Industrial Lubrication and Tribology

Microstructure in the joining zone during the friction welding of the two dissimilar steels

Nada Ratković, Vukic Lazić, Dušan Arsić, Ružica R. Nikolić, Radica Prokić Cvetković, Olivera Popović,

Microstructure in the joining zone during the friction welding of the two dissimilar steels

Nada Ratković, Vukic Lazić and Dušan Arsić
Faculty of Engineering, University of Kragujevac, Kragujevac, Serbia
Ružica R. Nikolić
Research Center, University of Žilina, Žilina, Slovakia, and Faculty of Engineering, University of Kragujevac, Kragujevac, Serbia, and
Radica Prokić Cvetković and Olivera Popović
Faculty of Mechanical Engineering, University of Belgrade, Belgrade, Serbia

Abstract

Purpose – The purpose of this paper is to point out the possibilities for friction welding of dissimilar steels which are used in various industries. In addition, friction welding is a welding method that is applied for executing the very responsible joints. This research is focused on friction and tribological processes in the friction plane of the two pieces during the welding.

Design/methodology/approach – The present study research has been conducted based on the experimental testing of cylindrical specimens and results are analyzed.

Findings – The austenite grain size is affected by several factors through the friction process phase and the compacting phase during the welding. The very fine grain is the consequence of the high degree of the plastic deformation of the near-the-contact layers even in the friction phase. The viscous layer, which is formed during the stable friction phase, is the area where the moving of matter occurs according to a very complex mechanism.

Originality/value – The paper contains useful results from the area of conventional friction welding of dissimilar steels and it can be very useful to researchers and engineers who deal with similar problems.

Keywords Friction welding, Hardness, Carbide phase, Joining zone, Mixing zone, Recrystallization

Paper type Research paper

Introduction

In the contemporary industrial practice, the need is growing for the joining of dissimilar materials. The joining of dissimilar steels is a task that requires complex analysis of the process itself, as well as the state of both materials (steels) in the joining zone. After heat treatment of the welded samples, one has to define the structural content, presence of individual phases that are created during the process or immediately after the friction process. The thermal-deformation cycles are the bases of the friction welding process, as they influence the diffusion processes, cause creation of the carbide phase, lead to extrusion of the material layers from the joining plane etc.; thus, the subject of consideration are the complex phenomena that are occurring during the very short time interval, as pointed by Ćirić (2001). On the other hand, dissimilar steels have different chemical compositions, heat conductivities, microstructures and mechanical characteristics, so the heterogeneous structure in the joining zone becomes even more complex and complicates the deeper analysis.

Friction welding has numerous advantages from the aspect of environmental and human resources protection, as emphasized by Veljić *et al.* (2015), and it creates the joints of very good mechanical properties (as shown in Ratković *et al.*, 2014; Sahin, 2005; Handa and Chawla, 2013; Ratković *et al.*, 2016b, 2009a, 2009b, 2016a; Savić *et al.*, 2008; Ma *et al.*, 2015; Liang *et al.*, 2015). The authors of those papers were dealing with problems of strength of the friction welded joints, as well as with the influence of certain welding parameters on the output mechanical characteristics of the joint. Ratković *et al.* (2014) were considering structural, chemical and deformation changes appearing in different zones of the friction welded joint, while Sahin (2005) presented an original experimental setup produced to achieve the friction welding of components having equal diameter and compared the obtained results with those from literature. When the subject matter is the analysis of mechanical characteristics of the executed welded joints, a detailed study was presented by Handa and Chawla (2013), which has included the friction welding process parameter optimization, microstructure and mechanical properties characterization and fracture behavior. Their experimental results indicated that the axial pressure has a significant effect

The current issue and full text archive of this journal is available on Emerald Insight at: **www.emeraldinsight.com/0036-8792.htm**

Industrial Lubrication and Tribology
70/2 (2018) 401–407

[ISSN 0036-8792]
[DOI 10.1108/ILT-08-2017-0234]

This research was partially financially supported by the Ministry of Education, Science and Technological Development of Republic of Serbia through Grant TR35024.

Received 15 August 2017
Revised 15 November 2017
Accepted 12 December 2017

on the mechanical properties of the joint and that it is possible to increase the quality of the welded joint by selecting the optimal axial pressures. Ratković *et al.* (2016a) presented an analysis of influence of the friction welding pressure on the plastic deformation level and the quality of the friction welded joint of the tempering and the high-speed steel. For instance, in papers by Ratković *et al.* (2009a, 2009b), the tensile strength of friction welded joints is increasing with an extension of the welding time. However, despite those benefits, the increased welding time could also lead to the presence of carbides in the zones of dynamic recrystallization, what also has to be kept in mind (Ratković *et al.*, 2016b). In addition, in papers by Savić *et al.* (2008) and Ma *et al.* (2015), the joining of the high-speed steel HS 6-5-2-5 and carbon steel C60 was analyzed, where an attempt was made to create a model for the friction welding of dissimilar materials, by monitoring the temperature cycles and variation of the microstructure during the welding process. Steel as material was also investigated in Samuthiram *et al.* (2014) with welded samples made from steel EN 24 (34CrNiMo6 by DIN) using different process parameters. The obtained results have shown that axial shortening exponentially increased with increased friction pressure while the influence of the welding time on hardness and strength is different, and the optimal parameters for high hardness values are 125 MPa of friction pressure, 180 MPa of forge pressure and 3 s of friction time; for high ultimate strength parameters, the values are 150 MPa of friction pressure, 220 MPa of forge pressure and 5 s of friction time. Similar research was also conducted by Ratković *et al.* (2009a, 2009b, 2016b), in which some analyses were conducted, which were related to structural and chemical changes in the joint, as well as to the influence of the welding parameters on the joint deformation – shortening and joint diameter. These results have shown that one of the most important parameters is the welding time and that by its extension, the deformation of joints is increasing. The main conclusion is also that the joining of the two dissimilar steels can be realized, but that it is necessary to select the optimal welding parameters.

Besides the welding of steels, it is important to emphasize that the friction welding is nowadays widely applied for joining non-ferrous metals and their alloys, like aluminum, which was considered by Kumar *et al.* (2016) for aluminum alloys, by Ambroziak *et al.* (2014) for aluminum alloys to steel, by Liang *et al.* (2015) for aluminum to magnesium, by Ratković *et al.* (2017) for aluminum to copper and by Nathan *et al.* (2016) for tungsten-based materials.

It should mention that there is numerous papers which give the review of rotary friction welding (Shete and Deoka, 2017; Li *et al.*, 2016; Handa and Chawla, 2014). In these research studies, particular emphasis is placed on the process parameters, joint microstructure, residual stresses, mechanical properties and their relationships, as well as on opportunities for further research and development of the process. In addition, all mentioned papers, especially (Li *et al.*, 2016), show analysis of different welding modes, materials and parameters, as well as the influence of heat due to rotation, in a very systematic way.

The objective of this paper is to explain the microstructural phenomena in the welding zone that appears in the complex conditions of friction and elevated temperature. Within the experimental part of this work, the cylindrical samples were prepared from the high-speed and the carbon steel. The friction welding of these steels is present in industrial practice, for instance, in the cutting tools industry. To obtain the high-quality heterogeneous joint of the mentioned steels, it was necessary to apply the optimal welding parameters.

Basic principles of the friction welding and characteristic joint's zones

Friction welding is a procedure of materials' joining in the solid state, as the weld is formed at temperatures lower than the melting temperature of the base metals (BMs). The BMs, considered in this paper, are the high-speed steel HS 6-5-2-5 and the carbon steel C60, whose chemical compositions are given in Table I.

The transformation of mechanical energy into the heat occurs at the joint point, i.e. in the contact zone, as a result of the friction process. The thin layers of material are transformed into the plasticized state and the welding is executed with the help of compressive forces. The plastic deformation of the micro-volumes in the material layers is increasing with an increase in the friction energy release; thus, the welding process is unfolding in several phases (Figure 1). In the first phase (Figure 1(a) – Position 1) the high-speed steel element is rotating, while the carbon steel element is static.

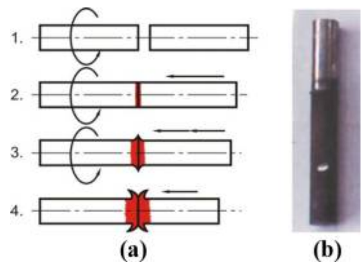
In the next phase (Figure 1(a) – Position 2), after sufficient angular velocity is reached, the steel elements are being brought into contact by the compressive force and the friction starts. At the beginning of the friction process, in the interaction of the HS 6-5-2-5 and C60 steels, the solid adhesive joints between the two BMs are created owing to sliding and action of the axial force. The third phase (Figure 1(a) – Position 3) is characterized by the intensive friction, which leads to heat release, and with the action of pressure, the conditions are created for realization of the joint. The rotation is stopped, and the maximum compacting pressure is introduced, which causes the intensive plastic deformation (Figure 1(a) – Position 4) and a wreath is formed (the "mushroom"). That is how the solid joint is formed.

During the process of intensive friction, the hard-facing of the high-speed steel layer onto the carbon steel occurs, when the tiny pieces of one steel are being transferred to the other steel, in the direction from central to peripheral zones of the sample; these layers are being extruded from the joint into the wreath by maximal pressure action. Separation (detachment) and transfer of particles from one steel to the other first occurs in the central portion of the sample. This is happening because of the uneven deformation over the cross section, and then due to the relatively high friction speed (number of rotations is n = 2,800 min^{-1}) and due to the relatively high pressures (the friction pressure is P_f = 80 MPa). Further, the deformation of those particles occurs and they are then being extruded to the periphery and out of the friction plane, along the complex form trajectory. The thickness of the HS steel layer hard faced onto the carbon steel is 0.02 to 0.06 mm. For this combination of BMs, the thickness of that layer can be 0.02 to 0.3 mm, while the maximum value can be 0.8 mm, depending on the friction time.

Table I Chemical compositions of steels HS 6-5-2-5 and C60

HS 6-5-2-5, (%)	C	Si	Mn	Cr	Mo	V	W	Co	P	S
	0.82	0.45	0.40	4.0	5.0	1.9	6.5	5.5	0.035	0.035
C60, (%)	C	Si	Mn	P	S					
	0.63	0.19	0.82	0.045	0.045					

Figure 1 (a) Basic phases of the friction welding and (b) appearance of the welded sample



Results of investigations have shown that in the friction zone, a carbide plane is formed at the frontal surface of the C60 steel element (Figure 2(a) – Position 1 and Figure 3 – Position 1); the front surface of this plane – toward the friction plane – is smooth and flat, while on the opposite side, the carbides are pressed into the C60 steel. The friction surface can have the piecewise wavy form, what points to the fact that during the friction phase, the material had a turbulent motion to a certain degree (Ratković *et al.*, 2016b).

Figure 2 (a) Characteristic zones of the welded joint of the HS 6-5-2-5 and C60 steels: 1 – the carbide plane created next to the friction plane; 2 – the viscous layer; 3 – the HS 6-5-2-5 layer hard faced onto the C60; 4 – the mixing zone; 5 – the dynamic recrystallization zone; and (b) the cross-section of the welded sample

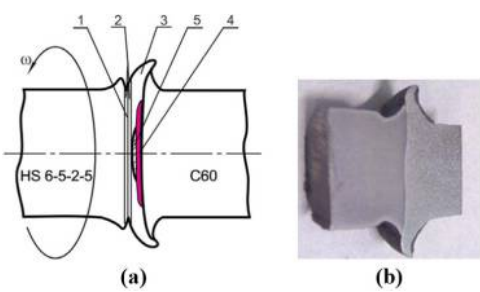
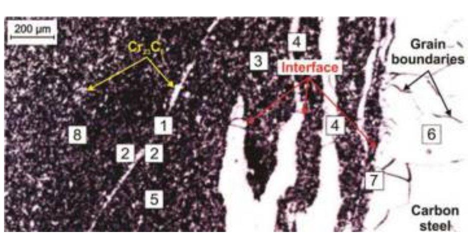


Figure 3 the Micro structure of the HS 6-5-2-5 and C60 joining zone: 1 – the carbide plane; 2 – the viscous layer; 3 – the HS 6-5-2-5 steel layer hard faced onto the C60 steel; 4 – the mixing zone; 5 – the dynamic recrystallization zone; 6 – BM (C60); 7 – the joint line; 8 – heat affected zone in the HS 6-5-2-5 steel [Ratković *et al.*, 2016a]



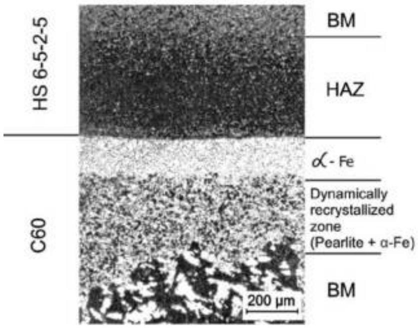
When, after a few fractions of a second up to several seconds, the quantity of the released heat is increased and the temperature is increased, the resistance to plastic deformation in the friction plane is reduced. The highest temperatures are reached in the thin material layers, while the friction coefficient is decreasing. The initiated diffusion processes are being intensified. The layer of metal in the viscous state is created in the friction plane, whose thickness is of the order of magnitude of several hundred parts of a millimeter (Sahin, 2005). The thickness of the viscous layer (Figures 2(a) and 3 – Position 2) depends on the friction regime. In this layer, one can find around 10 per cent of the carbide phase of the total amount of carbides [Handa and Chawla, 2013). With the extension of the friction time, the viscous layer is being freed of the carbide phases owing to carbides dissolving and depositing into the carbide plane. However, keeping in mind the specificity and complexity of the process, the phenomena related to creation and properties of the viscous layer are not completely investigated and explained, as well as the trajectories of the metal particles within it. The friction plane divides the viscous layer into two parts. The structure of the viscous layer is characterized by somewhat coarser crystal grains with respect to the neighboring layers, as well as by the lower content of the carbide phases. In the central portion of the sample, the viscous layer is created mainly parallel to the joint line, while in the sample's areas closer to the periphery, it is formed at a certain angle with respect to the joint line.

The mixing zone is created during the friction phase in the HS 6-5-2-5 steel layer hard faced onto the C60 steel. It has the shape of the spilled drop (Figures 2 and 3 – Position 4). Mixing of particles of both BMs occurs within this layer, as they are exposed to the complex motion between the two bars, one of which is rotating and the other is not. The mixing zone is characterized by inhomogeneity of the micro structure and chemical composition, what is a consequence of the heat and deformation conditions, which were present even in the initial phase of the friction welding. Investigations have shown that the mixing zone is spreading over the major portion of the sample's cross section when the friction time is the shortest, while for the welding with the friction time between 12 and 15 s, the diameter of this zone is significantly reduced (Handa and Chawla, 2013). The content of carbon in the mixing zone is increased owing to decarburization of the C60 steel layer immediately next to the joint (Figure 4 – bright ferrite areas).

Dynamic recrystallization zone

Considering that in the third phase of the friction welding process, a layer of the HS 6-5-2-5 steel, which is immediately next to the friction plane, is in the isothermal regime ($T > 1000°$), and that deformation occurring is of a high degree, the

Figure 4 Micro structure of the HS 6-5-2-5 and C60 mixing zone

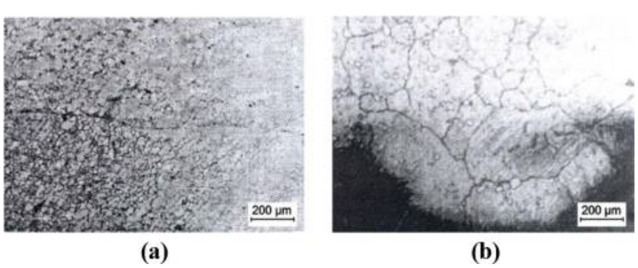


dynamic recrystallization process is immanent. The very beginning of this process is connected with the initial friction phase, and it continues throughout the following friction welding process and ends in the continuous cooling conditions. The zone of dynamically recrystallized grains is formed in conditions that are present next the friction plane in the central portion of the sample; it has the shape of the spilled drop (Figure 5) and it is characterized by the high plasticity conditions. Recovery of the structure by the dynamic recrystallization mechanism occurs, among others, owing to an additional condition, which is related to the action of the axial force during the friction phase and especially during the compacting phase. That leads to refinement of the metal grains, what results in the fine-grained structure (Figure 6 a).

Within the friction plane, the dynamic recrystallization process is unfolding until the end. However, in the boundary areas of the dynamic recrystallization zone, various sizes of grains appeared, as well as forming of the smaller grains (the

Figure 5 Highly plastic zone in the central portion of the sample (the spilled drop shape)

Figure 6 Micro structure: (a) dynamically recrystallized zone; (b) zone immediately next to the friction plane – forming of the sub-grains within the large austenitic grains (500×)



sub-grains), within the larger austenitic grain Figure 6(b). The sub-grains appear at the moment when the critical deformation degree is reached and they represent the first rim of the recrystallized grains.

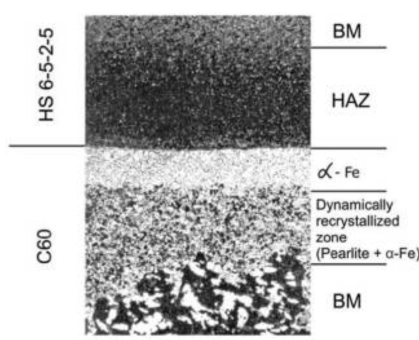
Investigation of certain number of samples has shown that the dynamic recrystallization happens somewhat less in the C60 steel than in the HS 6-5-2-5 steel, where the separated recrystallized layer can be clearly noticed. Analyses were also conducted to define and present the characteristic zones in the HAZ in both BMs. The dynamically recrystallized layer, whose structure is perlite-ferrite, is shown in Figure 7.

Carbides in the joining zone

During the friction phase, the adequate conditions for appearance of the carbide particles are realized. The carbide particles are thickening up and grouping into the lines that are forming the carbide layer, which can be continuous or uneven, i.e. discontinuous. The carbides are mainly oriented parallel to the friction plane, and the particles are obtaining the elongated form. It is also noticed that in samples, welded by friction with the shorter friction time, only a smaller portion of carbides have the elongated form, while the amount of elongated ones, parallel to the friction plane, increases with the increase in the friction time (e.g. up to 18 s). The carbides' dimensions are from 0.02 to 2.25 μm and they are mainly of the metal-carbon (MC) type (M = V, W, Mo). Diffusion of the carbon atoms from the carbon steel into the alloyed steel causes an increase of the carbon concentration within the friction plane. The products of the diffused carbon reaction with the carbide-forming elements (V, W, Mo) from the high-speed steel are the MC-type carbides and the carbon content increases.

The carbides' share in the carbide layer, created next to the friction plane, amounts to about 25 per cent, what is at the level of the share in the HS 6-5-2-5 steel and is significantly higher than in the other characteristic zones. In addition, it was established that the content of the carbide phase in the friction plane can be different, even for several times, from the content in the viscous layer, outside the friction plane, what depends on the size of particles. In the mixing zone of the two BMs, the dominant carbides particles are of size over 0.3 μm, while in the viscous layer, their size is 0.6 to 1.3 μm. The largest carbides appear in the mixing zone, where their size reaches 0.6 to 2.25 μm. It was noticed that the carbide particles in the HAZ of the HS 6-5-2-5 steel and in the mixing zone are significantly larger with respect to particles in the BM. The cause for such a phenomenon is

Figure 7 Perlite-ferrite recrystallized layer in C60 steel



Industrial Lubrication and Tribology
Volume 70 · Number 2 · 2018 · 401–407

dissolution of the smaller pieces in the solid solution during the friction welding process. In Figure 8 is given the presentation of the distribution and content of the carbide particles, expressed in percentage, in the characteristic zones of the welded joint in terms of the carbide particles size.

The larger carbides are separated and retained along the plane of friction, while the smaller carbide particles are moving into the viscous layer. The biggest share of the carbide phase is measured in the immediate vicinity of the HAZ of the high-speed steel.

Phase transformations during the welded samples annealing

When the high-speed steel is heated, the transformation of ferrite into austenite begins above the temperature of 800°C and it ends at about 900°C. With the increase of the austenitization temperature and extending the time of remaining in the two-phase austenitic-carbide region, a process of carbides' dissolution develops, as well as the diffusion of carbon and the alloying elements into the austenite. The rate of creation and growth of the austenite grains is varying with the temperature increase according to a certain law. The dissolution of the carbide particles occurs in the formed austenite. The smaller carbide particles, distributed along the grain boundaries, are the first to dissolve, what influences the growth of the austenite grain.

The effective rate of the austenite grain growth, during the heating within the temperature interval 0 to T_x, is defined by the following expression:

$$V_e = x/t = 4D_e \cdot T_x^2/k^2 \cdot x \tag{1}$$

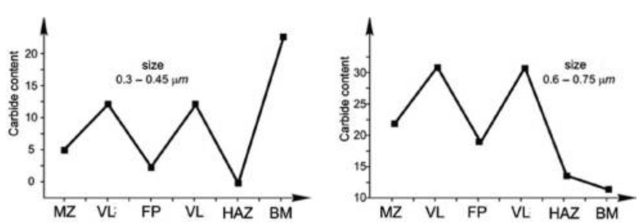
or, if the process was considered at a certain temperature T, by expression:

$$V = 4D \cdot T^2/k^2 \cdot x \tag{2}$$

where:

- t = is the time;
- D_e = is the effective diffusion coefficient of carbon in austenite;
- D = is the isothermal diffusion coefficient;
- T_x = is the temperature;
- x = is the distance at which the austenite front is progressing; and
- k = is the corresponding direction coefficient, which is determined from the Fe-Fe_3C state diagram.

Figure 8 Distribution of the different sizes carbide particles in the joint's characteristic zones



Notes: BM = base metals, HAZ = heat-affected zone, VL = viscous layer, FP = friction plane, MZ = mixing zone

The effective diffusion coefficient (D_e) constitutes one-third of the isothermal diffusion coefficient (D). That would practically means that for forming of one part of austenite at continuous heating within the temperature interval 0 to T a three times longer time period is needed than for the isothermal forming at a maximum temperature.

Unlike that, at equilibrium cooling of austenite to temperature A_{c1}, with smaller or bigger undercooling, austenite would become metastable, namely, it would be prone to transform faster into the stable structural phase. Practically, its free energy would fast become equal to free energy of the low-temperature phases (perlite and ferrite, namely, perlite and cementite).

The heat treatment – annealing, after the friction welding, is done for the purpose of reducing the hardness and eliminating the unfavorable structures in the joining zone. In the annealing process, owing to diffusion of carbon from the structural steel into the high-speed steel, a decarburized layer is created in the structural steel. It was established that in joints of these two steels, this process occurs within the temperature interval 550 to 800°C and that it is the most intensive at 750°C.

The soft ferrite layer, which lies between the two BMs of different yield stresses, behaves according to theory of small elastic deformations (Ratković *et al.*, 2009a); its structure is presented in Table II.

The ferrite at-the-contact layer, whose width and morphology depend on the annealing regime, has the lower hardness values than the rest of the sample; this is valid for both steels. The hardness distribution diagram along the joint is given in Figure 9. The hardness measurements on the welded samples were performed in the three directions: along the sample's axis and at radii of 2 mm and 6 mm. The friction time during this sample welding was 9 s.

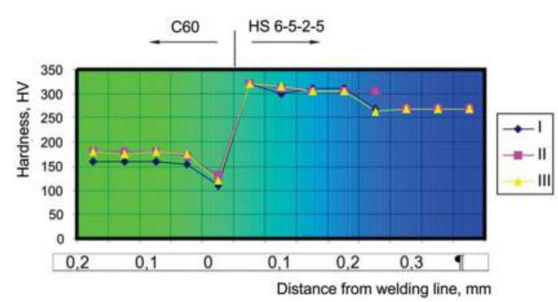
Annealing was done at 820°C for a period of 4 h, followed by cooling the furnace down to 500°C with further cooling in still air.

The carbon diffusion process is, in this case, considered as a harmful phenomenon, as it leads to the creation of large

Table II Content of carbides and the alloying elements in the α–solid solution of the HS 6-5-2-5 steel

Content of elements after annealing, (%)	Carbides	Cr	Mo	W	V
	22	3.3	0.6	0.3	0.2

Figure 9. Hardness distribution in the joint zone of the C60 and HS 6-5-2-5 steels for the three measurements directions: I – the sample's axis; II – r = 2 mm; III – r = 6 mm; friction time during the welding t_f = 9 s



carbides in the high-speed steel within the zone of width of 0.1 to 0.3 mm. The carbides' net is created in the mixing zone. Simultaneously with the carbon diffusion, a deeper diffusion of alloying elements occurs in the opposite direction, from the high-speed steel into the carbon steel. Those are the carbide-forming elements (Cr, Mo, W, V), which are reaching depths of several tents of microns.

Conclusions

The structure of the dissimilar steels joint, welded by friction, is heterogeneous, consisting of the following characteristic zones: viscous layer, carbide plane, high-speed steel layer "hard-faced" onto the carbon steel, mixing zone of the two BMs, the dynamic recrystallization zone and other zones – the heat affected zones and the BMs.

Based on authors' own micro-structural investigations and analysis of data from literature, it was established that the micro-constituents in the high-speed steel, hard faced onto the carbon steel during the friction phase are martensite, austenite and carbides. The carbides' content is lower than the BM content – the HS steel in the initial condition. The reason for that lies in the thermo-deformation conditions that appear during the friction welding, which influence the dissolution of one part of the carbide phase and its mixing with the BM. It is also established that the friction time significantly affects the carbide phase dissolution.

The austenite grain size is affected by several factors, through the friction process phase and the compacting phase during the welding. The very fine grain is the consequence of the high degree of the plastic deformation of the near-the-contact layers even in the friction phase.

The viscous layer, which is formed during the stable friction phase, is the area where the moving of matter occurs according to a very complex mechanism.

In the mixing zone, in the layer along the joint, the stability of austenite, retained after the cooling in the air, is higher than in the rest portion of the HAZ and in the BM. This layer does not represent a weak point, from the aspect of possible appearance of the brittle fracture during the exploitation of thus welded joints. However, in the machining by grinding, for instance, owing to the poor heat conductance of austenite, the tendency toward crack appearance is increased. That fact must not be neglected when the regime of the post-heat treatment of the friction welded samples is defined.

For the more complete and deeper analysis of all the phenomena appearing during the friction welding of the two dissimilar steels, one should need to create and adapt a mathematical model of the joints layers' motion, as well as of the carbide particles. This, however, exceeds the framework of this paper and should be considered as a topic for the future research.

References

Ambroziak, A., Korzeniowski, M., Kustron, P., Winnicki, M., Sokolowski, P. and Harapinska, E. (2014), "Friction welding of Aluminium and Aluminium alloys with steel", *Advances in Materials Science and Engineering*, Vol. 2014, pp. 15.

Ćirić, R. (2001), "Structural changes in the vicinity of the friction weld of steels", *Welding and Welded Structures*, Vols 1/2, pp. 31-36.

Handa, A. and Chawla, V. (2013), "Mechanical characterization of friction welded dissimilar steels at 1000 rpm", *Materials Engineering – Materiálové Inžinierstvo*, Vol. 20 No. 3, pp. 102-111.

Handa, A. and Chawla, V. (2014), "Friction welding - a review", *Machines Review*, Vol. 1 No. 2, pp. 34-38.

Kumar, R., Chattopadhyaya, S., Hloch, S., Krolczyk, G. and Legutko, S. (2016), "Wear characteristics and defects analysis of friction stir welded joint of Aluminium alloy 6061-T6", *Ekspolatacja i Niezawodnosc - Maintenance and Reliability*, Vol. 18 No. 1, pp. 128-135.

Li, W., Vairis, A., Preuss, M. and Ma, T. (2016), "Linear and rotary friction welding review", *International Materials Reviews*, Vol. 61 No. 2, pp. 71-100.

Liang, Z., Qin, G., Wang, L., Meng, X. and Li, F. (2015), "Microstructural characterization and mechanical properties of dissimilar friction welding of 1060 aluminum to AZ31B magnesium alloy", *Materials Science and Engineering*, Vol. 645, pp. 170-180.

Ma, H., Qin, G., Geng, P., Li, F., Fu, B. and Meng, X. (2015), "Microstructure characterization and properties of carbon steel to stainless steel dissimilar metal joint made by friction welding", *Materials and Design*, Vol. 86, pp. 587-597.

Nathan, S.R., Malarvizhi, S., Balasubramanian, V. and Rao, A.G. (2016), "Failure analysis of tungsten based tool materials used in friction stir welding of high strength low alloy steels", *Engineering Failure Analysis*, Vol. 66, pp. 88-98.

Ratković, N., Nikolić, R. and Samardžić, I. (2014), "Structural, chemical and deformation changes in friction welded joint of dissimilar steels", *Metallurgy*, Vol. 53, pp. 513-516.

Ratković, N., Arsić, D., Lazić, V., Nikolić, R. and Hadzima, B. (2016a), " The contact and compacting pressures influences on the plastic deformation parameters of the friction welded joint", *Materials Engineering - Materiálové inžinierstvo*, Vol. 23 No. 2, pp. 51-57.

Ratković, N., Arsić, D., Lazić, V., Nikolić, R.R. and Hadzima, B. (2016b), "Micro-structure in the joint friction plane in friction welding of dissimilar steels", *Procedia Engineering*, Vol. 149, pp. 414-420.

Ratković, N., Sedmak, A., Jovanović, M., Lazić, V., Nikolić, R. and Krstić, B. (2009a), "Quality analysis of al-cu joint realized by friction welding", *Technical Gazette*, Vol. 16 No. 3, pp. 3-7.

Ratković, N., Sedmak, A., Jovanović, M., Lazić, V., Nikolić, R. and Krstić, B. (2009b), "Physical and metallurgic changes during the friction welding of high-speed cutting steel and tempered steel", *Technical Gazette*, Vol. 16 No. 3, pp. 27-31.

Ratković, N., Arsić, D., Lazić, V., Nikolić, R., Hadzima, B., Palček, P. and Sedmak, A. (2017), " Influence of friction welding parameters on properties of the al-cu joint", *FME Transactions*, Vol. 45 No. 1, pp. 165-171.

Sahin, M. (2005), "Joining with friction welding of high-speed steel and medium-carbon steel", *Journal of Materials Processing Technology*, Vol. 168 No. 2, pp. 202-210.

Samuthiram, G., Kannan, T.T.M., Sureshkumar, M., Natarajan Ananda, V. and Vijayakumar, P. (2014), "Evaluation of mechanical properties of friction welded joints of EN-24 steel cylindrical rods", *International Journal of Mechanical Engineering & Robotics Research*, Vol. 3 No. 4, pp. 417-421.

Savić, B., Marković, S. and Ćirić, R. (2008), "Physical model of the friction welded joint of different types of steel", *FME Transactions*, Vol. 36 No. 2, pp. 93-97.

Shete, N. and Deoka, S.U. (2017), "A review paper on rotary friction welding", *International Conference on Ideas, Impact and Innovation in Mechanical Engineering (ICIIIME 2017)*, Vol. 5 No. 6, pp. 1557-1560.

Veljić, D., Sedmak, A., Rakin, M., Radović, N., Popović, N., Dascau, H. and Bajić, N. (2015), "Advantages of friction stir welding over welding with respect to health and environmental protection and work safety", *Structural Integrity and Life*, Vol. 15 No. 2, pp. 111-116.

Further reading

Todić, A., Čikara, D., Todić, T., Pejović, B., Čamagić, I. and Vukojević, V. (2017), "The influence of the vanadium content on the toughness and hardness of wear resistant high-alloyed Cr-Mo steel", *FME Transactions*, Vol. 45 No. 1, pp. 130-134.

Xua, Z., Lu, P. and Shu, Y. (2016), "Microstructure and fracture mechanism of a flash butt welded 380CL steel", *Engineering Failure Analysis*, Vol. 62, pp. 199-207.

Corresponding author

Dušan Arsić can be contacted at: dusan.arsic@fink.rs