Slovenská zváračská spoločnosť
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ZBORNÍK
43. medzinárodná konferencia
ZVÁRANIE 2015

BOOK
43. International Conference WELDING 2015

11. – 13. november 2015
Tatranská Lomnica, Vysoké Tatry, Slovenská republika
November 11 – 13, 2015, Tatranská Lomnica, High Tatras, Slovak Republic

Názov: **CD Zborník prednášok z 43. medzinárodnej konferencie ZVÁRANIE 2015**

Vydal: **Slovenská zváračská spoločnosť**
člen Zväzu slovenských vedeckotechnických spoločností – ZSVTS
člen Medzinárodného zváračského inštitútu – IIW (International Institute of Welding)
člen Slovenského plynárenského a naftového zväzu – SNPZ

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Publikácia je vydaná v rámci osláv Týždňa vedy a techniky na Slovensku 2015

Pre internú potrebu Slovenskej zváračskej spoločnosti.

Zostavil: Ing. Helena RADIČOVÁ, PhD.

Tlač: Slovenská zváračská spoločnosť

Vydanie: Prvé, november 2015

Rozsah: 175 strán (Zborník prednášok ZVÁRANIE 2015) + samostatné príspevky na CD

Náklad: 250 ks

ISBN: 978 - 80 - 89296 - 18 – 7
EAN: 9788089296187 čiarový kód

Za jazykovú a obsahovú stránku príspevkov zodpovedajú autori.
Príspevky neboli redakčne upravené.

XLIII. medzinárodná konferencia
ZVÁRANIE 2015
Tatranská Lomnica, 11.-13.11.2015
PRÍSPEVOK / PAPER

Vplyv doby zvárania na plastickú deformáciu počas zvárania trením rýchloreznej ocele a ocele na popúšťanie

Influence of welding time on plastic deformation during the friction welding of the high-speed steel and steel for tempering

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Abstrakt:

Hlavnou témou tejto štúdie je zváranie trením dvoch typov ocelí: rýchloreznej ocele (HS 6-5-2-5) a ocele na popúšťanie (C60). Z mnohých faktorov, ktoré ovplyvňujú proces zvárania sa v táto štúdia venuje analýze doby zvárania, a najmä dobe trenia z dôvodu axiálnej a radiálnej deformácie materiálu. Experimentálna časť štúdie analyzuje vplyv času zvárania na zmeny rozmerov zváraných oceľových častí.

Abstract:

The substance of the friction welding process, form the aspect of joining the dissimilar materials, is presented in this paper. The subject matter is friction welding of the two types of steels – the high-speed steel (HS 6-5-2-5) and the steel for tempering (C60). Out of several factors that are affecting the friction welding process, the focus in this paper is set on analysis of the welding time, especially the friction time. The reason for such a choice lies in the fact that the level of the axial and radial deformation, as well as the welded part shortening, depend mainly on the welding time, namely on the friction time only. The experimental part of this investigation included determination and analysis of influence of time on individual and total changes of dimensions of the welded steel parts.

1. Introduction

High-speed steels and tempering steels significantly differ with respect to their mechanical, technological and other characteristics, both in the solid state and in the hot state. To realize a joint of these two, completely different steels is a very complex task. Selection of the technological procedure of friction welding for joining the two different steels enables obtaining of the high quality joint, since the technological-metallurgical problems in friction welding of carbon and alloyed steels are significantly smaller than in their welding by some other procedures. Frequently, this is the only procedure for joining some metals, which, when welded by other methods, would produce very brittle phases.

These steels have different thermal conductivity and strength. This is why the welding parameters have to be selected in such a way that in the high-speed steel, which has the lower thermal conductivity and the higher strength in the hot state, sufficient degree of plastic deformation is achieved. It is especially important to determine the friction time, as well as the total welding time, since in that way the better weldability would be realized. Though the melting temperatures of the tempering and the high-speed steel are not very different, they have different capacity for plastic deformation. That affects the configuration of the joint's surface in the joining zone [1, 2]. Certain geometrical irregularities in the joining zone can be eliminated by increase of the welding time, as well as the compacting pressure, what influences the heat affected zone.

Friction welding of the high-speed and carbon steels is the most frequently used in manufacturing the cutting tools.

Analyses of the friction welding of dissimilar steels were presented in papers [3-5]. The description and the detailed analysis of friction welding of those steels are given in [6], while the valuable results and information are present in [7-10], as well as in some other references.

2. General theoretical remarks on friction welding

Unlike for other types of welding, for friction welding the manner of bringing heat to the joining spot is, in the physical sense, completely different. The base metal is heated by the heat that is transformed from mechanical energy, which is a result of the process of friction of the two materials confronting each other at the joining spot, namely in the contact zone. This source of heat, by location is the internal source, while the heat generation is strictly localized and it happens in the thin surface layers of metals. Among others, this is why the friction welding has advantages with respect to some other ways of metals joining.

The mechanisms of joining metals in the solid state, as well the process itself, are very complex. The essence of joining is based on forming the metal bond between components of the base metals. The metal bond is created during the approaching of the pure metal surfaces to a distance of the order of magnitude of the crystal lattice parameters.

Due to the fact that the metal surfaces of real solids are not ideally smooth and clean, the contact at the beginning of welding is realized only at peaks of roughness of those surfaces. Increase of the contact area is realized through the plastic deformation of the micro volumes of the metal layers close to the contact surfaces, at temperatures lower than the melting temperature of the base metals. This is why the external pressure is necessary. Conditions for beginning of the plastic deformation are facilitated by the decrease of the yield stress, which for majority of metals is decreasing with temperature increase.

The friction welding process occurs successively in several phases. Those time sequences, which characterize the process, include a series of the accompanying phenomena and changes within the contact zone; they are relatively very short, from several fractions of a second up to several seconds. The physical contact occurs first over almost the whole friction surface and the phase of the initial friction begins and lasts until the friction moment reaches its first maximum. The interaction occurs between the metal particles at the contact points and the strong adhesive bonds are created, thus leading to shear of the material particles and transferring of one metal onto the other. It is proven that at smaller friction speeds those particles are mainly being transferred in the zones closer to the perimeter of the bar, while at higher speed this occurs closer to the bar's axis. Then begins the phase of unstable friction during which the temperature increases and material endures a large plastic deformation. The thickness of the high plasticity could reach up to 2 *mm*. Mixing of the two metals' particles occurs at that point.

The stable friction occurs in the following phase, when the plastic deformation increases, especially in the layers close to the surface. The dynamic thermal balance is established between the developed heat and the heat transferred by conduction into the base metals over the total heat affected zone and into the environment via the extruded metal.

In the joining zone, the highly plasticized metal is moving according to mechanism of not only the rotational but the swirling (turbulent) flow, as well. The initial diffusional processes are intensified in this phase.

The stadium of the final friction phase follows and the braking occurs. The character, form and magnitude of the plastic deformation change due to the abrupt decrease of the friction speed. Deformation is moving towards the periphery of the bar and large quantity of material is being extruded out of the joint zone, what causes the shortening of components. The compacting of the parts is introduced at the end, without the action of the friction moment, namely there is no rotation of the welded parts. Intensive moving of material occurs in both the axial and radial directions. The metal bonds are activated between the two base metals and the common crystal lattices are formed in the boundary layers. In other words, the solid welded joint is formed.

3. Friction time and compacting time

The quality of the friction welded joint is mainly determined by the three basic control variables, which influence the metallurgical, physical and mechanical properties of the frictionally welded joint. Those are the friction speed, pressure and welding time.

The friction time depends on the base metal's properties (strength at the forging temperature, thermal conductivity, and phase transformations), welding speed, friction pressure, shape and dimensions of the welded components, etc. When dissimilar materials are welded, the friction time is selected with respect to the material of the lower hardness. The following expression is recommended for determination of the friction time [7]:

$$t_f = \left(r^2 \cdot R_{mf} \cdot n\right) / \left(\lambda \cdot p_f \cdot \rho\right) \tag{1}$$

where: r [mm] is the radius of the welded parts; R_{mf} [MPa] is the tensile strength at the forging temperature; λ [MPa] is the thermal conductivity; ρ [kg/dm^3] is the material density; p_f [MPa] is the friction pressure; n is the number of rpms.

The friction time (t_f) is the time needed for the contact surfaces to heat up to the required temperature T_{max} to provide for the secure welding process. The manner of selection of the friction time cannot be generally defined due to high deformation speed in the joint zone and due to the complex conditions at the friction surface.

The compacting time (t_c) is the time of the compacting pressure action. Duration of the compacting time must be sufficient to secure the complete realization of the plastic deformation, as well as the recrystallization process. The long compacting time can increase the danger of appearance of the cold cracks. According to experimental data, extension of the compacting time increases the tensile strength of the joint.

The total welding time is the sum of the friction and the compacting time. The friction time can last from 1 to 50 s, while the compacting time is 2 to 3 s. In this case the friction time was varying within the range from 3 to 18 s.

4. Experimental investigations

The experimental part of this work consisted of the friction welding of cylindrical samples of the tempering and the high-speed steel. The initial dimensions of the samples and the joining scheme are presented in Figure 1.

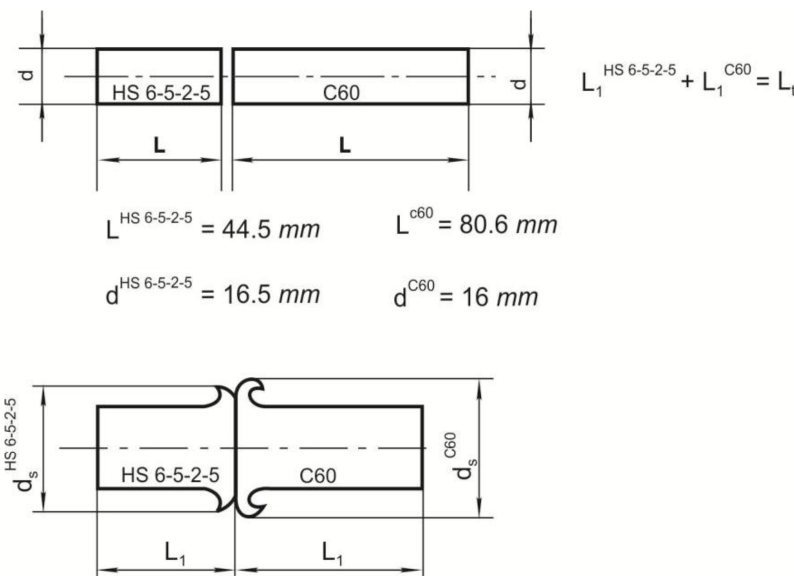


Fig. 1 *Schematic rawing of the high-speed and tempering steels' samples before (top figure) and after the joining (bottom figure).*

4.1 Data on the base metals

High-speed steel (HS 6-5-2-5) is the molybdenum-tungsten-cobalt high-speed steel of a special type. It is used for highly strained tools, for high cutting speeds, for machining of the stainless and thermo-resistant steels. It is also convenient for casting. Chemical composition of this steel is given in Table 1.

Tab.1 *Chemical composition of the HS 6-5-2-5 steel, %*

C	Si	Mn	Cr	Mo	V	W	Co	P	S
0.82	0.45	0.40	4	5	1.9	6.5	5.5	0.035	0.035

Carbon tempering steel (C60) is a steel that has high wear resistance and hardenability. It is applied in general metal working. Chemical composition of this steel is given in Table 2.

***Tab. 2** Chemical composition of the C60 steel, %*

C	Si	Mn	P	S
0.63	0.194	0.82	0.045	0.045

4.2 Plastic deformation

The objective of the experiment was to establish the influence of the friction and the compacting time on variation of sizes of samples along the longitudinal and lateral directions, for certain values of the friction and compacting pressures. The welding regime was defined by the following parameters: the friction pressure during the friction time was p_f = 80 [MPa], the compacting pressure during the compacting time was p_c = 200 [MPa]. Number of rpms was n = 2400 [rpm].

Results of the dimensions changes' measurements during the welding are presented in Table 3, while the graphical presentation of the dimensions' increase is given in Figure 2.

***Tab. 3** Influence of the friction time on shortening of samples and changes of the extruded materials' diameters at the joining spot of C60 and HS 6-5-2-5*

Time	t, *s*	3	4.5	6	7.5	9	10.5	12	13.5	15	16.5	18
Diameter at joint	D_i, *mm* C60	18	18.2	19.2	21.5	22.7	23.3	26.4	26.4	26.6	28	28.5
	D_i, *mm* HS	16.8	17	17.7	20	20.6	22	22.2	22.5	23	23.4	24
Diameter increment	Δd_i, *mm* C60	2	2.2	3.2	5.5	6.7	7.3	10.4	10.4	10.6	12	12.5
	Δd_i, *mm* HS	0.3	0.5	1.2	3.5	4.1	5.5	5.7	6	6.5	6.9	7.4
Length	L_1, *mm* C60	80.5	80.1	80	79.3	79	77.9	76.2	77.4	76.1	75.6	75.3
	L_1, *mm* HS	44.4	44.3	44	43	42.9	42.7	42.6	42.4	41.8	41.7	41.6
Total length	L_t, *mm*	124.9	124.4	124	122.3	121.9	120.6	118.8	119.8	117.9	117.4	116.9
Shortening	ΔL, mm C60	0.1	0.5	0.4	1.3	1.6	2.7	4.4	3.2	4.5	5	5.3
	ΔL, mm HS	0.1	0.2	0.5	1.5	1.6	1.8	1.9	2.1	2.7	2.8	2.9
Total shortening	Δlt, mm	0.2	0.7	0.9	2.8	3.2	4.5	6.3	5.3	7.2	7.8	8.2

Results of measurements show the samples' diameters are increasing with increase of the friction time, while the samples are simultaneously shortening.

In Figure 3 is shown the variation from the initial dimensions of samples to their final dimensions in terms of the friction time.

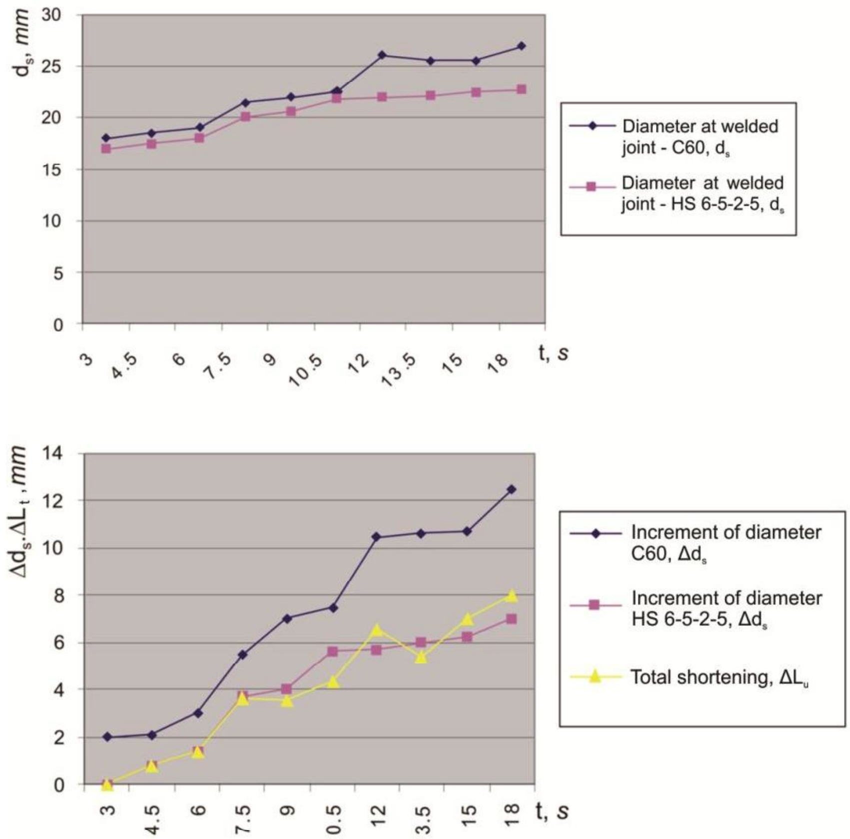


Fig. 2 *Influence of the friction time on variation of the geometrical parameters – diameter and length of samples*

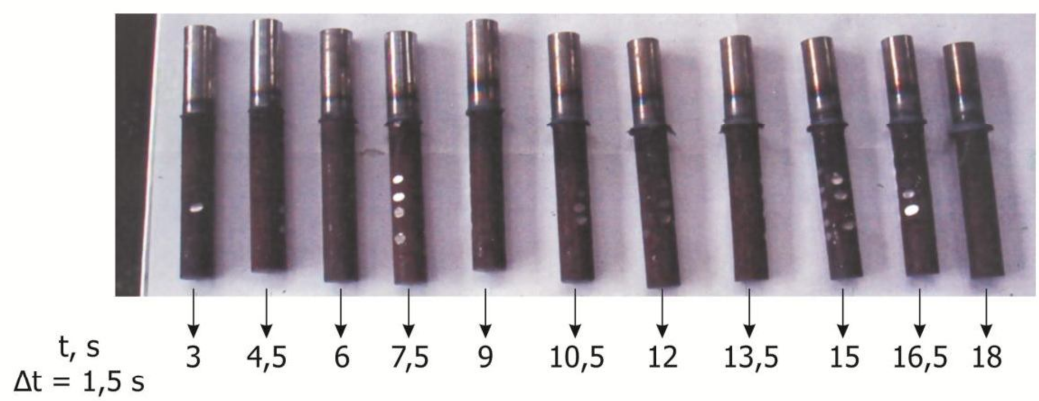
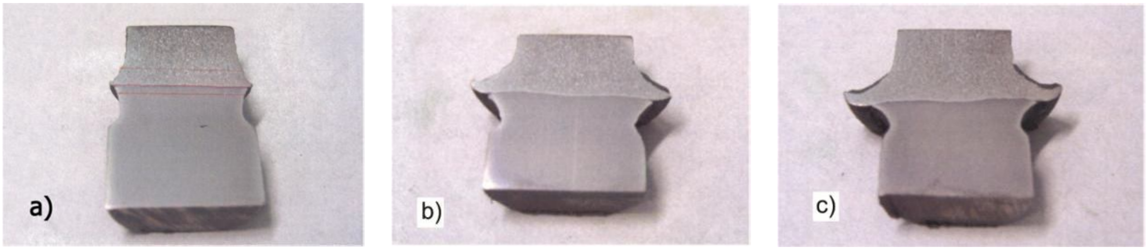


Fig. 3 *Macroscopical appearance of welded samples for different friction times*

In Figure 4 is shown the macroscopical appearance of the longitudinal sections of samples joints.

Experimental results have shown that the radial and tangential displacements are increasing with approaching to the contact surface. In the same cross-section, those displacements are increasing with both increase of the friction pressure and the friction time. For instance, in the measurements plane lies at a distance of 0.5 [mm] from the contact surface, the displacements there are significantly larger than in the plane that is at a distance of 1 [mm] from the joint. This points to appearance of the high plastic deformation. What concerns the friction time influence on displacements, it was shown that in the initial phases of the heating process displacements are increasing with time. After entering the final phase of the stable friction, the displacements remain practically unchanged.



a) 6*s* b) 12*s* c) 18*s*

Fig. 4 *Samples of steels HS 6-5-2-5 and C60 cross-sections for different friction times*

The plastic deformation parameters were calculated according to the following expressions:

- relative sliding

$$\gamma = \frac{\sqrt{(\Delta r)^2 + (\Delta s)^2}}{\Delta \ell}, \qquad (2)$$

where Δr and Δs are the corresponding displacements in the radial and tangential directions, respectively and Δl is shortening,

- strain

$$\varepsilon = \left(\gamma + \sqrt{1+\gamma^2}\right)^{\frac{1}{1-k}} - 1, \qquad (3)$$

where k is the corresponding strain coefficient,

- strain rate

$$\dot{\varepsilon} = \frac{\Delta \varepsilon}{t}, \qquad (4)$$

where t is the compacting time.

Values of the calculation results of the deformation parameters are given in Table 4, for the distance of 0.5 [mm] from the joining line, for the points at the radii of 2.5 [mm] and 4 [mm] on the high-speed steel sample.

Tab. 4 *Dependence of the plastic deformation parameters on the friction time for the high-speed steel HS 6-5-2-5*

		Position of the measurement point with respect to the rotation axis					
p_f, *MPa* 80	*t*, *s*	*r* = 2.5 *mm*			*r* = 4 *mm*		
		Parameters of plastic deformation					
		γ	ε	$\dot{\varepsilon}$	γ	ε	$\dot{\varepsilon}$
	6	0.38	0.2	0.12	1.54	0.84	0.32
	10	1.48	0.81	0.24	2.54	1.29	0.39
	13	1.76	0.94	0.32	3.1	1.52	0.52

5. Conclusion

Analysis of the obtained experimental results points to the fact that the process variables significantly influence appearance, unfolding and final result of the plastic deformation of both welded steels. The level and rate of the plastic deformation are increasing with increase of the friction time and especially with approaching to the joint plane, as well as with moving away from the rotation axis. This is due to nature of the friction process, where the deformation intensifies the displacements of the micro-volumes of material towards the perimeter. Results show that the deformation is larger for the tempering steel than for the high-speed steel. At constant stress conditions (unchanged friction pressure and compacting pressure), the plastic deformation increases with increase of the friction time, what confirms the theoretical assumptions.

Friction welding can be successfully applied for joining these two types of steel and the quality of the executed welded joint depends solely on the process parameters, i.e. on their optimal values.

Taking into account the dynamics and complexity of the plastic deformation process, it is hard to relate all the relevant parameters into a single mathematical model. However it is extremely valuable to determine the duration of all the influential parameters. The friction time is the example that illustrates the duration of all the deformation phenomena from the beginning until the final forming of the friction welded joint.

Acknowledgement

This research was partially financially supported by European regional development fund and Slovak state budget by the project "Research Centre of the University of Žilina" - ITMS 26220220183 and by the Ministry of Education, Science and Technological Development of Republic of Serbia through grants: ON174004, TR32036, TR35024 and TR33015. The authors are very grateful for this funding.

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Odborný príspevok recenzoval: doc. Ing. Ondrej Híreš, CSc., Dubnica nad Váhom