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PHYSICAL AND METALLURGIC CHANGES DURING THE FRICTION WELDING OF HIGH-SPEED CUTTING STEEL AND TEMPERED STEEL

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Original scientific paper

This paper outlines the basic principles of welding by friction of high-speed cutting steel and tempered steel from the viewpoint of metallurgic processes that are going on in the material. The bases of welding by friction of different materials are outlined in a theoretical way. The experimental part of the paper also relates to friction welding of samples made of different metals: high-speed cutting steel (HS 6-5-2-5) on one hand and the tempered steel (C60) on the other.

Key words: *friction welding, base metal, friction phases, diffusion, joint line, friction time*

Fizikalne i metalurške promjene tijekom zavarivanja trenjem brzoreznog i kaljenog čelika

Izvorni znanstveni članak

Ovaj rad daje osnovne principe zavarivanja trenjem brzoreznog čelika i kaljenog čelika s motrišta metalurškog procesa koji se odvija u materijalu. Osnove zavarivanja trenjem različitih materijala navedene su teorijski. Eksperimentalni dio rada odnosi se na zavarivanje trenjem uzoraka izrađenih od različitih metala: brzoreznog čelika (HS 6-5-2-5) s jedne i kaljenog čelika (C60) s druge strane.

Ključne riječi: *zavarivanje trenjem, osnovni metal, faze trenja, difuzija, linija šava, vrijeme trenja*

1
Uvod
Introduction

Friction welding falls under procedures of joining metals in solid state. The joint is realized by action of a pressure force on contact area, converted into plastic state. Concentrated separation of friction heat and plastic deformation of joints next to the line of contact are the basis of friction welding process. Physical essence of this process is based on transformation of mechanical into thermal energy.

One of the first applications of welding was manufacturing of cutting tools, in a way that high-speed cutting steel and tempered steel were mutually welded. Resistance properties of these steels significantly differ in hot state, because during the hot face contact a certain penetration of high-speed cutting steel into tempered steel occurs. Their thermo-physical properties also differ. Therefore it is necessary to determine welding parameters so as to overcome great differences in thermal stability of these two steels.

2
Basic phases of friction welding process
Osnovne faze procesa zavarivanja trenjem

During the friction welding with continuous drive, energy gets released in the friction area by rotation of one welded part while the other welded part stands still. Adhesion joints are formed in the most protuberant points of contact by molecular and mechanical action on contact surfaces at the very beginning of the process. Adhesion bonds are stronger than the base metal so shearing will occur at the small distance from the contact surface; then comes the separation and transfer of particles from one base metal to the other.

Friction welding process consists of the following phases (Figure 1):

1 Establishing of contact
2 Phase of the initial instable friction
3 Phase of stable friction
4 Phase of braking and compression.

The initial friction phase occurs at the very beginning of the friction process and lasts until the friction force reaches the first maximum. Occurrence of the first maximum can be explained by hydrodynamic phenomena in the contact layer. By interaction of metal particles, which rotate at the speed that is approximately equal to the half of angular speed of the welded parts, the hydrodynamic lubrication occurs, accompanied by the maximum friction moment.

Particles of both base metals get mixed in the second phase. In a very narrow area, several micrometers wide, in the area of increased temperatures, the diffusion redistribution of particular alloying elements occurs. Significant plastic deformation can occur in this phase on both base metals because they become softened at high temperature.

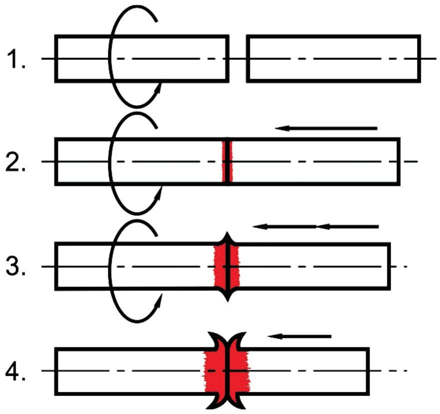

Figure 1 *Basic phases of friction welding process*
Slika 1. *Osnovne faze procesa zavarivanja trenjem*

The order of magnitude of the second phase duration ranges from several tenths of a second to several seconds, which depends on base metal properties and welding mode. This phase is regarded as complete when the process reaches the quasi-steady state. Then follows the third phase

– the phase of stable friction. Plastic deformation in this phase no longer rises by depth, but laterally in thin surface layers. The equilibrium exchange of heat between the quantity of developed heat and heat conducted by convection into base metal is established in this phase. Maximum temperatures are reached in the friction plane, which leads to the reduction of the friction factor. High-plastic metal moves according to the mechanism of rotational turbulent flow. In the third phase, the initialized diffusion processes are further intensified.

The final step of the friction phase represents the phase four and that is the time of braking. Character, shape and size of plastic deformation change in this phase, and all this due to the abrupt reduction of the friction rate. The quantity of the released heat also decreases. The friction moment increases and reaches its second maximum, and then it drops to zero.

The last phase of friction welding process is compression. There is no rotation of the welded parts in this phase because it is stopped by braking. The movement of metal layers in axial and radial direction occurs, together with developing the minor heat quantity. Bearing in mind that welded parts are moved closer to the distance of the order of magnitude of crystal lattice parameters, metal bonds will be formed between base metals, that is the common crystal lattices.

3
Diffusion processes and structural changes during the friction welding
Difuzijski procesi i promjene u strukturi tijekom zavarivanja trenjem

Mutual facing of the two cylindrical parts, one of which rotates, and the second one is steady, leads to very complex changes in material close to the contact area. The contact itself is realized on the outpost surface peaks, thus the high specific pressures of the order of magnitude (0,1 – 0,2 of theoretical material strength) occur at these points of effective contact. Although these pressures last shortly (approximate duration is 10^{-6} s), their action leaves multiple consequences.

Namely, they cause deformation of elements on macro- and micro level. Therefore, geometrical properties of the contact change both in shape and size. The initial roughness and waviness decrease, and the initial smooth surfaces become rough. Parts of material separate from the base metal and topography of the contact appears which is completely different from the initial one. This process lasts for a certain period of time until one stable contact surface has been formed, the so-called "operating roughness".

Action of high specific pressures causes thermal-deformation processes, which cause activation of line and point defects. Due to the increase of atom potential energy, new vacancies occur. The density of dislocations significantly increases. Both dislocations and vacancies do not surface, but concentrate below the surface and form micro cracks that affect separation of metal particles in friction process.

A very important and expressed phenomenon during friction welding is the diffusion. Diffusion relocation of alloying elements is directed toward surface layer of the material. The rate and flow of the diffusion process are, apart from temperature, affected by many other factors such as crystal structure of coupled metals, nature and concentration of diffusion element, number of line and other defects, etc. Diffusion causes minor or major chemical and physical changes of material. In the vicinity of the contact surface, in dislocation zones, areas of metal discontinuity or change of the crystal structure, diffusion processes change. All the structural imperfections reduce activation energy, which contributes to acceleration of the diffusion process. For example, along the grain boundaries diffusion activation energy is approximately twice smaller than inside the grain. Those are why diffusion processes in inter-phases, as well as on inter-crystalline surfaces, develop at the higher speed than inside the grain. The existence of dislocations per se also means proportionally larger "reservoir" for relocation of atoms, which reduces energy of activation, so the diffusion can start at somewhat lower temperatures. In the near vicinity of dislocations, it is possible to have continuous appearance of vacancies, what accelerates the diffusion process. The diffusion rate along the dislocation line depends on the size of Burgers vector.

In the friction contact, due to the increased state of stress and intensive plastic deformation, multiple increases in the density of line and point defects occur, thus the diffusion process is more intense on the slip planes and grain boundaries, i.e., at the points where conservation of energy of residual elastic strain is more prominent.

With the complex strains, it has been established that there is a natural tendency that atoms with larger diameter are relocated to the area of the tensile stress, and atoms with smaller diameter to the area of compressive stress [1].

The structure of the metal layer surface in the friction conditions is exposed to different effects that lead to the change of basic parameters of the crystal lattice. It has been established that during the friction welding the diffusion of alloying elements (W, Co, Cr) occurs from the high-speed cutting steel into the carbon steel up to the depth of approximately 5 μm [2], as well as to the diffusion of carbon in the opposite direction.

All these changes and processes in contact area and wider, unambiguously point out to the very complex mechanism of the friction process flow and joining of different base metals.

4
Area of contacts and area of base metals mixing
Područje dodira i područje miješanja osnovnog metala

Since the coupled pair, high-speed cutting steel on one hand and tempered steel on the other, are materials of different thermal conductivities, as well as of the different strengths ($R_{0,2}$, R_m), an uneven joint line may be formed in the friction phase. In areas where high-speed cutting steel sharply and deeply penetrates into the tempered steel, there is the danger of appearance of faults of incomplete penetration type. That is why the friction welding parameters must be selected within the optimal limits to realize sufficient mutual plastic deformation, bearing in mind that yield stresses of coupled steels significantly differ.

In the friction phase on the joint line the transition layer is formed because the base metals mix with each other. Since the incomplete penetration of microscopic proportions may occur, as well as physical and chemical nonuniformity, mechanical properties of the welded joint can be lower than those of the weaker base metal. They get increasingly deteriorated with the increasing thickness of

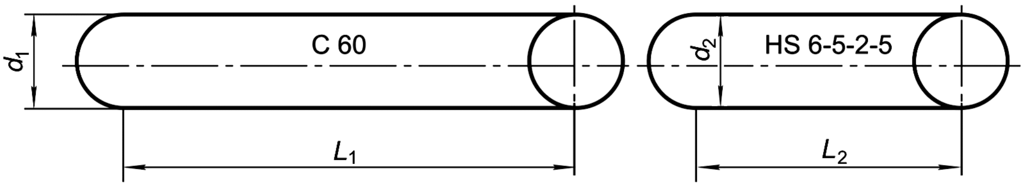

Figure 2 *Sample – pair for trial friction welding*
Slika 2. *Par uzoraka za proces zavarivanja trenjem*

Table 1 *Chemical composition, %*
Tablica 1. *Kemijski sastav, %*

HS 6-5-2-5	C	Si	Mn	Cr	Mo	V	W	Co	P	S
	0,82	0,45	0,40	4,00	5,00	1,90	6,50	5,50	0,035	0,035

the transition layer.

In the friction phase [3] the surfaced layer of high-speed steel (10-200 μm) is formed over the tempered steel, thus this micro layer becomes the "high-speed cutting steel". At the same time, the share and dispersion of carbide phases increase, the polishing of facing surfaces occurs. The transition layer achieves the biggest thickness at the end of the second phase of the friction welding process. In the third phase, the thickness of the same layer decreases because of its drawing down and extrusion outside the joint (into the rim of the extruded metal).

Carbide areas mostly occur in the central part of the sample, in areas with diameter of 0,5-3 mm.

In the area of carbide fields, the structure consists of martensite 0,5-0,55 % C, then 40 % and more of residual austenite and carbide, most often interstitial vanadium carbide. Because of high temperatures and intense plastic deformation, the special carbides dissolve in austenite. However, there is also a possibility of separation of special carbides, rich with carbon, in areas close to the contact line and not only in the area of carbide fields, due to the increased diffusion of carbon caused by large plastic deformation.

During the friction welding, thermal cycle is characterized by very fast heating above the A_{C1} point, very short stay in interval ranging from A_{C1} to A_{C3}, fast cooling. After cooling in the air, the microstructure of the high-speed cutting steel immediately next to the joint is mostly of the martensite type.

The heat developed because of the friction is mostly brought into the base metal, while the slight portion of the heat is released into the environment. Also, the major portion of the heat is brought into C60 due to its higher thermal conductivity and higher degree of plastic deformation. That is why the width of HAZ of this steel is larger. Opposite to this, in the contact area of the high-speed cutting steel the higher concentration of heat occurs and therefore the higher temperatures are than it is the case with tempered steel. Therefore, HAZ of the high-speed steel will be narrower.

4
The experiment
Pokus

The preliminary tests in this paper refer to the friction welding of cylindrically shaped samples, made of the high-speed cutting steel (HS6-5-2-5) and tempered steel (C60) (Figure 2).

5.1
Basic data on the material
Osnovni podaci o materijalu

The high-speed cutting steel (HS 6-5-2-5) is molybdenum steel of a special type. It is applied for high-strained tools for machining, intended for high cutting speeds, larger cross sections of shavings; these are milling cutters, spiral twist drills, taps, dies etc.

The declared chemical composition of this high-alloyed steel is given in Table 1.

Carbon steel (C60) has guaranteed chemical composition and it is intended for tempering. Out of all unalloyed steels for tempering, it has the best hardenability. It is highly resistant to wear. It has small resistance to electrochemical and chemical corrosion, but it is regarded as non-weldable by the welding procedures by melting (MMA, GMAW, GTAW).

It is applied for parts in automotive industry, general machine-building industry, for example for shafts, axles, parts of some tools, etc.

Steel C60 has the nominal chemical composition given in Table 2. Welding of the test samples made of the high-speed cutting steel on one hand and high-carbon steel on the other was performed on the machine, type MZT 30-2 NC with digital control (Figure 3).

Table 2 *Chemical composition, %*
Tablica 2. *Kemijski sastav, %*

C60	C	Si	Mn	P
	0,63	0,19	0,82	0,045

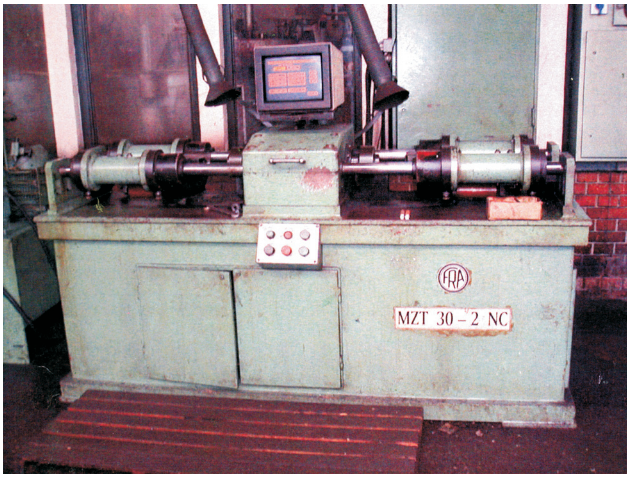

Figure 3 *Friction welding machine*
Slika 3*. Stroj za zavarivanje trenjem*

***Table 3** Results of measuring the initial and final dimensions of samples welded by friction*
***Tablica 3.** Rezultati mjerenja početnih i konačnih izmjera uzoraka zavarenih trenjem*

Time	t, s		3	6	9	12	15	18
Length	L_1, mm	C60	80,5	80	79	76,2	76,1	75,3
Length	L_2, mm	HS 6-5-2-5	44,4	44	42,9	42,6	41,8	41
Total length	L, mm		124,9	124	121,9	118,8	117,9	116,9
Shortening	ΔL_1, mm	C60	0,1	0,4	1,6	4,4	4,5	5,3
Shortening	ΔL_2, mm	HS 6-5-2-5	0,1	0,5	1,6	1,9	2,7	2,9
Total shortening	ΔL, mm		0,2	0,9	3,2	6,3	7,2	8,2
Diameter at the joint	d_1, mm	C60	18	19,2	22,7	26,4	26,6	28,5
Diameter at the joint	d_2, mm	HS 6-5-2-5	16,8	17,7	20,6	22,2	23	24
Diameter increment	Δd_1 mm	C60	2	3,2	6,7	10,4	10,6	12,5
Diameter increment	Δd_2, mm	HS 6-5-2-5	0,3	1,2	4,1	5,7	6,5	7,4

5.2
Process parameters
Parametri procesa

The following parameters were applied during experiment:

- Number of revolutions n = 2400 rpm,
- Welding time t = (3-18) s,
- Friction pressure p_t = 80 MPa,
- Compression pressure p_s = 210 MPa.

The friction time is the main parameter that mostly affects the quality of the joint. It was varied during experiment from 3 to 18 s. That variation influences the shape of the joint line and the macro- and micro structure of the joint zone. The most favorable shapes of the joint line and the best mixing of base metals occur during friction ranging from 10,5 to 15 s (narrow tole). Pressures of friction and compression affect both the friction process itself and the result of welding. At lower friction pressure (70 MPa), with prolonged time (15 s), one achieves better extrusion of softened metal and carbide outside the joint, which cannot happen during friction pressure of 110 MPa. Similarly, at this pressure the shape of the joint line is quite uneven due to greater extrusion of layers heated up to high temperatures and uneven plastic deformation of roughness on the contact surfaces.

Macroscopic view of the welded joint cross section (high-speed cutting steel and C60) obtained for the friction time of 9 s and the friction pressure of p_t = 80 MPa, compression pressure of p_s = 210 MPa is shown in Figure 4.

5.3
Plastic deformation during the friction welding
Plastična deformacija tijekom zavarivanja trenjem

One of the objectives of these tests was determining the effect of the friction time and compression on dimensional change of samples welded by friction.

Results of dimensional measurements are given in Table 3, and they refer to friction pressure of 80 MPa and compression pressure of 210 MPa. The initial measuring length of elements made of C60 was L_1 = 80 mm, and diameter d_1=16 mm, while for the element made of HS 6-5-2-5, those dimensions were L_2 = 44,5 mm, d_2 = 16,5 mm.

Figure 5 shows the graphic view of sample length shortening (a) and graphic view of diameter increase (d_s) (b) as functions of the friction time.

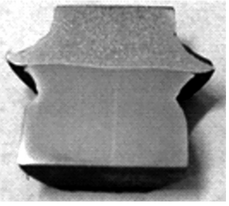

***Figure 4** Macroscopic view of cross section of a sample welded by friction*
***Slika 4.** Makroskopski pogled poprečnog presjeka uzorka zavarenog trenjem*

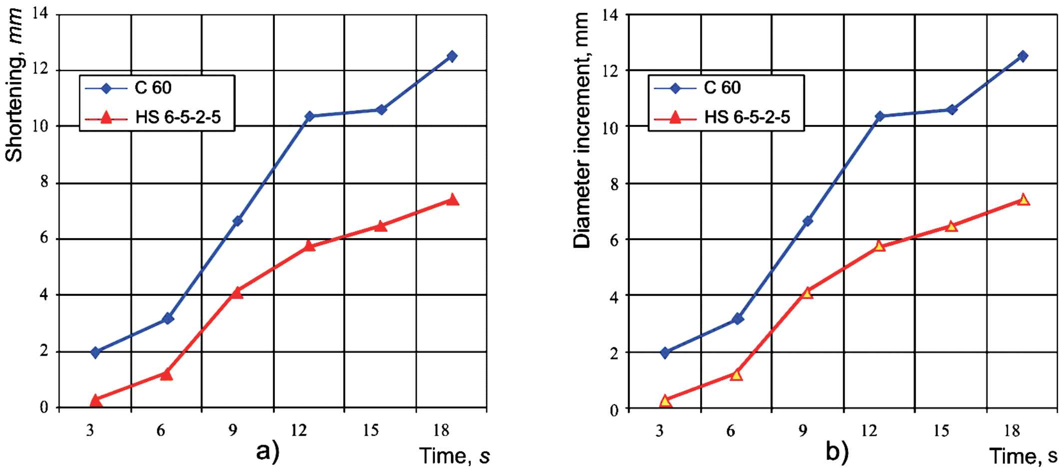

***Figure 5** Effect of friction time on samples length shortening and diameter increase*
***Slika 5.** Utjecaj vremena trenja na skraćenje duljine uzorka i povećanje promjera*

Measurement results show that shortening of elements made of C60 is rather larger than shortening of elements made of HS 6-5-2-5. It can be noticed that shortening is uneven in the course of complete friction welding process. Therefore, one can conclude that deformation conditions of transfer of the friction welding process from the second to the third phase are established after approximately 10 s.

5.4
Micro hardness and microstructure of areas near the line of contact
Mikro-tvrdoća i mikro-struktura područja u blizini linije dodira

Mean values of hardness measured along the axis of the welded sample (I), as well as at distances from axis of 2 mm (II) and 6 mm (III), are shown in Figure 6.

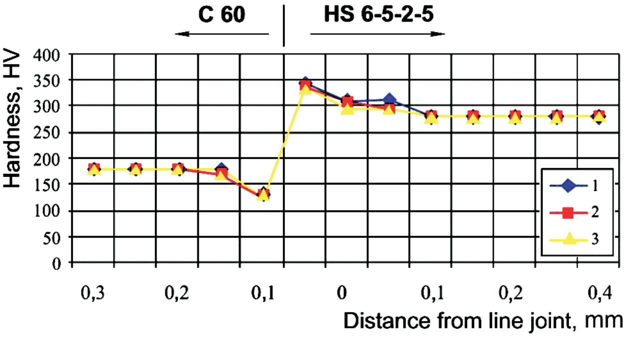

Figure 6 *Arrangement of micro hardness in the joint zone of HS 6-5-2-5 and C60* [8]
Slika 6. *Razmještaj mikro-tvrdoće u području šava čelika HS 6-5-2-5 i C60* [8]

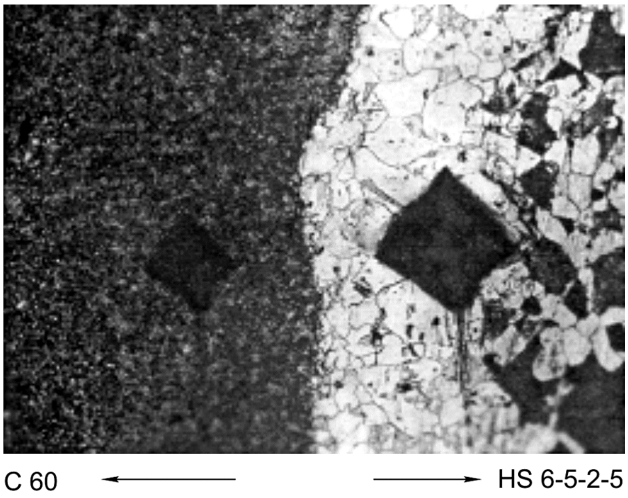

***Figure** 7 Microstructure in the area of joining (200×)*
***Slika** 7. Mikrostruktura u području šava (200×)*

Analysis of microstructure (Figure 7) and micro hardness (Figure 6) (before and after subsequent tempering) showed that the most favorable values of hardness (especially for HS 6-5-2-5) are obtained after annealing. It was carried out according to the procedure 820 ºC/4 h. During the annealing process, because of carbon diffusion from C60 to HS 6-5-2-5, the decarbonized ferrite layer is formed in C60 whose width and morphology depend on the annealing mode. Narrow and soft ferrite layer in layers near the contact line of C60 has lower values of hardness than the remaining part of C60. On the other hand, carbonizing occurs in the area next to the joint of steel HS 6-5-2-5 (due to diffusion of carbon from C60), which leads to the hardness increase. Figure 7 shows the micro structure of the welded joint and the size of patterns having occurred during the hardness measurement.

6
Conclusion
Zaključak

In this paper in a theoretical and experimental manner was pointed to the complex processes that occur during the friction welding of different steels. Hence, mechanical, chemical, structural and other properties of base metals differ among themselves, what makes the joining mechanism complex during the friction welding. Progressive heat release and consequent plastic deformation, contribute to intensity and rate of diffusion between the facing surfaces of the high-speed cutting steel and tempered steel.

The welded joint realized by friction will fulfill technical requirements only if one applies optimal welding parameters (friction time, friction and compression pressure).

7
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