Physical Model of the Friction Welded Joint of Different Types of Steel

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The paper comprises the phenomena encountered in the friction rotation welding process with a continual drive of different types of steel. The rotation friction welding with a continual drive of the HSS steel M2 was carried out with carbon steel 1060. Characterization of the phenomena, taking place within the welded joint over the friction phase was determined through direct measurement, made of the temperature cycles followed by examining the structure and analytical procedure. Thorough studies enabled setting up of the model of the friction welded joint of different types of steel with characteristic zones.

Keywords: *HSS steel, carbon steel, friction welding, microstructure, model.*

1. INTRODUCTION

The process of rotation friction welding with continuous drive (FW) is carried out through the following five phases: (i) initial friction, (ii) unstable friction, (iii) stable friction, i.e. quasi-stationary phase, (iv) breaking and (v) pressing-upsetting [1,2]. The phase of stable friction (phase III) begins when the layer of considerable plasticity and small strength is spread along the whole friction plane. Plastic deformation in this phase is characterized by transition from plastic deformation to the deformation of thin layers of base metals (BM). It is considered that in this phase the heat exchange is established, which is characterized by the dynamic heat balance between the extend heat and the heat which is transferred to BM and the environment [3-5].

However, close to friction plane, the viscous layer of metal is formed, and its shape, size and the path of flow of metal particles layers, either qualitatively or quantitatively have not been described yet [6-8].

The purpose of this study is to establish a model of the friction welded joint of these steels with characteristic zones in the third phase of FW process, on the basis of analysis of the flowing of the matter and the distribution of carbide phase in friction plane area.

2. EXPERIMENT

2.1 Material and experimental data

HSS Steels M2 and carbon heat treatable steel 1060 (the bars of 10 mm in diameter), Table 1, were welded by the procedure of rotation friction welding with continuous drive (FW). The basic parameters of FW process in the phase of friction are: friction pressure P_f [MPa], friction time V_f [s] and the number of revolutions n (in the experiment n = const = 2850 min^{-1}). The parameters in the phase of upsetting are the pressure P_u [MPa] and time V_u [s]. Only the sample of steel M2 was rotated. Variable parameters in the experiment were P_f, V_f and P_u.

Quantitative and qualitative analysis of layers in the friction plane, high plasticity zone and in the viscous layer was carried out on the experimental samples.

Processes occurring in the viscous layer and neighbouring zones were investigated during experiments by the optical, quantitative optical microscopy and electron microscopy as well as by the analysis of rheological appearances [9].

3. RESULTS AND DISCUSSION

3.1 The shape of the flowing of matter in friction plane area

Detailed analysis of microstructure and phase composition of the welded joint, particularly the viscous layer and viscoplastic layer was performed by the optical and quantitative optical microscopy and electron microscopy. The analysis covers mostly by phenomena occurring in phase III of the FW process.

As reported in studies [7,8] and according to the authors' investigation result, a viscous metal layer is formed in phase III of the FW process.

Electron microscopy (JEOL microscope JSM 5300, Japan) revealed the friction plane and the viscous layer formed in the third (III) phase of friction.

The viscous layer is formed on both sides of the friction plane. In that layer, the displacement of the viscous mass of metal and of the solid carbide particles occur, according to the mechanism of the rotational, both luminary or local turbulent flow, Fig. 1.

This complex current circuit falls into the class of multi phase (multi-component) flows of non-Newton fluids, which have not still been investigated enough, so that the results obtained cannot not be compared with the data from the literature.

Regarding the mechanism of flowing, it is obvious that during the process of rotational FW steel M2 with 1060 the dominant shape of the flowing of matter is laminar. Also, in the first and the second phase of friction, the secondary flow occur (transition of laminar into turbulent movement, formation of whirls of different dimensions and structures, twirl-like flowing with recirculating zones), Fig. 2.

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Table 1. Chemical compositions and hardness of basic materials M2 and 1060 in agreement to AISI

Steel	Content of elements, wt. %									Hardness, HB 2.5/62.5/20	State
	C	Si	Mn	Cr	W	Mo	V	S	P		
M2	0.86	–	–	4.07	6.03	4.75	1.82	0.0036	0.0137	260 – 272	Soft annealed
1060	0.63	0.194	0.82	0.0036	0.00273	–	–	–	–	–	

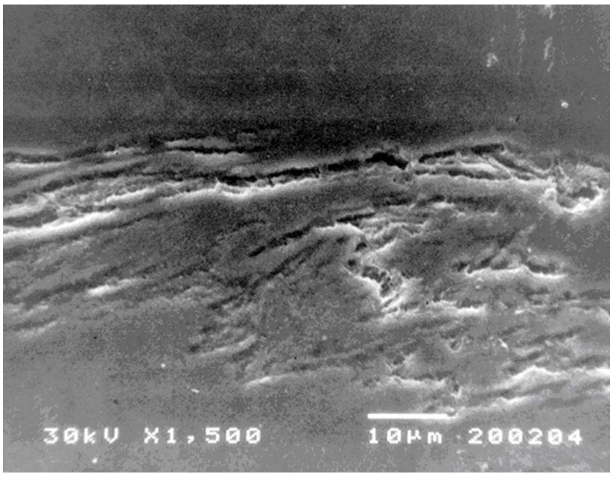


Figure 1. Local turbulent flow in friction plane area during the FW process of steel M2 with 1060; SEM, 1500X

According to Figure 2a, the influence of friction time V_f on the shape of the joint line (shape of the flowing of matter) depends greatly on thermal-deformation conditions realized during the FW process. During short friction times ($V_f \approx 1$ s), the transferred parts of both metals (BM) are heated at lower temperatures and they are deformed with a smaller degree of deformation. Along with rising of V_f, temperature rises too, and the deformation of contact layers is bigger. When friction times are sufficiently long ($V_f \approx 13$ s), contact layers are in highly plastic and viscous state, so the process of deformation is reduced to the deformation of thin surface layers.

According to Figure 2a, the shape of the secondary flows (mixing of particles of both BMs) in friction plane area is the following: when V_f is shorter, besides the dominating laminar flowing, the secondary turbulent flows appear, as well as whirl. When V_f is longer, the flowing of the highly plastic and viscous metal is laminar.

3.2 Distribution of carbide phase in friction area

On the basis of the analysis of microstructure, it was determined that the process of deformation of metal in the third phase of friction ($V_h \approx 13$ s) is characterized by transition from the plastic deformation along bigger depth onto the deformation of thin surface layers BM.

Content, size and location of carbide particles affect the character of the process in the characteristic zones and vice versa. Thus, non-dissolved carbides, i.e. solid particles in solid-liquid metal (viscous layer) and in high-plasticity zones (outside the layer), may have a substantial effect on the character of metal displacement, Fig. 3. At the same time, thermal-deformation conditions have a substantial effect on the dissolution phenomena and mechanical fractures of the carbide phase, etc. These occurrences cause changing of the shape and size of carbide phase.

The volume content of non-dissolved carbide particles after FW without upsetting was measured at a distance of 1 mm from the rotational axis in the viscous layer, zone of mixing of both BM, HAZ metal in steel M2 and in steel 1060 outside the HAZ. The mean

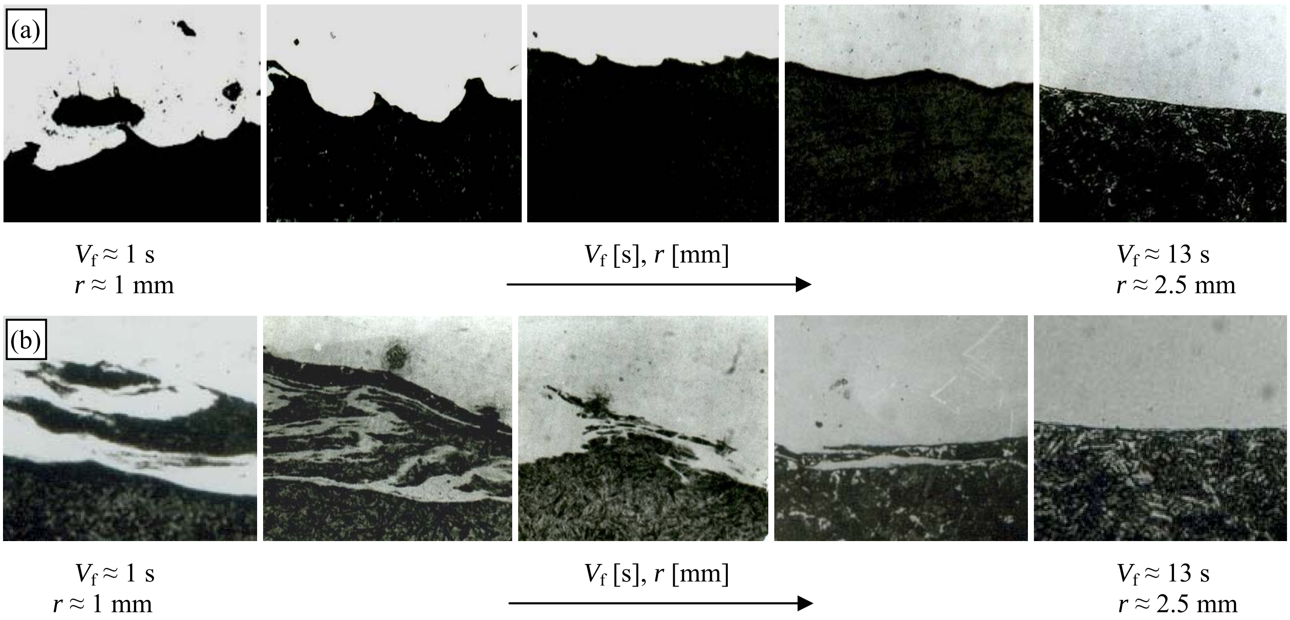


Figure 2. The shape of the line of joint steel M2 with 1060 (a) and characteristic shapes of mixing of particles of both BMs, magnification 50X (b) in the function axial distance from time of friction plane and radial distance from the rotation axis; M2 (light spots), 1060 (dark spots). Regime FW: $P_f = 80$ MPa, $n = 2850$ min^{-1}, FW without upsetting and after that cooled in the air, magnification 500X

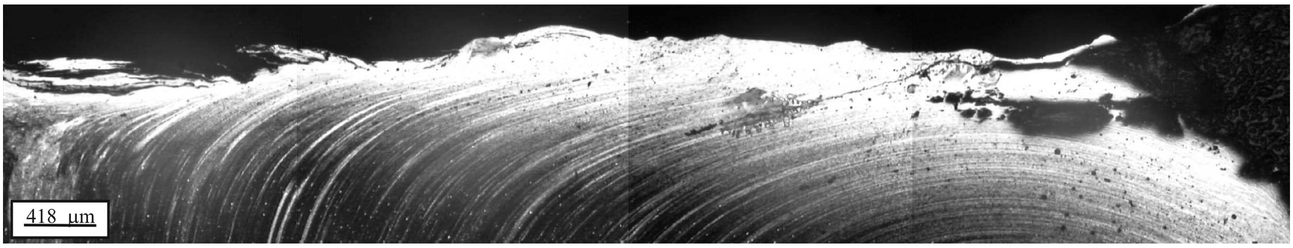


Figure 3. Displacement of the carbide phase in the joint area in the steel M2

Table 2. Volume content and the average size of the carbide particles in the area of FW joint between steel M2 and steel 1060

Zone	Content of non-dissolved carbides [vol. %]	Mean average of carbide particles [mm]
Friction plane	24.05	0.93829
Viscous layer (outside friction plane)	5.70	0.63780
Zone of mixing of both BM	9.38	0.97125
HAZ in steel M2	10.43	0.91381
Steel M2	26.90	0.63597

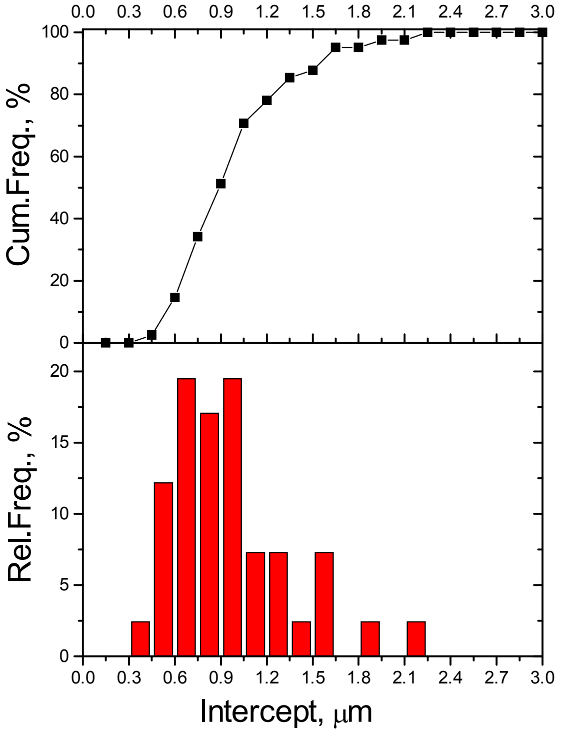


Figure 4. Function and histogram (probability) of carbide particles distribution per sizes in the friction plane

measured content of the carbide phase and average size of the carbide particles in characteristic zones are given in Table 2. The probability density of size distribution on the carbide particles in the friction plane is shown in Figure 4.

In literature [9] the adapted physical-mathematical model was established, which explains the movement of carbide particles in viscous environment.

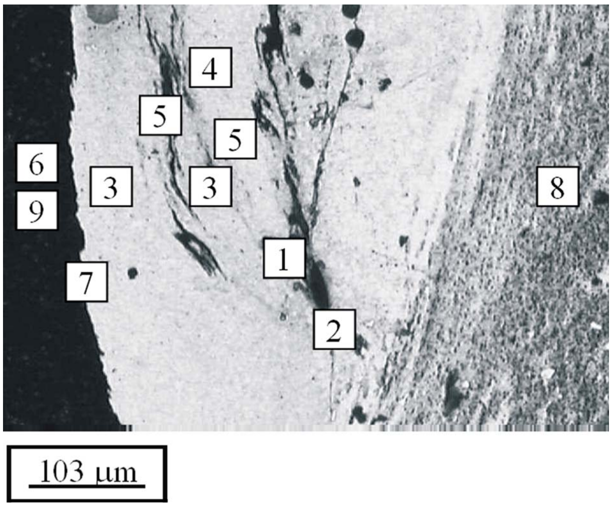
The measurement was carried out by linear method on the automatic device for the analysis of the picture “Quantimet 500 MC” manufactured by the Leica company, with the help of the optical microscope.

According to Table 2 the lowest share by volume of carbides is measured in the viscous layer out of the friction plain (5.70 %). The volume share of carbides in the carbide layer itself which is formed along the friction plane is 24.05 %; it is almost at the level of share in M2 and it is considerably higher than in other characteristic zones.

The phenomenon of appearance of significant differences in the concentration of carbide phase in the characteristic zones in steel M2 in the area of friction plane can be explained by the analysis of the field of tension of pressure and in the viscous metal immediately near the friction plane.

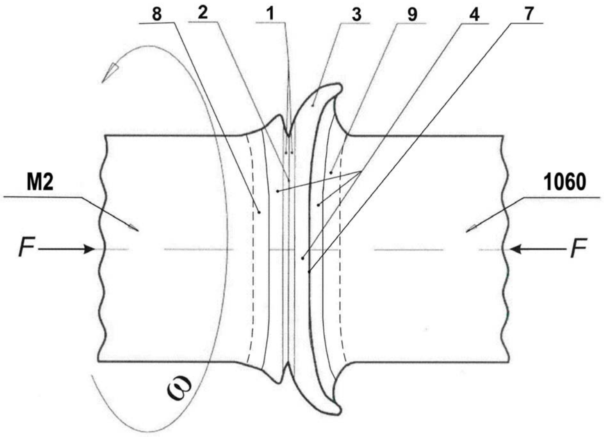
3.3 Physical model of the friction welded joint of HSS steel and carbon steel

Based on detailed microstructure investigation, the physical model of the friction welded joint of HSS steel and carbon steel with characteristic zones was established, Fig. 6. Microstructure in the area of welded joint is presented in Figure 5, and the microstructures of metal in the characteristic zones in Figures 6-10 in the third phase of FW process.



1 – Viscous layer; 2 – Carbide layer; 3 – Layer M2 surfaced onto 1060; 4 – Viscoplastic layer; 5 – Particles of steel 1060 in M2; 6 – Steel 1060; 7 – Line of joint; 8 – HAZ in M2; 9 – HAZ in 1060

Figure 5. The microphotograph of the characteristic zones of the vicinity of the friction plane in third friction phase of the process FW of M2 with 1060



1 – Viscous layer (Fig. 7); 2 – Carbide layer (Fig. 8); 3 – Layer M2 surfaced onto 1060 (Fig. 9); 4 – Viscoplastic layer (Fig. 10); 7 – Line of joint; 8 – HAZ in M2; 9 – HAZ in 1060

Figure 6. The model of the FW joint HSS steel and carbon steel with the characteristic zones in the vicinity of the friction planes in the third friction phase of the process FW

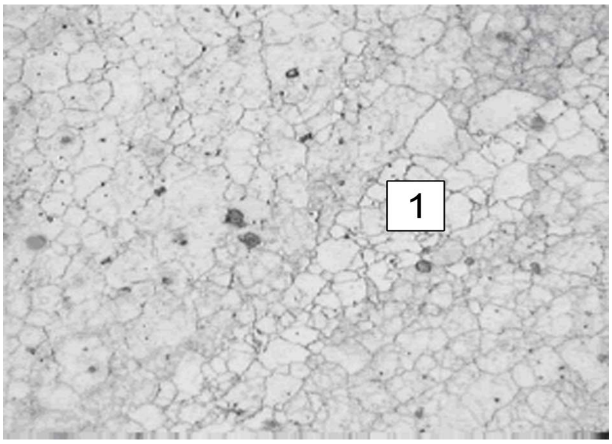


Figure 7. Viscous layer

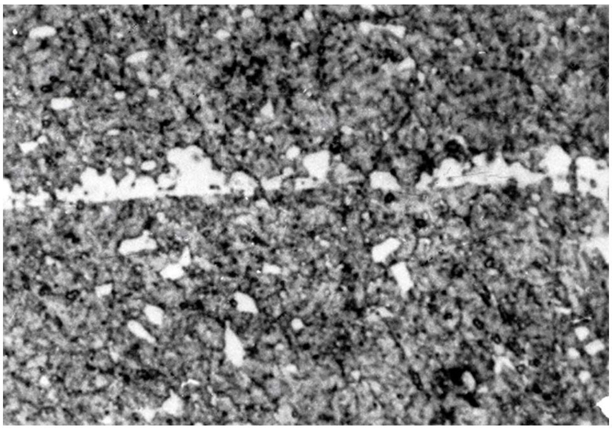


Figure 8. Carbide layer

Viscous layer 1 in Figures 5 and 6 is formed in the third phase of FW immediately near the friction plane. In the friction phase, the matter in this zone is a suspension of the viscous solution of steel M2 and solid carbide particles [9]. After cooling, the content of the undissolved carbides in this layer is lower in relation to the adjoining zones, Fig. 7.

During the FW process, carbide layer is formed on the front of the rotational steel bar M2. On the longitudinal cross-section, the layer is seen in the shape of the line of carbides, Fig. 8. The content of carbide in this layer is significantly higher in relation to the adjoining zones. The phenomenon of forming of this layer is explained in literature [9] on the basis of the analysis of rheological occurrences.

Figure 9. Layer M2 surfaced onto 1060

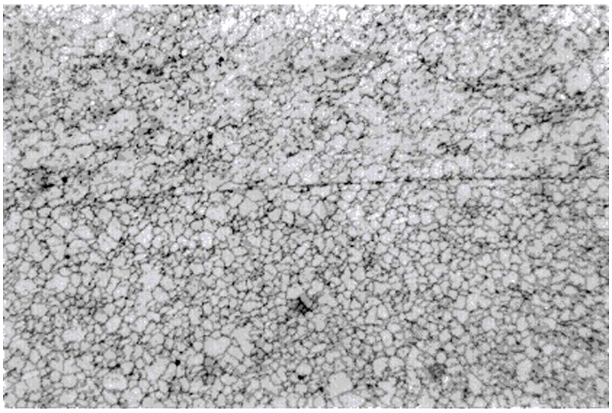


Figure 10. Viscoplastic layer

Due to the difference in thermal-physical properties between BMs at the very beginning of the friction process, the steel M2 is surfaced onto the 1060, Fig. 9. The result of this is that the friction plane is moved into M2 (friction is done between the two layers of steel M2).

Viscoplastic layer is most frequently formed in layer M2 surfaced onto 1060. During the friction phase, this zone is heated at the temperatures higher than those of the standard plastic deformation. In this layer, the thermal-deformation conditions necessary for the realization of the process of dynamic recrystallization and obtaining of a very tiny grain, Fig. 10, are reached.

The mixing zone of particles of both BMs, 5 in Figure 5, is formed in the first and second friction phase. Along with the prolonging of V_f, this undesirable zone is most frequently extruded out of the friction plane. Characteristic shapes of the mixing of particles of both BMs are given in Figure 2.

The areas 8 and 9 in Figures 5 and 6 represent the heat-affected zones (HAZ) in steels M2 and 1060.

4. CONCLUSIONS

- On the basis of the tests performed, the physical model of the friction-welded layer with characteristic zones is established (viscous layer, friction plane, carbide plane, surfaced layer, viscoplastic layer, mixing zone, other zones – HAZ, BMs).

- The properties of the characteristic zones are considerably different regarding composition, structure and properties, and they have high influence on the properties of the welded joint. Out of the above mentioned zones, the biggest volumes share of carbide phase was measured in carbide plane (24.05 %) and the lowest in viscous layer, outside of the friction plane (5.70 %).
- The forming of the above mentioned zones is the consequence of the thermal-deformation conditions applied during FW process. During FW process, some phases move along complex trajectories, first of all, within the friction plane, viscous and viscoplastic layer and carbide plane. These processes are done parallel to the numerous metallurgical changes in both BMs (dissolving, mechanical breaking, plastic deformation and recrystallization, phase transformations, diffusion, etc).
- The biggest differences in properties were determined within the area of viscous layer and carbide plane. Moving of matter in viscous layer, which is a suspension of the solution of steel M2 and carbide particles, is a consequence of the differences in the field of velocity and tension. Because of that, and also due to the differences in physical properties of certain phases, delayering of phases along the characteristic zones occurs.

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ФИЗИЧКИ МОДЕЛ ПРОЦЕСА ЗАВАРИВАЊА ТРЕЊЕМ РАЗЛИЧИТИХ ВРСТА ЧЕЛИКА

Биљана Савић, Светислав Марковић, Радован Ћирић

У раду се истражују феномени који се појављују у процесу ротационог заваривања трењем са континуалним погоном различитих типова челика.

Ротационим заваривањем трењем заварен је челик Č7680 са угљеничним челиком Č1730. Карактеристични феномени до којих долази у фази трења у области равни трења утврђени су директним мерењем фазног састава, температурних циклуса, анализом микроструктуре и аналитичким поступком.

На основу укупних истраживања постављен је модел трењем завареног споја различитих типова челика са карактеристичним зонама.