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Research paper

Influence of Friction Pressure at a Given Burn-off Length on the Mechanical and Microstructural Properties of Welded Joints from Medium-Carbon Alloyed Steels in Rotaty Friction Welding

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Abstract

This study investigates the influence of friction pressure at a given burn-off length on the microhardness, tensile properties and microstructure of the welded joints from steel 32-2-Mn and 40-Cr-Ni. Phase transformations occurring in the materials to be welded as a result of thermal deformation effects are analyzed. The change in the length of the thermomechanical affected zone (TMAZ) depending on the friction pressure is shown. The results of the distribution of microhardness in the weld, clearly illustrating the formation of hardened and weakened areas. The results of tensile tests of welded joints are given. Analyzed the place of fracture at various welding parameters. The necessity of studying the distribution of internal residual stresses to explain the mechanism of fracture of welded joints is shown.

Keywords: *rotaty friction welding, welded joints, thermomechanical affected zone, microstructure, microhardness, tensile strength*

1. Introduction

The increased interest in the process of friction welding is associated with the wide spreading of this technology at the enterprises of mechanical engineering due to the technological advantages of this method and the high quality of the welded joints of the similar and dissimilar materials. There are works of scientists aimed at finding the optimal modes and the study of mechanical and microstructural properties of friction welds from a wide range of steels used in aviation, rocket and space, automobile, oil, geological exploration and other industries [1-18]. Unfortunately, detailed studies of welded joints from medium-carbon alloyed steels in modern publications are presented very little. However, their widespread use for the production of drill pipes with welded locking parts dictate the need for research in this direction to improve the quality and enhance the functional properties of the welded joint, as one of the most vulnerable points in the structures.

The welding process is carried out in several stages. The welded blanks are installed in a stationary clamp, one of them is told rotary motion, blanks approach and heat up to temperature necessary for formation of welded joint, then rotation is quickly stopped, and to blanks apply the axial force of forging.

The various process parameters taken into consideration here are: friction pressure (pressure required to generate the required heat for welding), upset pressure (the axial pressure applied on the stationary work piece once rotation of the spindle is stopped), burn-off length (loss of overall length after welding) and rotational speed (the speed at which the spindle is rotated). Graphical representation of the process is as shown in Fig. 2.

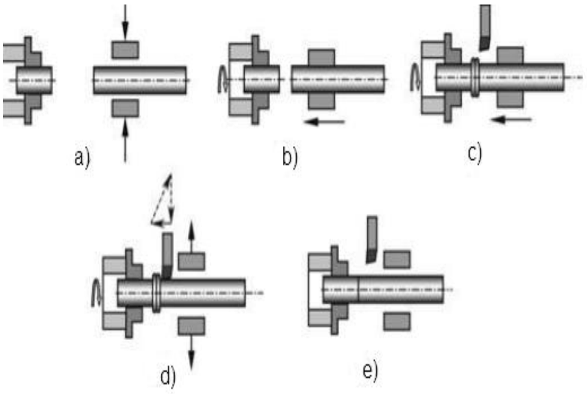


Fig. 1: Stages of friction welding process (a, b, c, d, e)

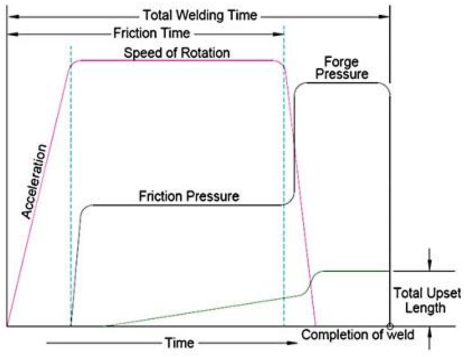


Fig. 2: Graphical presentation of the process

All parameters are interconnected and affect the formation of a welded joint. Obviously, the friction pressure plays a large role when parts are heated. In the heating stage, the metal is brought to the plasticity state, after which the necessary force is applied. The heating time depends on the magnitude of the friction pressure, since a given precipitation value is reached faster with increasing pressure. All this has a direct impact on the nature of the thermal deformation influence on the materials being welded.

The purpose of this study was to establish the influence of friction pressure on the formation of the microstructure and tensile properties of welded joints from medium carbon steels used for the production of drill pipes.

2. Experimental Work

The chemical composition of the welded materials is shown in Table 1.

Table 1: The chemical composition of the welded materials

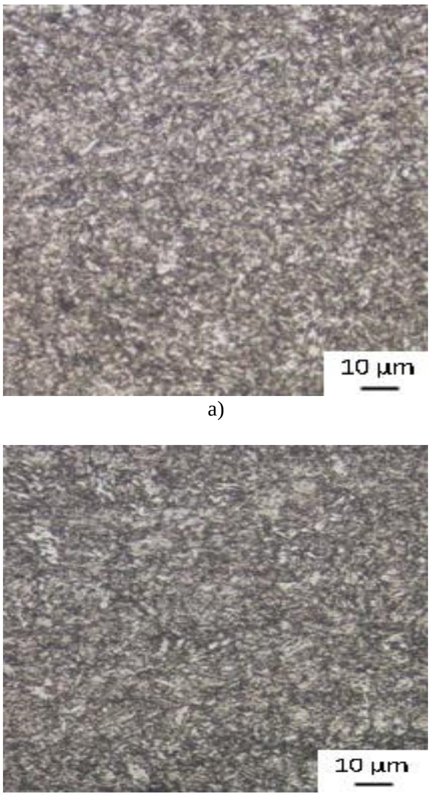
Material	C	Mn	Si	S	P	Cr	Ni	Cu	Mo
32-2Mn	0,32	1,07	0,18	0,002	0,006	0,09	0,10	0,17	0,02
40-Cr-Ni	0,31	0,53	0,32	0,006	0,004	0,51	1,06		0,09

The steels were subjected to volumetric heat treatment of quenching and high tempering to obtain the level of mechanical properties indicated in Table 2.

Table 2: Mechanical properties of the of the base metals

Material	HRC	Yield strength σ_{02}, MPa	Tensile strength σ_B, MPa	Elongation δ_5, %
32-2Mn	23,9-26,2	744-765	849-864	15,5-17,9
40-Cr-Ni	27,4-29,9	790-811	958-964	13,3-14,8

Microstructure of the of the base metals is shown in Fig.3



b)

Fig. 3: Microstructure of the base metals: a) 32-2Mn; b) 40-Cr-Ni

Friction welding of pipe billets with a diameter of 63.5 mm and a wall thickness of 4.5 mm for the purpose of making experimental samples was carried out in production conditions on a Thompson-60 friction welding machine according to the modes presented in Table 3.

Table 3: Process parameters used during friction welding

№ mode	Friction pressure P_1, kN	Friction time* τ, sec	Forge pressure P_2, kN	Burn-off length l, mm	Rotational speed n, rpm
1	50	5,86	130	8	800
2	70	4,01			
3	90	2,17			
4	110	1,59			

**The Friction time was set automatically and read from the computer interface of the friction welding machine*

Metallographic analysis, determination of microhardness and mechanical properties were carried out by standard methods.

3. Results and Discussion

To study the effect of heat caused by friction and plastic deformation on the metal structure, metallographic studies of the weld were performed using an optical microscope. During the etching of the longitudinal microsection, a thermomechanical affected zone (TMAZ) was revealed, having a darker color, see Fig. 4.

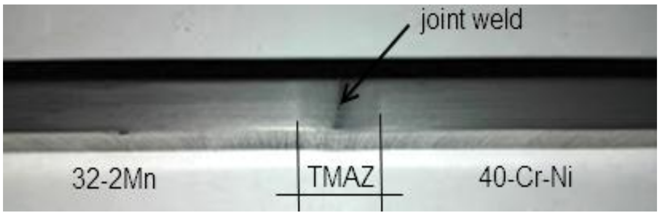
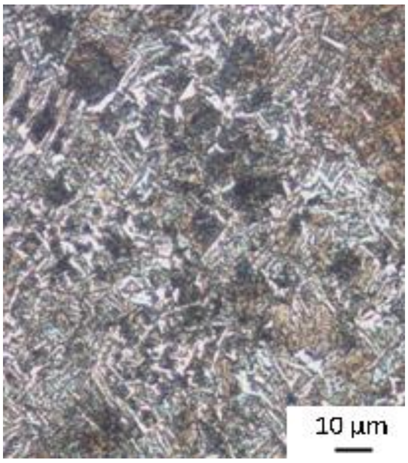


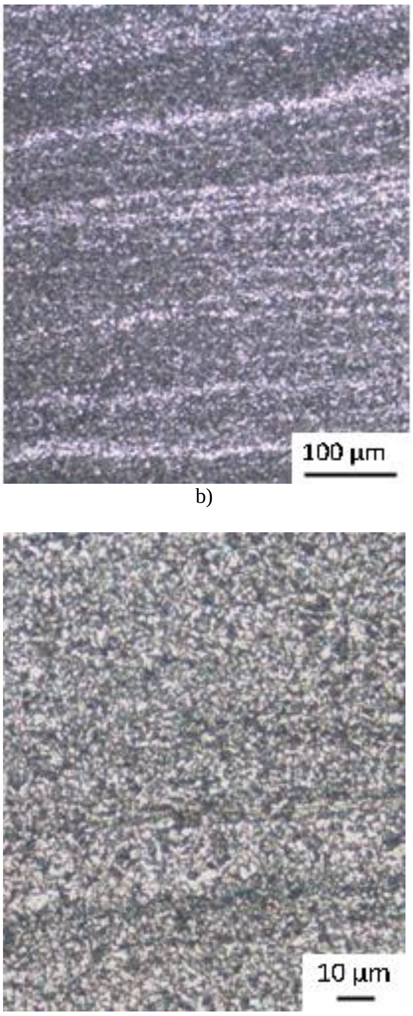
Fig. 4: The macrosection of the joint welds of 32-2Mn and 40-Cr-Ni steels formed by rotary friction welding

The fig.5 and fig.6 show micrographs taken from various weld zones using the example of a regime with a friction pressure of 110 kN.

Obviously, the effect of temperature and pressure gave rise to changes in the microstructure. According to the length of the thermomechanical affected zone, both from the side of 32-2Mn steel and from 40-Cr-Ni steel, three zones can be distinguished: the zone of deformation and temperatures exceeding the critical point A_{C3} (zone 1), the zone of deformation and temperatures in the range from A_{c1} to A_{c3} (zone 2), the recrystallization site in which the temperature was close to A_{C1} (zone 3). Consider the microstructural features of each of the zones.



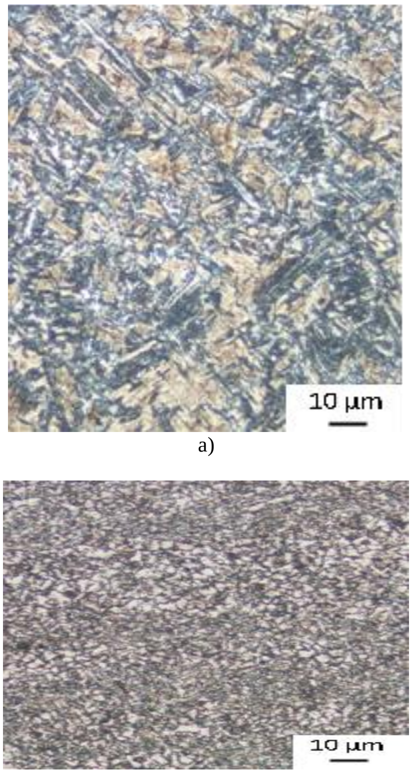
a)



b)

c)

Fig.5: Typical microstructure of the friction welding parts 32-2-Mn:a) the center of the deformed zone 1; b) deformed zone 2; c) recrystallization zone 3



a)

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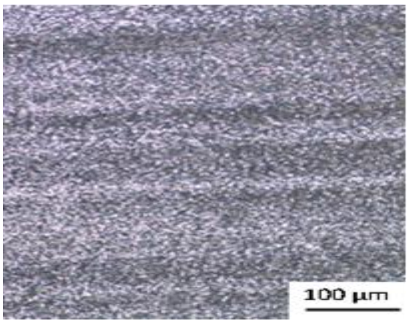

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Fig.6: Typical microstructure of the friction welding parts 40-Cr-Ni:
a) the center of the deformed zone 1; b) deformed zone 2; c) recrystallization zone 3

In the areas adjacent to the welded joint of zone 1, one can observe the formation of martensitic structure from the side of steel 40-Cr-Ni and a mixture of martensite and bainite from the side of steel 32-2-Mn (Fig. 4, a, Fig. 5, a). The formation of quenching structures in the TMAZ of both steels is associated with their local heating up to temperatures above the temperature of their polymorphic transformation and further accelerated cooling due to the realization of rapid heat exchange between a narrow zone heated during the friction process and adjacent regions of the metal at room temperature. Thus, phase transformations in this zone occurred in the solid state. It should be noted that in this area the distribution of grain size and geometry is complex. Along with large grains, the formation of smaller grains takes place. The deformation of the material in this zone is oriented parallel to the welded joint.

When moving away from the welded joint, the microstructure undergoes changes. In zone 2 on the side of both steels, it is a layered structure and consists of alternating bands of quenching structure and fine ferrite-cementite mixture, smoothly changing direction from parallel to the welded joint to the perpendicular (Fig. 4, b, Fig. 5, b). It can be assumed that in the process of welding plastic deformation in this zone proceeded unevenly. Plots with different degrees of deformation were formed, which differed in the mechanisms of transformation of the microstructure during the heating and cooling phases. In areas with a higher degree of deformation, with a higher hardenability, the formation of a martensitic-type microstructure took place. In other regions, the transformation proceeded by the diffusion mechanism. It can also be noted that the grain size here is significantly smaller than in zone 1.

Zone 3 (Fig. 4, c, Fig. 5, c), in which there are no visible signs of residual plastic deformation, is characterized by the formation of equiaxed small grains of ferrite and perlite, which indicates the intensive development of recrystallization processes in this zone. The microstructure is small, uniform.

Studies have shown that the pressure during heating of the overall picture of the change in microstructure over the length of TMAZ does not change. The influence of this parameter is expressed in the change in the length of each of the zones that make up the total length of the zone of thermomechanical influence.

Table 3 shows the average values of the length of each section, measured using optical metallography.

Table 3: The length of sections of the TMAZ when the friction pressure parameter is changed during welding of steel 32-2-Mn and 40-Cr-Ni

P_2, кН	50		70		90		110	
Material	32-2-Mn	40-Cr-Ni	32-2-Mn	40-Cr-Ni	32-2-Mn	40-Cr-Ni	32-2-Mn	40-Cr-Ni
Total length of TMAZ, mm	3,3	3,4	2,8	2,9	2,3	2,4	2,2	2,2
Zone 1	0,40	0,73	0,35	0,65	0,34	0,54	0,28	0,52
Zone 2	2,8	2,62	2,33	2,17	1,42	1,44	0,96	0,98
Zone 3	0,10	0,05	0,12	0,08	0,54	0,42	0,96	0,7

According to Table 3, it can be traced that with an increase in the heating pressure, the total length of the TMAZ decreases, and the width of the sections in which the temperature exceeded the critical points also decreases. At the same time, the length of the recrystallization section in which the temperature was below the critical values, on the contrary, increases. This fact can be explained as follows. As the friction pressure increases, the heating of the contacting surfaces intensifies and the metal layer, brought to elevated temperatures, is squeezed out more easily and carries a significant part of heat from the junction to the burr. As a result, the process proceeds faster, and the heat does not have time to spread over a considerable distance, which explains the reduction in the total length of the TMAZ, the decrease in temperature in the peripheral areas and the increase in the length of the recrystallization zone.

Consider the microhardness distribution over the length of TMAZ (Fig. 7).

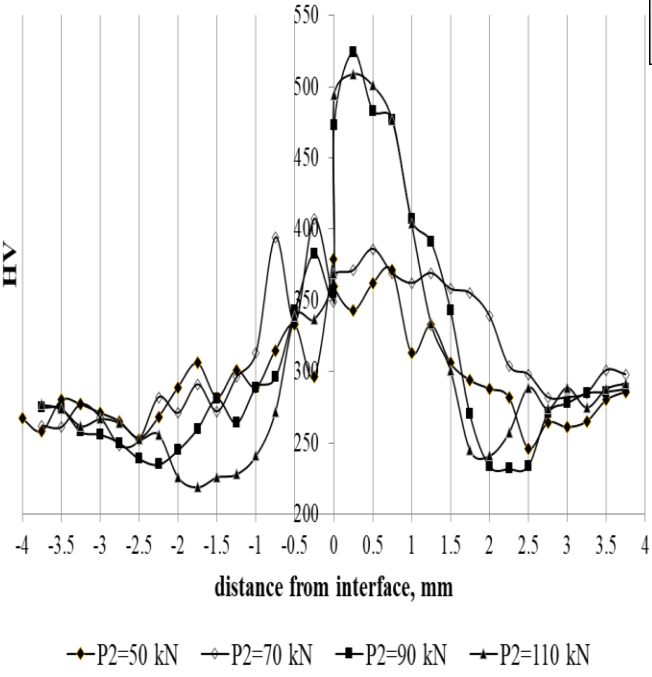

Fig. 7: Microhardness distribution over the length of TMAZ

The results obtained indicate that the nature of the change in microhardness corresponds to structural changes. It is seen that in the process of welding in the TMAZ, the formation of both hardened and weakened sections occurred. The presence of the martensitic phase explains the high hardness in zone 1, adjacent to the welded joint. When moving away from the welded joint, the values of microhardness smoothly decrease, reaching a minimum in the zone of recrystallization.

With an increase in the heating pressure, the values of microhardness of martensite in zone 1 increase, which indicates an intensification of the processes of martensitic transformation. That is, increasing deformation and temperature near the welded joint contributes to a more complete flow of phase transformations in these areas. At the same time, with increasing friction pressure, a narrower region of high temperature localization can be observed, and, as a consequence, a narrower extension of the hardened section near the welded joint, and an intensification of the softening process in zone 3, characterized by minimal microhardness, can be noted.

It was of interest to determine the mechanical properties of welded joints after the implementation of the studied modes. The results of mechanical tensile tests are presented in table 4.

Table 4: Tensile properties of friction welded 32-2-Mn and 40-Cr-Ni joints

Welding mode		**σ_{02}, MPa**	**σ_B, MPa**	**δ_5, %**	**Tensile fracture of welded joint**
№	**P_2 , kN**				
1	50	807	870	12,0	from the side of steel 32-2-Mn at a distance of 4 mm from the weld joint
2	70	783	865	15,6	from the side of steel 32-2-Mn at a distance of 5 mm from the weld joint
3	90	806	876	17,3	from the side of steel 32-2-Mn at a distance of 18 mm from the weld joint
4	110	786	880	16,3	from the side of steel 32-2-Mn at a distance of 7 mm from the weld joint

Table 4 shows that the fracture of the samples in all cases occurred on the material 32-2-Mn, while the values of the strength properties are at a level not lower than the base metal, and in some cases exceed them. At P_2 = 50 kN, the sample fracture occurred closest to the boundary between the TMAZ and the base metal. The value of the elongation is reduced. . With an increase in friction pressure and, as stated above, a reduction in the length of the TMAZ, the place of fracture of welded joints is shifted from the welded joint to the base material of steel 32-2-Mn, despite the formation of a longer, softened area. Such a mechanical behavior of samples of welded joints when tensile tested after the implementation of modes 3 and 4 is probably due to the redistribution of internal stresses in the welded joint and the balancing of internal compressive and tensile stresses along the length of the TMAZ at higher friction pressures. In view of this circumstance, the sealing of stresses within the local volume of the metal subjected to thermodeformational influence, and the displacement of the site of fracture to the base material of less strong steel, could occur. This sets the direction for further research on the stress state of the weld.

4. Conclusions

With the implementation of rotary friction welding on an automatic welding machine with increasing friction pressure, a predetermined deformation, characterized by burn-off length, is achieved faster, the process is reduced and the heat does not have time to spread to vast areas of the metal. This leads to a decrease in the length of the TMAZ and an increase in the degree of localization of high temperatures and deformations near the welded joint. At the same time, the place of tensile fracture is gradually shifted from the zone of influence of temperatures and deformations to the base metal of less resistant steel 32-2-Mn, in spite of the presence of weakened areas in the TMAZ. It seems relevant to study the distribution of internal stresses over the length of the TMAZ weld.

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