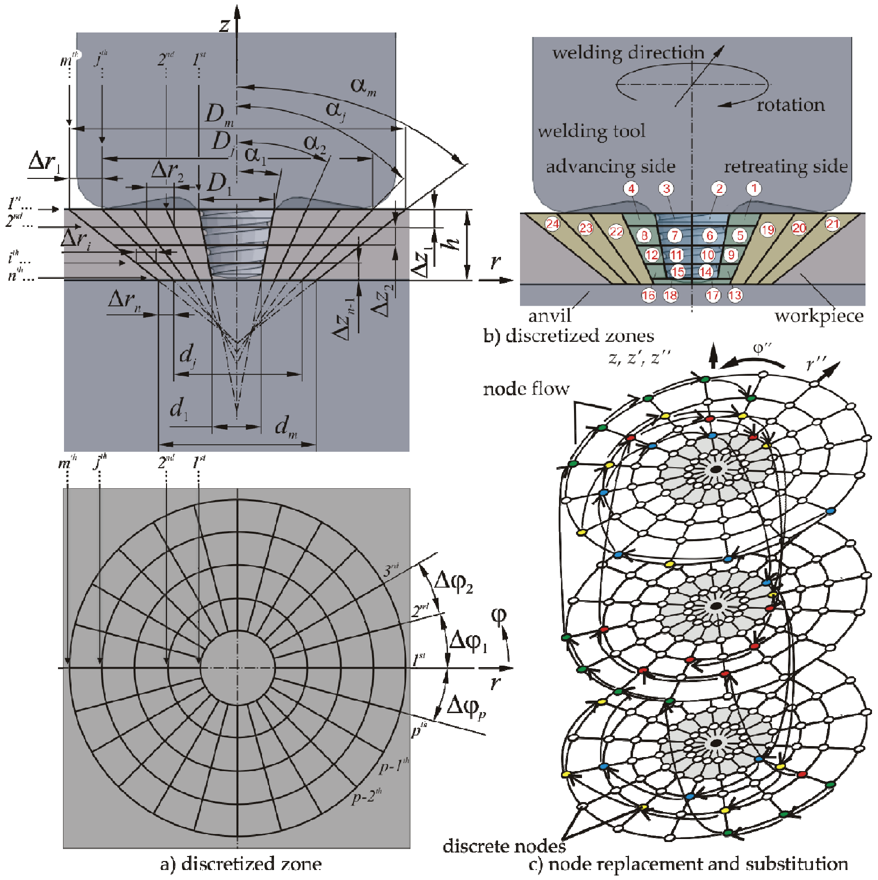

Fig. 4 a) Secondary discretized space, b) Zones of material deposition, c) Node replacement and substitution schematic

Knowing the rotation direction of the welding tool and the angle of the thread (Fig. 4b), the material flow around welding tool can be assumed as well as the material deposition place. However, it is not possible to predict with 100% probability where the material will depose. That is the main reason why the discretized space is grouped in 21 zones with different deposition probability. Zones and their locations are shown in Fig. 4b. For example, if the material from zone 1 is stirred and started to travel, it is possible that in the following discretized moments of time, it will be deposed in zones 5, 9, 13, 6, 10, 14 or 17. Deposition zones are listed from the highest probability of deposition to the lowest one.

Material from zone 21 stays in zone 21 or goes to zone 20, etc. Deposition probability is calculated due to the experimental results of material flow in material. Computer is naming material (nodes) and calculating if it has already moved or not in discretized time. Also, it is looking for an adequate space where the nod will be set up and it searches it until all demands are fulfilled. The scheme of material flow numerically described as "node replacement and substitution" procedure is shown in Fig. 4c.

However, the probabilistic procedure with its experimental background makes it possible that the computer will not find a suitable place for nodes in a real (short) time. To make the calculation possible, it is assumed that calculation procedure in the selected discretized time moment is finished if more than 80% of nodes have changed places and amount of generated heat is estimated. After that, the computer goes on to the next discretized time moment, rediscretizes space and repeats the calculation procedure.

4.2. The results of numerical simulation

Before numerical simulations, sets of experimental investigations are carried out with the goal to estimate the parameters necessary for the generated heat analytical estimation [5]. These results are used as an input for numerical simulations.

Numerical simulating of the FSW with a goal to estimate amount of generated heat is performed by software FSW – specially developed for these purposes [5]. The simulation is performed for two cases:

1. Estimation of amount of heat generated during FSW regardless of the material flow,
2. Estimation of amount of heat generated during FSW with taking into consideration the material flow with simulation of material flow (an example is shown in Fig. 5).

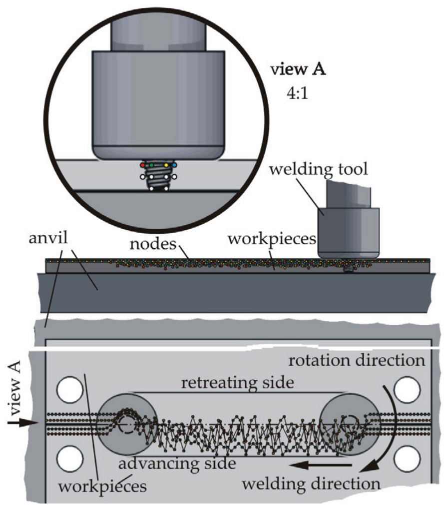

Fig. 5 Scheme of nodes and their positions after numerical calculations

FSW consists of several phases [4, 5]: plunging, first dwelling, welding, second dwelling and pulling out. The maximal material flow around the welding tool is appearing during the welding phase; therefore, it is of interest to be analyzed. Fig. 6 shows a diagram of the mechanical power delivered to welding tool $P(t)$, amount of generated heat during FSW without regarding material flow $Q(t)$ and amount of generated heat during FSW regarding on material flow $Q^*(t)$.

Fig. shows the ratio of the generated heat with concern on material flow and mechanical power.

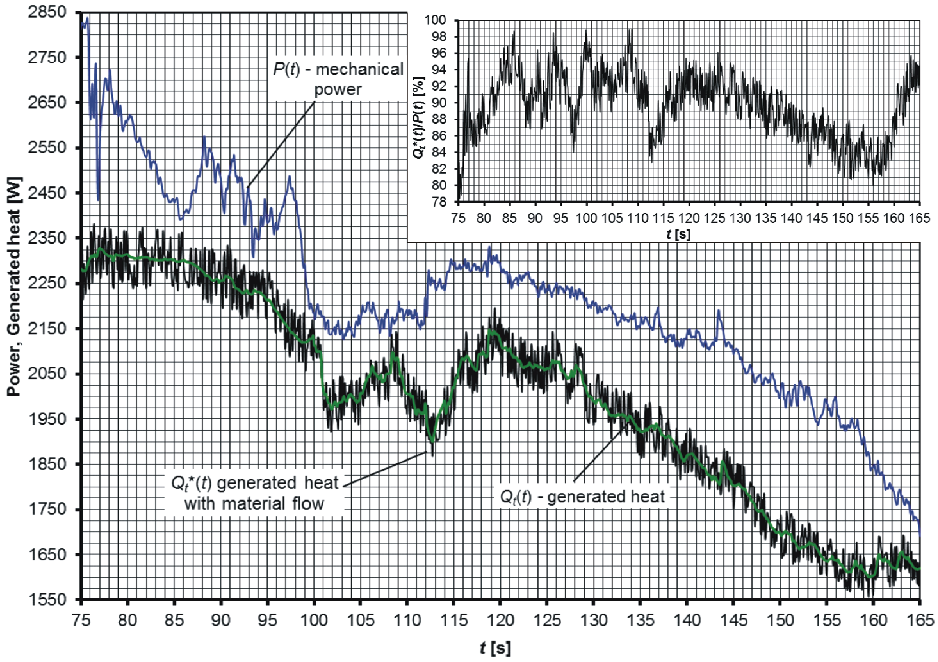

Fig. 6 Results of simulation

5. CONCLUSIONS

To estimate the amount of heat generated during the friction stir welding is a challenging task that requires a multidisciplinary approach – synergy of experimental experiments, analytical models and numerical calculations. As an unstable type of energy, heat is difficult for direct management: the only possible option for management of the heat is management of the parameters affecting it.

The existing analytical models for estimation of amount of generated heat depend on the proper analysis of the heat generating as well as the heat flow in the surrounding space. Most of them recognize conduction and convection as dominant heat flow models, and some of them involve radiation with a hint of improvement of precision. Since heat generation during FSW happens in a situation where both materials in contact travel, heat is "mechanically traveling" with material, too. The welding tool rotates and transversally travels along the joint line and the workpiece material rotates around the welding tool with some transversal movement while the sources of heat generation travel.

The main idea of the presented research is to investigate the influence of the material flow around the welding tool upon heat generation during FSW. The material flow analysis is a complex process and it requires significant computational time, no matter if it is done semi analytically or purely numerically. The numerical procedure for the material flow analysis called "node replacement and substitution" is implemented into existing analytical model for estimation of amount of generated heat and the results of both calculations are compared.

The "node replacement and substitution" implementation into the analytical model for the generated heat estimate has given no specific change of amount of generated heat during plunging and pulling out phases – generated heat varied app. ±0.25% (maximal value of 15 W in plunging phase) compared to the amount of heat estimated without considering material flow. During welding phase the difference is about ±4% (maximal value of 116 W) compared to amount of heat estimated without considering the material flow. Calculation time for a model with implementation of material flow increases for about 45% (from 21 day to 32 days on a modest laptop computer having dual-core processor at 3.1 GHz).

The final conclusion is that opinion is on the user: if the results have to be extraordinary precise "node replacement and substitution" should be implemented in already computer resource demanding calculation procedure. The material flow around the welding tool has a minor influence on the heat flow and heat generation; it is reasonable to exclude it from heat estimation analysis/simulation if possible. Influence of the material flow on stresses and strain of workpieces is significant and can not be excluded from analyses of residual stresses.

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NUMERIČKA SIMULACIJA UTICAJA KRETANJA MATERIJALA KOD POSTUPKA ZAVARIVANJA TRENJEM SA MEŠANJEM NA GENERISANJE TOPLOTE

Zavarivanje trenjem sa mešanjem je tehologija zavarivanja u čvrstoj fazi pomoću alata koji inicira i realizuje spajanje materijala. Tokom ovog postupka, alat deformiše materijal radnih komada u zoni zavarivanja, pri tom ih primorava da se kreću, mešaju i deponuju kao metal šava. Tokom celokupnog postupka zavarivanja alat inicira generisanje toplote. Određivanje količine generisane toplote pri zavarivanju trenjem sa mešanjem je zahtevan posao koji zahteva multidisciplinarni pristup i analizu mnogobrojnih uticajnih faktora. Kretanje deformisanog materijala oko alata se javlja tokom celokupnog procesa zavarivanja, međutim, nikada nije analiziran uticaj kretanja materijala na količinu generisane toplote. Ovaj rad daje jedan pogled na mogući uticaj kretanja materijala na generisane toplote. Numeričke simulacije su dale rezultate koji su upoređeni sa ciljem utvrđivanja koliko kretanje materijala utiče na generisanje toplote pri zavarivanju trenjem sa mešanjem.

Ključne reči: *zavarivanje trenjem sa mešanjem, generisanje toplote, kretanje materijala*