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Study of energy dissipation and rigidity of welded joints obtained by pressure butt welding

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ABSTRACT

Introduction. When studying the energy dissipation associated with internal friction in a weld, it is extremely important to choose a measurement technique, since the reliability and integrity of the data obtained depends on it. At the same time, it is necessary to investigate the change in internal friction depending on the presence of defects in the weld. Of the variety of methods for non-destructive testing of joints obtained by pressure welding, only ultrasonic is currently used. However, lightly oxidized lacks of welding penetration are not detected, which can be detected only in the presence of other defects accompanying it. Compounds of dissimilar materials are not controlled by ultrasound at all. Therefore, the development of non-destructive testing methods for such compounds is very relevant. **The purpose of the work:** to find a procedure for testing the quality of a welded joint in metals and alloys that will be a quick and simple alternative to the known methods of non-destructive testing, by measuring the energy dissipation in the weld of the sample by the static hysteresis loop method. **The method of investigation** is non-destructive quality control of the welded joint in metals and alloys by measuring the energy dissipation in the weld of the sample by the static hysteresis loop method. **Results and discussion.** It is established that with an increase in the lacks of welding penetration, the energy dissipation increases at the same values of the torque amplitude under static loading conditions. The rigidity of the qualitative welded joints remains constant, and the joints with lacks of welding penetration decrease with increasing torque amplitude. The relationship of strength with stiffness and damping ability obtained by the static hysteresis loop method is preserved for various structural states of the sample material.

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Introduction

When dissipating the energy associated with internal friction, it is extremely important to choose a measurement technique, since the reliability and integrity of the data obtained frequently depends on it. Measurements in metals and alloys are performed for two purposes. On the one hand, the absolute values of internal friction tend to be determined; on the other hand, measurements are carried out to obtain values connected with a change in a solid body state or with a difference between its various states. This paper examines the change in internal friction in welded samples depending on the presence of defects in the weld. Therefore, the primary interest is not so much the measurement of the absolute values of internal

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friction, but also its changes, and, besides, the equipment sensitivity to such changes should be sufficiently high. In this case, special attention should be paid to reducing the complexity of measurements.

The energy method can be used to study energy dissipation in such materials for which, by appropriate choice of the chemical composition and heat treatment, it is possible to obtain samples possessing practically the same specific gravity and elastic properties, but having a large difference in the ability to dissipate energy during oscillations. This method requires the amplitude registration of the steady-state oscillations of the sample, which presents significant difficulties under production conditions [1]. The relative energy dissipation in the sample material under study during its oscillations is calculated according to the measurement data on a special installation.

The use of the *dynamic hysteresis loop method* is impractical due to the low equipment sensitivity to dynamic deformations.

The *resonance curve method* is used at low deformation levels, when the irreversible losses are small and the oscillatory system can be considered almost linear [2–5]. The application of this method is considered for any nonlinearity of the amplitude dependence of energy dissipation in work [6]. The method sensitivity to internal friction changes is very low with a high quality factor of the system, which does not allow using this method to detect defects in a welded joint.

It is also impossible to use the dependence of the system resonant frequency on the level of irreversible energy losses in the material of the elastic element, since the change in the resonant frequency will be more affected by deviations in the sample dimensions than the defect presence in the weld.

Nowadays only *ultrasonic testing*, as a non-destructive method, is used for testing butt joints obtained by pressure welding. At the same time, the testing results are greatly influenced by the heterogeneity of the internal structure; lightly oxidized lacks of welding penetration are not detected. It can be detected only in the presence of other defects [5]. Joints of dissimilar materials are not generally controlled by ultrasound [16]. Therefore, the development of non-destructive methods for testing such joints is very important.

In the given paper the internal friction is determined by the method of the *static hysteresis loop* of the sample. The use of the *static hysteresis loop method* allows determining the energy dissipation almost directly in the weld. To obtain positive results, sensitive devices [7, 8] can be used to record small displacements. The measurement of energy dissipation by the *static hysteresis loop method* is carried out in this case when the welded joint is loaded with an alternating torque.

The efficiency of joints depends on its strength, rigidity and damping capacity. The presence of lack of welding penetration in a joint increases energy dissipation and reduces strength. Despite the widespread use of butt welding by pressure, there are no reliable methods for detecting the main defect of these joints, that is, lightly oxidized lacks of welding penetration.

The aim of the study is to create a procedure for testing the quality of a welded joint in metals and alloys, which will be a quick and simple alternative to the known methods of non-destructive testing, by measuring the energy dissipation in the sample weld using the *static hysteresis loop method*.

Research Methodology

To conduct the research, samples were obtained on the *MF-327* machine by friction welding and on the *MCP-30* machine by butt welding. Friction welding and butt welding were chosen as the most widely used in industry, and also because the features of joints obtained by pressure butt welding are most fully combined in joints obtained by these types of welding [9-10]. The research was carried out on joints of similar steels (*steel 45** + *steel 45*) and dissimilar ones (*steel 45* + *steel R6M5***). The choice of sample materials is due to its general industrial application. Welding modes for blanks with a diameter of 25 mm are given in Table 1 for joints *steel 45* + *steel 45* and *steel 45* + *steel R6M5* obtained by resistance welding. The heating time for blanks made of similar steels varied within 15 seconds, while the heating time for blanks made of dissimilar steels was increased to 25 seconds.

* Quality structural steel; ~ 0.45 % of carbon.

** High-speed steel; ~ 6% of tungsten, ~ 5 % of molybdenum.

Table 1

Modes of resistance welding of blank pairs (st*eel 45* + *steel 45*) and (*steel 45* + *steel R6M5*)

Mode No.	Total draft, mm	Secondary voltage, V	Heating time, sec
1	2	3.5	15–25
2	3	3.5	15–25
3	4	3.5	15–25
4	5	3.5	15–25
5	6	3.5	15–25
6	10	3.5	15–25

Table 2 shows the modes for joints steel 45 + R6M5 and steel 45 + steel 45, obtained by friction.

Table 2

Modes of friction welding of blank pairs (*steel 45* + *steel R6M5*) and (*steel 45* + *steel 45*)

Mode No.	Rotation speed, rpm	Specific heating pressure, N/mm^2	Specific forging pressure, N/mm^2	Heating time sec
1	1,500	156	236	2
2	1,500	156	236	8
3	1,500	156	236	9
4	1,500	156	236	12
5	1,500	156	236	15
6	1,500	156	236	25
7	1,500	156	236	30
8	1,500	27	27	3
9	1,500	27	27	5
10	1,500	60	60	5
11	1,500	60	60	10
12	1,500	100	100	6
13	1,500	160	160	5
14	1,500	170	170	10

All blanks and the ones from a solid bar of *steel 45* and *steel R6M5* were annealed at 850 °C for 10 hours after welding. The specimens were turned on a lathe to ensure the uniformity of dimensions in diameter. The specimen diameter at the welding point was 17.2 ± 0.05 mm, and the specimen length was 170 mm. The grip sections of the specimens were cut off without further machining.

As it was mentioned in the introduction, internal friction was determined by the *static hysteresis loop method*. This fact allows determining the energy dissipation almost directly in the weld [1, 3–15].

The research was conducted on a *KM-50-1* testing machine designed for torsion testing of metal specimens. The energy dissipation measurement by the *static hysteresis loop method* was conducted when loading the welded joint with an alternating torque, and the displacements were recorded by a laser sensor with digital indexing *LAH-G*, with a resolution of 0.5 µm.

The indicator readings were taken after several preloading cycles, which corresponded to the closing of the hysteresis loop. After the loop was removed at one amplitude of the alternating torque, the loading cycle was performed at larger torque amplitude, for which a hysteresis loop was also built and so on. The welded joint loading with torque was carried out only in the elastic deforming area of the entire specimen. The energy dissipation in the welding area when applying an alternating moment greater than the static

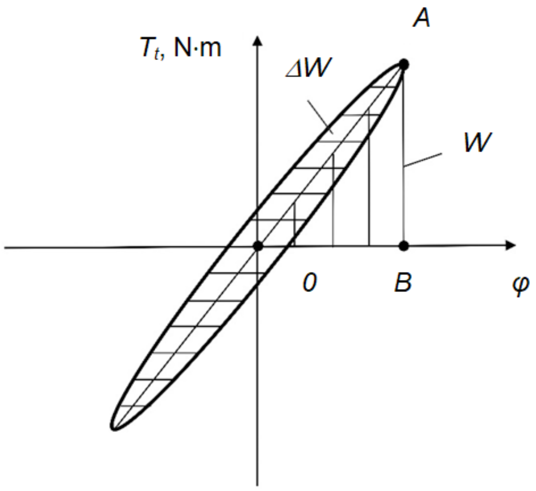


Fig. 1. Hysteresis losses in a welded joint

pre-displacement is similar to plastic deformation in its characteristics [6]. Microfriction leads to the absorption of energy by the contact — hysteresis. Hysteresis losses in the welded joint were determined by the loop area (fig. 1).

Various values can be chosen as a measure of internal friction, regardless of the sources of energy losses. The most commonly used absorption coefficient is $\psi = \Delta W/W$, where ΔW is the irreversible dissipated energy in one loading cycle in the coordinates: torque T_t and the corresponding displacement φ. The amplitude value of the potential energy is characterized by the area of the triangle *OAB* (fig. 1).

The energy dissipation, determined by the *static hysteresis loop method*, is the sum of losses for joints *steel 45* + *steel 45* and it is described by the dependence $W = 2W_1 + W_3$; and for samples *steel 45* + *steel R6M5* by the dependence $W = 2W_1 + W_2 + W_3$. In these dependencies W_1, W_2 characterize the energy dissipation in the base metal volume of *steel 45* and *steel R6M5* respectively between the weld and the sensor blade, and W_3 is the energy dissipation in the weld [4, 6, 12].

It follows that in order to obtain the energy dissipation *W* in the weld, it is necessary to subtract the energy dissipation in the base material from the total energy dissipation.

The absorption coefficient of the weld is also determined by subtracting losses in the base material from the total absorption coefficient.

This paper presents rigidity *C* as the rigidity of the specimen part between the sensor blades.

Results and its discussion

The influence of the gauge length (*l*) on the parameters under consideration was studied on annealed specimens. Energy dissipation in the specimen material under alternating torque loading increases directly proportional to the distance between the sensor blades when increasing from 2 to 6 mm (fig. 2). Lines **1**, **2**, **4** characterize the energy dissipation in *steel R6M5* at amplitude values of the torque T_t = 196; 176.4; 137.2 N·m and 3, 5 – energy dissipation in *steel 45* at amplitude values of torque T_t = 196; 176.4 N·m. The increase in energy dissipation is due to the increase in the specimen material volume where the measurement is taken. The volume increase occurs because of the gauge length increase when a diameter is constant.

The absorption coefficient, being a relative characteristic, remains constant with the increase in the gauge length both for *steel 45* (φ = 0.05) and for *steel R6M5* (φ = 0.6). The measurements were carried out at torque amplitude of 176.4 N·m. The measured rigidity value decreases with increasing distance between

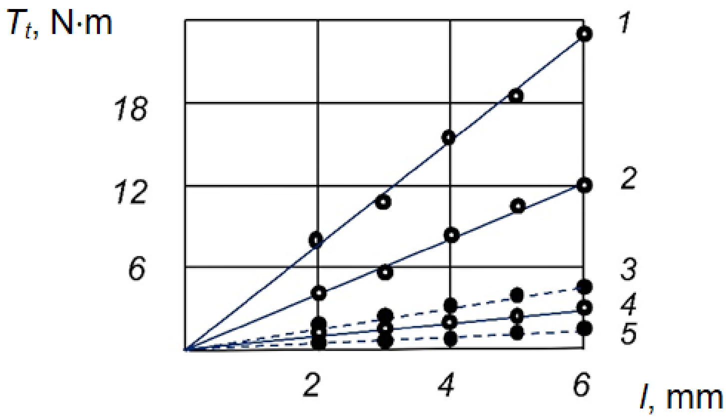


Fig. 2. Dependence of energy dissipation on the gauge length *l* at various torque values

the sections of the sensor blades (fig. 3). The dependences were obtained for *steel 45* – line **1** and *steel R6M5* – line **2** at torque amplitude of 176.4 N·m

The decrease in rigidity is connected with the fact that when increasing the distance between the sections of the sensor blades at a constant torque T_t, the angle of rotation of the sections φ (fig. 1) increases relative to each other. This dependence becomes more and more convex with a significant increase in the gauge length.

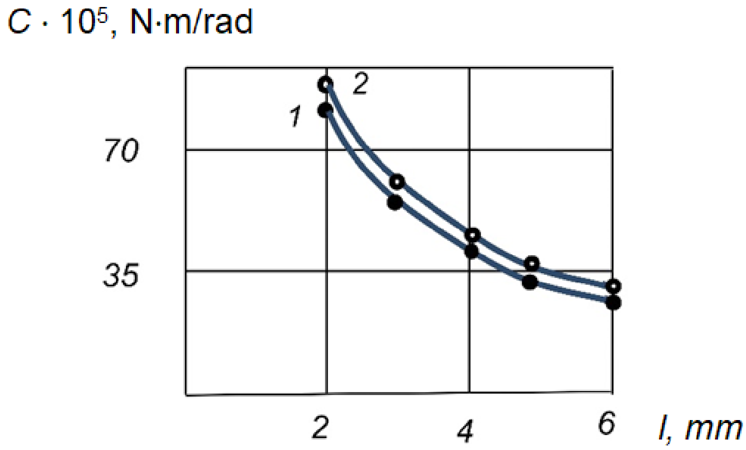


Fig. 3. Dependence of stiffness on the gauge length *l*

The energy dissipation in the welds changes when changing the torque value. Figures 4 and 5 shows the amplitude dependences of energy dissipation in the welded joints of *steel 45* + *steel 45* and *steel 45* + *steel R6M5*, respectively, as well as in solid specimens from these steels: **2**, **3** are joints obtained by friction welding; **1**, **4** are joints obtained by resistance welding; **5**, **6** are solid specimens, respectively, from *steel 45* and *steel R6M5*.

The energy dissipation shown in the figures in *steel 45* and *steel R6M5* under alternating loading of specimens in the elastic area occurs due to local microplastic deformation of separate overstressed grain sections. Grain sections overstress arise because of the anisotropy of the modulus of elasticity [4, 17]. Inter granular displacements play a secondary role, since the main mechanism of plastic deformation is intragranular displacements [17].

The vast majority of the dissipated energy in welds is due to lack of welding penetration, which [7, 18] can be represented as a dense mechanical contact. During alternating loading of the contact by a tangential force, a preliminary displacement occurs in it in mutually opposite directions [16]. In this case, plastic and elastic shear deformations of micro irregularities of a rough surface are carried out. When the micro displacement occurs primarily in the plastic deformation process, the material is hardened and increases its elastic limit; re-displacement after unloading is performed within the limits of elasticity but with micro friction, therefore, the deformation takes on an elastic-frictional nature, similar to the nature of plastic deformation. Sliding of the contact elements takes place in addition to its deformation. It does not enter this sliding all at once, but sequentially one after the other. This is due to the fact that micro irregularities are involved into shear by micro friction on the contact areas of elements compressed in different ways. Besides, the rigidity of micro irregularities is different.

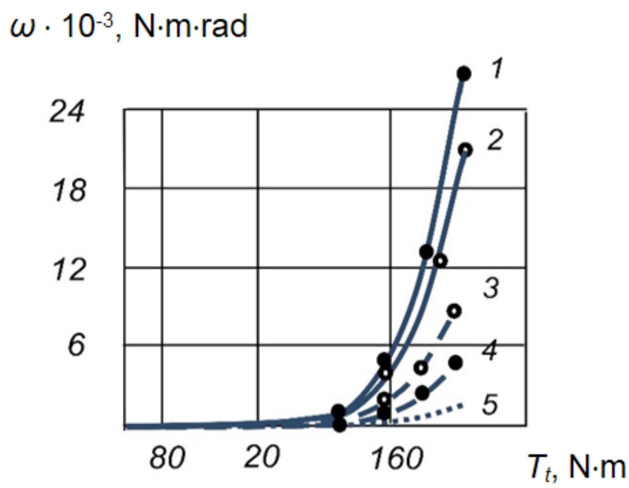


Fig. 4. Amplitude dependence of energy dissipation in welded joints of *steel 45* + *steel 45*

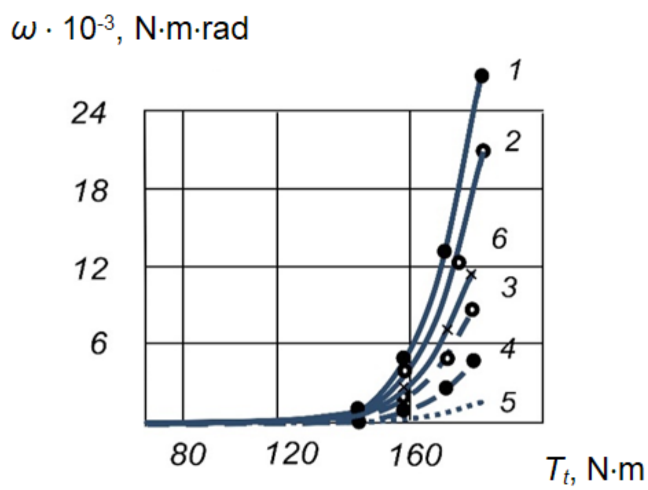
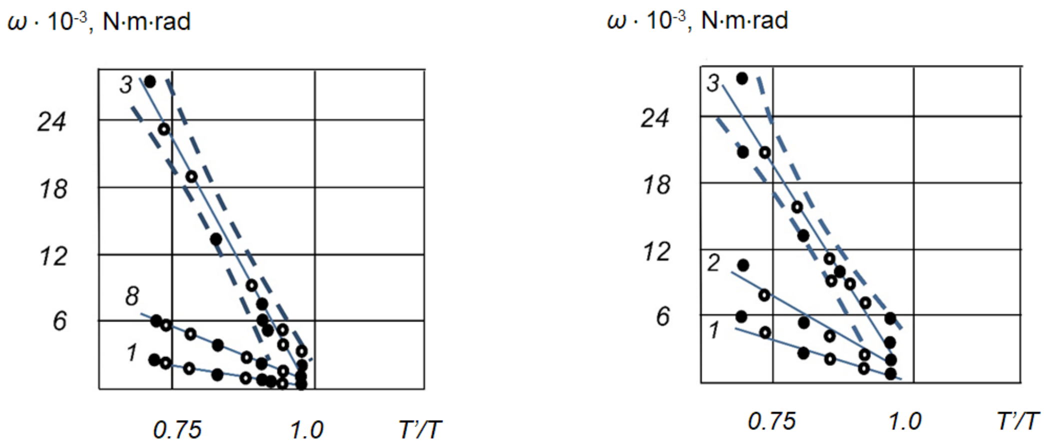


Fig. 5. Amplitude dependence of energy dissipation in welded joints of *steel 45* + *steel R6M5*

Welds with different amounts of lack of welding penetration dissipate energy in different ways similarly to the shear strength of the contact. The greater lack of welding penetration, the more energy is dissipated in the weld. Firstly, this is explained by the fact that a larger number of micro irregularities are deformed in a larger contact area and a larger number of contact elements slip. Secondly, lack of welding penetration reduces the polar resisting moment of a section, and this leads to the occurrence of large shear stresses in those welds that have greater lack of welding penetration, when loading all joints with equal torque. More shear stress causes more micro displacement, resulting in more energy dissipation in the weld. The difference in the energy dissipated in welds with different values of lack of welding penetration increases with the increase in the loading amplitude.

Energy dissipation connection with relative joint strength for different torque amplitudes turned out to be satisfactory (fig. 6). Lines **1**, **2**, **3** correspond to amplitudes of 147; 156.8; 176.4 N·m; “○”denotes joints obtained by friction welding; “●” denotes resistance welding. The ratio of the breaking moment of the specimen to the breaking moment of the specimen from annealed *steel 45* is plotted along the abscissa axis. This designation is accepted in all figures.



a *b*

Fig. 6. Relation between energy dissipation and relative strength of welded joints:
a – steel 45 + steel 45; *b – steel 45 + R6M5* for different torque amplitudes

The dependence of the absorption coefficient on the loading amplitude (fig. 7) is similar to the dependence of energy dissipation. Lines **2**, **3** are joints obtained by friction welding; **1**, **4** are joints obtained by resistance welding; 5a, 5b are solid specimens of *steel 45* and *steel R6M5*. The connection of the relative strength of joints with the weld absorption coefficient is shown in fig. 8. The designations are similar to those in fig. 6.

With the increase in the loading amplitude, the rigidity of specimens made of *steel 45* and *steel R6M5*, as well as welded specimen without lack of welding penetration, remains constant (fig. 9). Line **2** is joints obtained by friction welding; **1**, **3** are joints obtained by resistance welding; **4**, **5** are solid specimens of *steel 45* and *steel R6M5*.

Rigidity constancy is explained by the direct proportional dependence of the deformation on the load when loading the specimen in the elastic area. The rigidity of joints with lack of welding penetration decreases with increasing loading amplitude due to the deformation of the micro irregularities of the rough surface and the contact element sliding. In general, the amplitude dependence of the rigidity of welded joints is non-linear [2, 3, 9].

At small loading amplitudes, the rigidity of specimens made of *steel 45* and *steel R6M5* may turn out to be less than the rigidity of welded joints that have lack of welding penetration. This is due to thermomechanical hardening of the material of the near-weld zone during welding. Post-annealing does not completely eliminate the effects of the welding cycle.

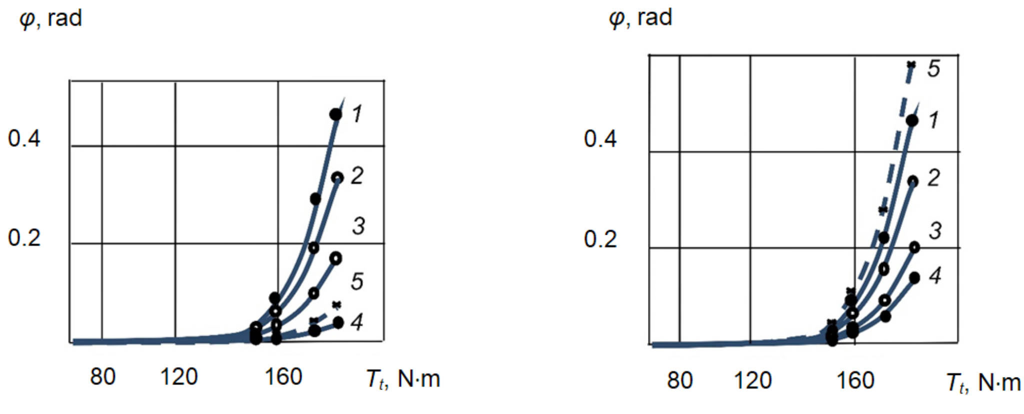


Fig. 7. Amplitude dependence of the absorption coefficient for welded joints:
a – steel 45 + steel 45; *b – steel 45 + steel R6M5*

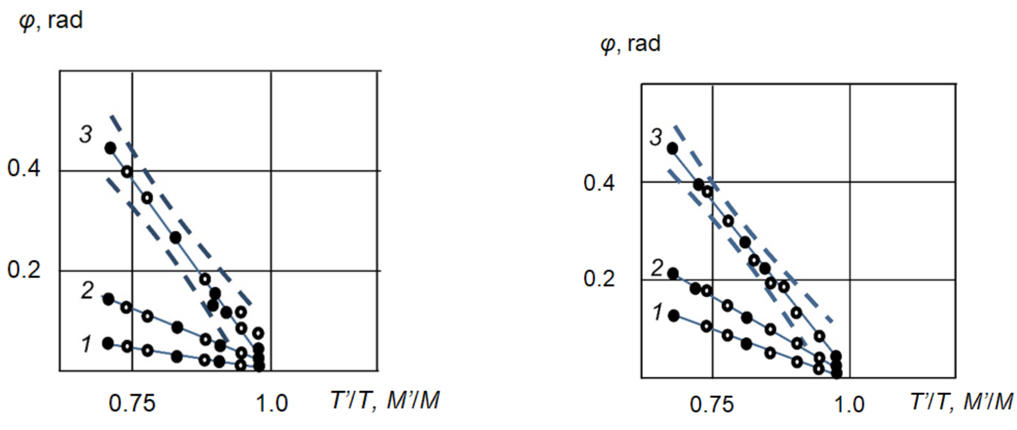


Fig. 8. Relation between the absorption coefficient and relative strength of the joint:
a – steel 45 + steel 45; *b – steel 45 + R6M5* for different torque amplitudes

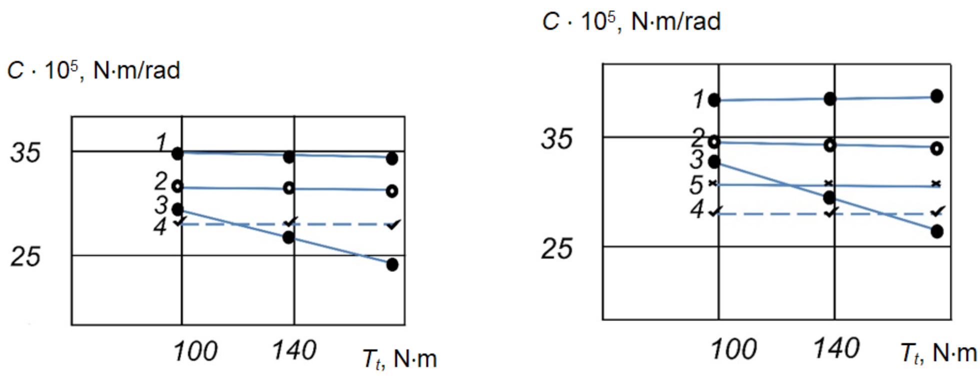


Fig. 9. Amplitude dependence of stiffness of welded joints:
a – steel 45 + steel 45; *b – steel 45 + steel R6M5*

The connection of the rigidity of welded joints with relative strength is shown in fig. 10. The dependences are plotted at the amplitude of the torque T = 137.2 N×m. The **dashed lines** indicate 96 % confidence interval for the theoretical regression line. A similar area is built on all graphs.

Non-destructive methods are proposed to determine the strength of butt joints obtained by pressure welding, according to its rigidity and damping ability [9, 15, 16] based on the experimental studies discussed

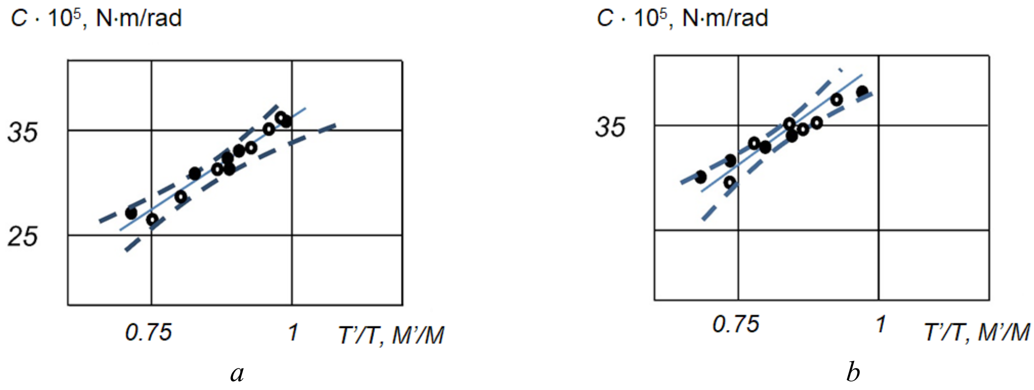


Fig. 10. Relation between rigidity and relative strength of welded joints:
a – steel 45 + steel 45; b – steel 45 + steel R6M5

above. These methods are based on the premise considering lack of welding penetration as a mechanical contact between two solid bodies, which possesses enhanced damping properties. It is proposed to control connections by the *static hysteresis loop method*.

The characteristics for evaluating the strength of welded joints are absorption coefficient, energy dissipation and rigidity of joints with a static method of control. The amplitude dependences of the characteristics under consideration are built for a batch of joints welded in different modes according to this method. Then, the destruction of joints is carried out. Further, the correspondence of each curve to the amplitude dependence of certain strength is established. Based on these data, the dependence graphs of the absorption coefficient, energy dissipation or rigidity of the joint strength for certain torque amplitudes are built (Fig. 6, 7, 8). These dependencies are the main calibration charts for determining the joint strength. Knowing the energy dissipation or the absorption coefficient or rigidity of joints at certain loading amplitude, one can determine its strength.

The choice of controlled joint characteristics depends on the specific conditions. If it is impossible to maintain exactly the distance between the sensor blades, then it is better to evaluate the strength by the absorption coefficient, which does not depend on the gauge length. If the loading amplitude is not clearly fixed, it is better to determine the strength of joints by its rigidity. Besides, the rigidity of the joints changes if there are pores, which reduce the cross section, while the absorption coefficient practically does not change. The control of joints in terms of energy dissipation, absorption coefficient and its rigidity is associated with large labor intensity in processing experimental data. Labor intensity can be reduced if the energy dissipation is estimated according to the width of the hysteresis loop (fig. 11).

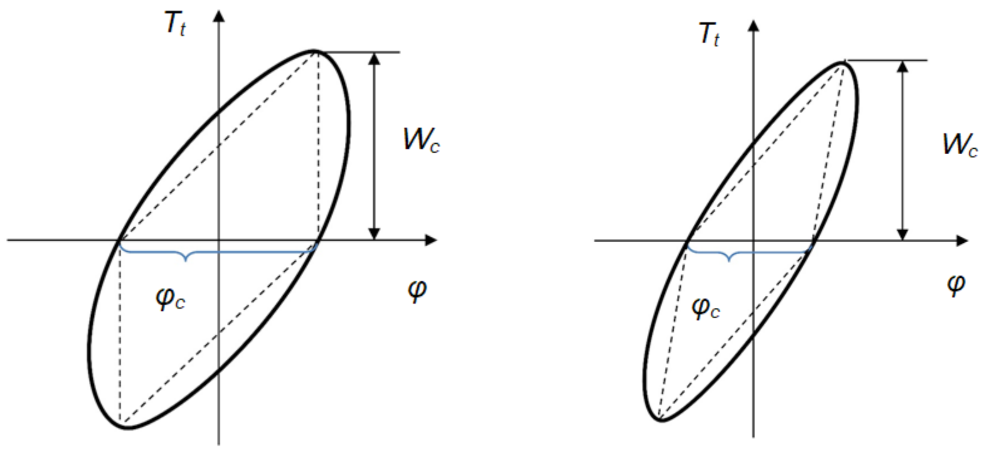


Fig. 11. Mechanical hysteresis loops for specimens with different strengths

The area of the loop *W* can be approximately represented as the area of two triangles with the base φ_c (loop width in radians and loop height) the amplitude of the torsion moment is T_t in N·m.

The energy dissipation will be proportional to the loop width at the same torque for all specimens.

The connection of the torsion strength of annealed specimens with the width of the mechanical hysteresis loop at torque amplitude of 176.4 N·m is shown in fig. 12, where a) and b) are specimens made of *steel 45* and *steel R6M5*, and "○" and "●" are joints obtained by friction welding and resistance welding, respectively. When controlled by the *static hysteresis loop method*, for its closure it is necessary to perform several cycles of preloading during torsion, and it is obtained automatically during bending vibrations.

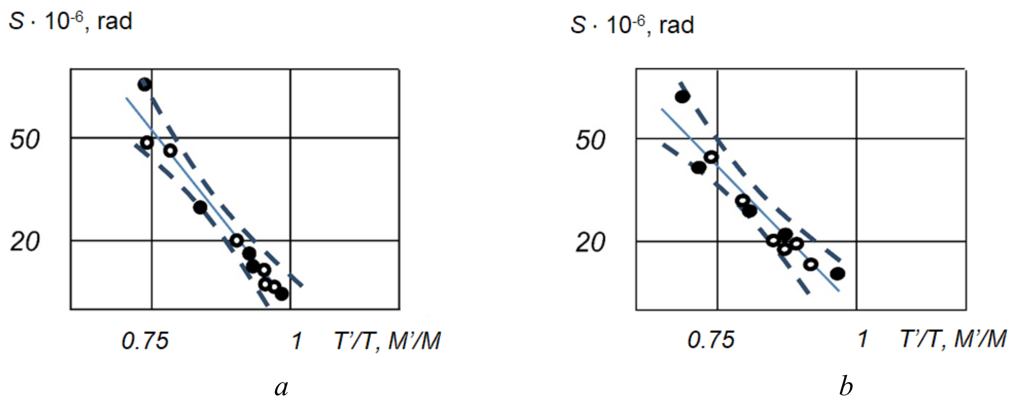


Fig. 12. Relation between the mechanical hysteresis loop width and relative torsional strength for annealed joints:
a – steel 45 + steel 45; *b – steel 45 + steel R6M5*

In order to clarify the effect of the material structure on the weld quality, metallographic studies of joints (*steel 45 + steel 45*) and (*steel 45 + steel R6M5*) were carried out. Metallographic analysis was performed with the help of instrumental microscopes at ×400 magnification. Micrographical etching is standard for these steels.

The specimens were subjected to various types of heat treatment, simulating the conditions (temperature and duration of heating during welding, cooling intensity, etc.) for the formation of the weld structure. The data obtained made it possible to specify the technological parameters of butt welding, as well as friction welding, namely, heating time, etc. (Tables 1, 2)

Conclusion

It has been established that with an increase in lack of welding penetration, the energy dissipation increases at the same values of the torque amplitude under static loading conditions. It has been revealed that the rigidity of qualitatively welded joints remains constant, and the rigidity of joints with lack of welding penetration decreases with an increase of torque amplitude.

The usage of the *static hysteresis loop method* allowed establishing the connection of the rigidity and damping ability of welded joints with its strength. It allows this method to be used as a non-destructive testing method for assessing the quality of butt joints obtained by pressure welding.

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Conflicts of Interest

The authors declare no conflict of interest.