ISSN 2522-4182

DOI: 10.32347/2522-4182.18.2026.8-19
УДК 624.012.26

STRENGTH OF WELDED JOINTS IN CLASS A500C REINFORCING BARS UNDER LOW-CYCLE REPEATED LOADS

Yulii KLYMOV

Kyiv National University of Construction and Architecture
31, Povitryanykh Syl Ave., Kyiv, Ukraine, 03037

yuliiklymov@gmail.com, https://orcid.org/0000-0002-4275-7058

Yulii KLYMOV
Professor of the Department of Reinforced Concrete and Stone Structures,
D.Sc. (Eng.)

Abstract. For more than 25 years now, A500C class reinforcement has been the most widely used in reinforced concrete structures. The introduction of class A500C reinforcement has been accompanied by extensive research into its mechanical properties, bond with concrete, weldability and behavior under repeated loading. In particular, data have been obtained on the state diagram, the fulfilment of standardized mechanical properties such as yield strength, tensile strength, elongation at break, the bond with concrete of crescent-shaped reinforcing bars, thermal weldability, and the strength of butt and cross-shaped welded joints. At the same time, the strength of both the class A500S reinforcement itself and its welded joints under low-cycle and repeated loading remains poorly understood.

This paper presents the results of experimental research on the most widely used types of welded joints for class A500C reinforcing bars – the C1-Ko type butt joint and the K1-Кт type cross joint under low-cycle repeated loading.

The research carried out included tests on samples of 20A500C reinforcing bars made from St3Gps steel and 25A500S reinforcing bars made from 25G2S steel in their as- manufactured condition, their butt welds C1-Ko for tensile strength and cross-shaped joints K1-Кт with 10A500C and 12A500C reinforcing bars for rationalization by welding under monotonically increasing and low-cycle repeated loading. The maximum cycle stresses were taken as $0,8\sigma_y$, which amounted to 400N/mm^2, and the minimum cycle stresses as 80 N/mm^2. The stress range and cycle asymmetry coefficient were, respectively, $\Delta\sigma$=320N/mm^2 and ρ=0.2. The number of loading cycles was set at 50, after which the specimens were subjected to a monotonically increasing load until failure.

It has been established that failure of the C1-Ko welded joint under monotonically increasing and low-cycle repeated loading occurs within the heat-affected zone. In tests under monotonically increasing loading, the tensile strength of the C1-Ko welded joint for 20A500C reinforcing bars was 0,88–0,92, and for 25A500C reinforcement made of 25G2S steel – 0.89–0.90 times the strength of the reinforcement in its as- manufactured condition.

The test results showed that repeated loading did not have a lasting effect on the strength of C1-Ko butt welds in 20A500C and 25A500C reinforcing bars. The reduction in strength compared with a monotonically increasing load did not exceed 1–2%, and was within the test accuracy limits, amounting to 0,87–0,90 of the tensile strength of the reinforcement in its manufactured state.

Failure of the K1-Кт welded joint under a monotonically increasing load occurred in the base metal, whereas under low-cycle repeated loading, failure occurred either in the base metal or in the heat-affected zone. The reduction in strength due to welding of class A500S reinforcement bars – 20A500C and 25A500C – in a K1-Кт type welded joint with reinforcement bars of, respectively, 10A500C and 12A500C, under a monotonically increasing load did not exceed 1–2% and was within the test accuracy limits, which, on the whole.

The test results showed that low-cycle repeated loading did not have a lasting effect on strength of

C1-Ko and K1-Kт welded joints made from 20A500C and 25A500C reinforcing bars; the reduction in strength, compared with tests using amonotonically increasing load, did not exceed 1–2% and was within the test accuracy limits, as was the case with tests on reinforcement in its manufactured state.

Keywords: welded; joint: strength; class A500C; low-cycle repeated loading

PROBLEM STATEMENT AND ANALYSIS OF PREVIOUS RESEARCH

A significant number of reinforced concrete structures used in modern industrial, civil, transport and hydraulic engineering construction, including the spans of railway and road bridges, crane girders, foundations and floor slabs supporting unbalanced process equipment, and others are subjected to repeated loads during their service life.

The A500C class reinforcement used in such structures, as per DSTU-3760, has specific characteristics that affect both the strength of the reinforcement itself and the welded joints used. Firstly, the reinforcement has a crescent-shaped cross-sectional profile, in which the transverse ribs do not intersect with the longitudinal rib, which prevents the formation of stress concentrators at the points where the ribs intersect and positively affects the reinforcement's resistance to repeated loading. Secondly, A500C class reinforcement according to DSTU-3760 is thermomechanical hardened, a feature of which is the varying strength of the layers within the cross-section. Thus, the outer layer, formed as a result of quenching with water during the manufacturing process from 900°C to 400–500°C, has greater strength, whilst the inner core, formed as a result of self-tempering under conditions close to isothermal, has lower strength, approaching that of steel in its as-cast condition. In this case, the strength of the reinforcing bar is determined by the integral strength of the outer layer and the inner core.

This structure of the reinforcement has a negative impact on the strength of its welded joints, which involve heating to temperatures of 500–700°C without subsequent cooling, leading to a loss of strength to almost the level of the initial state.

The weldability of thermomechanical strengthened reinforcement of class A500C is the subject of the works [1–3], which, in particular, investigated thermal weldability [1], improvements to welding technology [4], and the strength of various types of welded joints [4,5,6].

It has been established that at heating temperatures of 650°C and above, there is a significant drop in the temporary resistance and yield strength of the reinforcement to values close to those of the material in its as-received condition, i.e. a complete loss of the thermomechanical strengthening effect [1], which limited the number of types of welded joints for A500C class reinforcement. Thus, for a butt joint of A500C class reinforcement of type C1-Ko, according to [3], the strength reduction ranged from 8 to 20% and depended on the diameter and mark of steel, reflecting the behavior of thermomechanical strengthened A500C class reinforcing bars when heated during the welding process [1].

A similar trend was observed for cross-shaped welded joints of types K1-Kт and K3-Pp according to [2], for which the hardening during welding in tests amounted to, respectively, up to 4% and between 4% and 10%. In shear tests of cross-shaped welded joints between A500C class reinforcement and A240C class reinforcement, the reduction in strength compared to the initial state was up to 11%, and for joints between A500C class reinforcements – up to 20% [2].

As regards the testing of A500C class reinforcing bars and their welded joints under repeated loading, such studies have only been conducted under multiple repeated loading cycles, with a view to determining fatigue strength and the number of such studies is insufficient to draw definitive, well-founded conclusions.

At the same time, it is known that the presence of welded joints leads to a reduction in the strength of the reinforcement under repeated loading and depends on the type of welded joint. The types of welded joints used can be broadly divided into two groups. The first group comprises welded joints formed by directly welding the reinforcement elements through the melting of the base metal. The second group comprises welded joints formed by the deposition of filler material between the elements.

The reduction in the strength of welded joints in the first group under repeated loading is due to the presence of a stress concentration point formed by the settlement of the components at the moment of welding. In welded joints of the second group, the joint area can be conventionally divided into a zone of metal that has been melted and a zone of base metal that has been heated to a temperature below its melting point. In turn, the molten metal zone consists of filler metal that has not been mixed with the base metal, and a region of diffusion mixing between the filler and base metals, where hardening cracks form, reducing the strength of the welded joints in the reinforcement under repeated loading cycles.

The works [7–21] are devoted to studies of the strength of welded reinforcement joints under multiple repeated loading (fatigue), within the scope of these studies, data have been obtained on residual stresses [7–13] and fatigue cracks developing in welded joints [14–16], the strength of butt [13,17] and T-joint welded connections [18]. The experimental data obtained formed the basis for computational assessments of the strength of welded joints under repeated loading, including the modelling of fatigue crack propagation [19], and the prediction and assessment of the strength of welded joints based on fracture mechanics [20, 21].

In current regulatory documents, the effect of multiple cyclic loads on the strength of reinforcing bars and their welded joints is taken into account in fatigue calculations by adopting an appropriate fatigue life curve DSTU-B V.2.6-156.

As regards the strength of welded joints and A500C class reinforcing bars according to DSTU-3760 under low-cycle repeated loading, no such experimental studies have been conducted to date, despite the fact that most structures operate precisely under such conditions, and a reduction in the strength of reinforcing bar joints occurs even under static loads.

In light of the above, the study of the strength of welded joints of A500C class reinforcement under low-cycle repeated loading represents a pressing task from both a theoretical and practical perspective.

The purpose of the work is to conduct experimental studies to determine the failure mode and strength of butt C1-Ko and cross-shaped K1-Kт welded joints in A500C class reinforcing bars, formed by contact and contact-spot welding respectively in accordance with DSTU-B V.2.6-169 under low-cycle repeated loading.

MAIN MATERIAL AND RESULTS OF RESEARCH

For the purposes of testing, the following welded joints of A500C-grade reinforcing bars were selected, as these are the most commonly used in modern construction for the fabrication of reinforcement cages and meshes in reinforced concrete structures:

- C1-Ko type butt joint, produced by resistance spot welding;
- K1-Kт type cross-shaped joint, performed by contact spot welding.

For the tests, samples of 20A500C reinforcement made from St3Gps steel mark and 25A500C reinforcement made from 25G2S steel mark were selected from industrial production batches with a carbon equivalent close to the minimum. The chemical composition of St3Gps and 25G2S steel mark for 20A500C and 25G2S reinforcing bars is given in Table 1.

The experimental research programme included:

- tensile testing of reinforcement specimens in accordance with DSTU-10080 to determine the mechanical properties of the reinforcement in its initial state;
- fabrication and tensile testing in accordance with DSTU-B V.2.6-168 of welded joints C1-Ko and K1-Kт under a monotonically increasing load;
- fabrication and testing of welded joints C1-Ko and K1-Kт under low-cycle repeated loading, respectively, for tensile testing in accordance with DSTU-10080 and hardening by welding in accordance with DSTU-B V.2.6-168.

Tabl.1. Chemical composition of steel
Табл.1. Хімічний склад сталі

Diameter, mm	Chemical composition of steel, %										C_{eq}
	C	Mn	Si	S	P	Cr	Ni	Cu	As	Ti	
20	0,20	0,58	0,07	0,033	0,008	0,04	0,01	0,01	0,005	0,0021	0,31
25	0,22	1,13	0,02	0,019	0,015	0,16	0,02	0,03	0,007	0,002	0,45

The mechanical properties of the reinforcement in its as-manufactured condition (yield strength, ultimate tensile strength, relative elongation after fracture and relative uniform elongation) were determined during tensile testing in accordance with DSTU-10080 of three specimens.

For the cross-shaped welded joints K1-Кт, 10A500C reinforcement was used as the transverse bar for the 20A500C longitudinal bar, and 12A500C for the 25A500C longitudinal bar.

The C1-Ko and K1-Кт welded joints were fabricated in accordance with the relevant provisions of. In particular, the C1-Ko welded joints were fabricated on an MSO-606 machine using the continuous melting method without preheating. The set length was taken within the range (0.6–1.0)d, the melting length within (0.3–0.5)d, and the diameter of the burr was not less than 1.2d. The heating temperature of the rods during welding was measured using a “Raynger MX” optical pyrometer and, in the area adjacent to the fusion line, was 780°C … 870°C. and at distances of 10 and 30 mm from the fusion line – 415°C … 570°C and 360°C … 398°C, respectively. K1-Кт cross-shaped welded joints were performed on an MTP-75 machine; the relative reduction was 0.25–0.32d (d – diameter of the smaller rod). The clamping force of the electrodes was set at 2.5–4.0 kN. The heating temperature of the main (longitudinal) rod during welding was measured using a ‘Raynger MX’ optical pyrometer and ranged from 326°C to 400°C.

In tests involving low-cycle repeated loading, the maximum cycle stress was taken as 0.8, which amounted to 400 N/mm², and the minimum cycle stress as 80 N/mm². The stress range and cycle asymmetry coefficient were, respectively, $\Delta\sigma$=320N/mm² and ρ=0.2. The number of loading cycles was set at 50, after which the specimens were subjected to a monotonically increasing load until failure. A total of five specimens of each type of welded joint were tested.

The composition of the experimental studies for determining the strength characteristics of the reinforcement in the as-manufactured condition is given in Table 2, the strength of welded joints C1-Ko and K1-Кт under monotonically increasing load testing – in Table 3, and the strength of welded joints under low-cycle repeated tensile loading and weld hardening – in Table 4.

Tabl.2. Testing of reinforcement samples in their manufactured condition
Табл.2. Склад випробувальних зразків у вихідному стані

№ п/п	Diameter, mm	Reinforcement class	Steel mark	Number of samples	Type of test, regulatory document	Parameters to be specified
1	20	A500C	St3Gps	3	Tensile strength according to DSTU-10080	σ_y, σ_u, δ_5, δ_p
2	25	A500C	25G2S	3		

Tabl.3. Composition of welded reinforcement joints tested under a monotonically increasing load
Табл.3. Склад зварних з'єднань арматури, які випробувались при монотонно зростаючому навантаженні

№ п/п	Type of welded joint	Weldable reinforcing bars		Number of samples, pcs	Type of test, regulatory document
		bar 1	bar 2		
1	С1-Ко	∅20А500С	∅20А500С	3	Tensile strength according to DSTU-10080
	С1-Ко	∅25А500С	∅25А500С	3	Tensile strength according to DSTU-10080
2	К1-Кт	∅20А500С	∅10А500С	3	Rationalization by welding according to DSTU-B V.2.6-168
	К1-Кт	∅25А500С	∅12А500С	3	Rationalization by welding according to DSTU-B V.2.6-168

Tabl.4. Composition of welded reinforcement joints tested under low-cycle repeated loading
Табл.4. Склад зварних з'єднань арматури, які випробувались при молоциклових повторних навантаженнях

№ п/п	Type of welded joint	Weldable reinforcing bars		Number of samples, pcs	Type of test, regulatory document
		bar 1	bar 2		
1	С1-Ко	∅20А500С	∅20А500С	5	Tensile strength according to DSTU-10080 under low-cycle repeated loading
		∅25А500С	∅25А500С	5	Tensile strength according to DSTU-10080 under low-cycle repeated loading
2	К1-Кт	∅20А500С	∅10А500С	5	Tensile strength according to DSTU-B V.2.6-168 under low-cycle repeated loading
		∅25А500С	∅12А500С	5	Tensile strength according to DSTU-B V.2.6-168 under low-cycle repeated loading

The test results for the reinforcement specimens in their as-manufactured condition are given in Table 5, for the welded joint, С1-Ко under monotonically increasing and low-cycle repeated loading tests, respectively, in Tables 6 and 7, and the welded joint К1-Кт under monotonically increasing and low-cycle repeated loading tests, respectively, in Tables 8 and 9.

Tabl.5. Test results for the reinforcement specimens in their as-manufactured condition
Табл.5. Результати випробувань зразків арматури у вихідному стані

Diameter, mm	Number of samples, pcs	σ_y N/mm²	σ_u, N/mm²	$\sigma_{u,m}$, Н/мм²	σ_y/σ_u	δ_5, %	δ_{max}, %
20	1	565,5	696,7	659,2	1,23	22,5	10,6
	2	562,4	624,8		1,11	20,0	11,7
	3	562,4	656,1		1,17	20,0	10,9
25	1	559,9	695,8	695,5	1,24	19,2	12,6
	2	559,9	699,8		1,25	20,8	11,4
	3	559,9	689,8		1,23	19,2	10,9

Notes: $\sigma_{u,m}$ - the average value of the ultimate resistance

Tests on samples of the C1-Ko reinforcement welded joint revealed the following.

Failure of the C1-Ko welded joint under monotonically increasing and low-cycle repeated loading occurred within the heat-affected zone.

The average strength of the C1-Ko welded joint under monotonically increasing load for diameters 20A500C and 25A500C was 600.5 N/mm² and 615.5 N/mm² respectively (Table 6). The range of strength values for the welded joint was 24.3–12.3 N/mm² and did not exceed the standardized range value of 38.0 N/mm² as per DSTU-B V.2.6-168.

The strength of the C1-Ko welded joint during tests with a monotonically increasing load for 20A500C reinforcement was 0,88–0,92 and for 25A500C reinforcement made of 25G2S steel – 0.89–0.90 times the strength of the reinforcement in its as-manufactured state (Tabl. 5, 6), which, on the whole, corresponds to previous tests of welded joints of A500C-class reinforcement [4].

The average value of the tensile strength of the C1-Ko type welded joint for 20A500C reinforcement during low-cycle repeated loading tests was 599.5 N/mm², and for 25A500C reinforcement – 604.9 N/mm². Thus, the reduction in the tensile strength of the welded joints compared with loading under a monotonically increasing load did not exceed 1–2% and was within the test accuracy limits.

Tabl.6 Test results for the C!-Ko welded joint under a monotonically increasing load
Табл.6. Результати випробувань зварного з’єднання C!-Ко при монотонно зростаючому навантаженні

Type of welded joint	Diameter, mm	σ_w, N/mm²	$\sigma_{w,mm}$, Н/мм²	$\sigma_{w,max}$, Н/мм²	$\sigma_{w,min}$ Н/мм²	R, Н/мм²	$\frac{\sigma_{w,mm}}{\sigma_u}$
C1-Ko	20	609,4	600,5	609,8	582,5	24,3	0,91
		582,5					
		609,8					
	25	614,3	615,5	622,3	610,0	12,3	0,89
		622,3					
		610,0					

Notes: σ_w - the ultimate value of the resistance of a welded joint; $\sigma_{w,mm}$ - the average value of the ultimate resistance of a welded joint; $\sigma_{w,max}$ - the maximum value of the ultimate resistance of a welded joint; $\sigma_{w,min}$ - the minimum value of the ultimate resistance of a welded joint; R - Range of the ultimate resistance values of welded joints; $\sigma_{u,m}/\sigma_{w,m}$ - the ratio of the average ultimate resistance of the reinforcement in its manufactured condition to the average ultimate resistance of the welded joint

Tabl.7. Test results for the C1-Ko welded joint under a low-cycle repeated loading
Табл.7. Результати випробувань зварного з’єднання С1-Ко при малоцикловому повторному навантаженні

Type of welded joint	Diameter, mm	σ_w, N/mm²	$\sigma_{w,ml}$, Н/мм²	$\sigma_{w,max}$, Н/мм²	$\sigma_{w,min}$ Н/мм²	R, Н/мм²	$\frac{\sigma_{w,ml}}{\sigma_{u,mm}}$
C1-Ko	20	606,5	599,5	605,7	570,0	35,7	0,99
		570,0					
		603,2					
		589,8					
		605,7					
C1-Ko	25	606,8	604,9	608,5	599,0	9,5	0,98
		599,0					
		600,0					
		608,5					
		606,1					

Tabl.8 Test results for the K1-Kт welded joint under a monotonically increasing load
Табл.8. Результати випробувань зварного з'єднання К1-Кт при монотонно зростаючому навантаженні

Type of welded joint	Connected bars		σ_w, N/mm^2 2	$\sigma_{w,mm}$, Н/мм^2	$\sigma_{w,max}$, Н/мм^2	$\sigma_{w,min}$, Н/мм^2	R, Н/мм^2	$\frac{\sigma_{w,mm}}{\sigma_u}$
	longitudinal	transverse						
К1-Кт	∅20 А500С	∅10 А500С	662,5	651,3	662,5	640,6	21,9	0,98
			640,6					
			650,8					
К1-Кт	∅25 А500С	∅12 А500С	686,0		699,3	680,0	19,3	0,99
			680,0					
			699,3					

Tests on samples of the K1-Kт reinforcement welded joint revealed the following.

Failure of the K1-Kт welded joint under a monotonically increasing load occurred in the base metal (Table 8), whereas under low-cycle repeated loading, it occurred either in the base metal or in the heat-affected zone (Tabl. 9).

Tabl. 9. Test results for the K1-Kт welded joint under a low-cycle repeated loading
Табл. 9. Результати випробувань зварного з'єднання К1-Кт при малоцикловому повторному навантаженні

Type of welded joint	Connected bars		σ_w, N/mm^{22}	$\sigma_{wl,mm}$, Н/мм^2	$\sigma_{wl,max}$, Н/мм^2	$\sigma_{wl,min}$, Н/мм^2	R, Н/мм^2	$\frac{\sigma_{wl,mm}}{\sigma_{u,mm}}$
	longi-tudinal	trans-verse						
К1-Кт	∅20 А500С	∅10 А500С	650,3[1]	646,0	660,3	630,0	30,3	0,99
			642,6[2]					
			660,1[2]					
			648,0[1]					
			630,0[1]					
К1-Кт	∅25 А500С	∅12 А500С	679,0[1]	677,6	679,0	668,5	10,5	0,98
			668,5[2]					
			678,0[2]					
			683,7[2]					
			671,2[1]					

Notes: [1] - breakage of the base metal; [2] breakage in the thermal influence zone

The average strength of the K1-Kт welded joint under a monotonically increasing load for 20 A500C and 25A500C reinforcement bars was 651.3 N/mm² and 688.4 N/mm² respectively (Tabl. 8) and depended on the strength of the metal in its as-received condition. The range of strength values for the welded joint was 21.9 and 19.3 N/mm² and did not exceed the standardized range value according to DSTU-B V.2.6-168, which is 38.0 N/mm².

The hardening of A500C grade reinforcement in a K1-Kт type welded joint under a monotonically increasing load did not exceed 1.. 2% and fell within the test accuracy limits. Furthermore, the results obtained are, on the whole, consistent with data from previously conducted tests on K1-Кт type welded joints for weld hardening [3].

The average strength of the K1-Кт welded joint of 20A500C reinforcement in weld hardening tests under low-cycle repeated loading was 646.2 N/mm², and that of 25A500C reinforcement was 677.6N/mm². Thus, the weld hardening of the K1-Kt joint under low-cycle repeated loading, compared with a monotonically increasing load, did not exceed 1–2% and was within the test accuracy limits.

CONCLUSIONS

Experimental studies were conducted on the most commonly used types of welded joints for A500C class reinforcing bars – the tensile strength of C1-Ko-type butt joints made by resistance spot welding and the hardening of K1-Кт-type cross joints made by resistance spot welding under low-cycle repeated loading.

The effect of low-cycle repeated loading on the fracture behavior and strength characteristics of welded joints was assessed on the basis of tests on samples of A500C- class reinforcing bars - 20A500C made of St3Gps steel and 25A500C made of 25G2S steel in the as-received condition (as-supplied condition), for C1-Ko and K1-Кт welded joints under monotonically increasing and repeated loading. For the cross-bar of the K1-Кт cross-shaped welded joints, 10A500C reinforcement was used for the 20 A500C longitudinal bar and 12A500C for the 25A500C longitudinal bar during weld hardening tests.

For the repeated loading tests, the most ‘severe’ loading regime was adopted, with the maximum possible cycle load of $0{,}8\sigma_y$=400 N/mm², a cycle stress range of $\Delta\sigma$=320 N/mm² and a minimum cycle asymmetry factor of ρ=0.2. The number of loading cycles was set at 50, after which the specimens were brought to failure under a monotonically increasing load. A total of five specimens of each type of welded joint were tested.

It was established that the failure of the C1-Ko type welded joint under a monotonically increasing and low-cycle repeated load occurs in the heat-affected zone. In tests with a monotonically increasing load, the tensile strength of the C1-Ko welded joint for 20A500C reinforcement was 0.88–0.92, and for 25A500C reinforcement made of 25G2S steel – 0.89–0.90 times the strength of the reinforcement in its manufactured condition (Tabl. 5, 6), which, in general, corresponds to previously conducted tests of welded joints of A500C class reinforcement [4].

According to the test results, low-cycle repeated loading did not have a lasting effect on the strength of the C1-Ko butt welds of 20 A500C and 25 A500C reinforcing bars; the reduction in strength compared to a monotonically increasing load did not exceed 1–2%, was within the test accuracy limits and amounted to 0.87–0.90 of the tensile strength of the reinforcement in its manufactured state.

Failure of the K1-Кт welded joint under a monotonically increasing load occurred in the base metal (Tabl. 8), whereas under low-cycle repeated loading, failure occurred either in the base metal or in the heat-affected zone (Tabl. 9). The reduction in strength due to welding of A500C class reinforcement bars – 20A500C and 25A500C – in a K1-Кт type welded joint with reinforcement bars of, respectively, 10A500C and 12A500C, under a monotonically increasing load did not exceed 1–2% and was within the test accuracy limits, which, in general, is consistent with the data from previously conducted tests of K1-Кт type welded joints for hardening by welding [3].

According to the test results, low-cycle repeated loading did not have a sustained effect on the work hardening of C1-Кт joints made of 20 A500C and 25A500C reinforcing bars; compared to tests with a monotonically increasing load, the work hardening did not exceed 1–2%, and remained within the test accuracy limits, as was the case with tests on reinforcement in its manufactured state.

To draw definitive conclusions regarding the effect of low-cycle repeated loading on the strength characteristics of C1-Ko and K1-Кт welded joints of A500 class reinforcement, further tests must be conducted using 12A500S… 16A500C made of St3ps steel, as well as shear strength tests on K1-Кт joints for the full range of diameters, since K1-Kt is a standardized strength joint and the manufacturing process has a significant effect on the softening of the main bar due to welding.

ETHICAL DECLARATIONS

The authors have no relevant financial or non-financial interests to report.

LITERATURE

1. **Клімов, Ю. А.** (2017). Теплова зварюваність арматури класу А500С. *Будівельні конструкції: Теорія і практика, (1)*, 22–27. https://doi.org/10.32347/2522-4182.1.2017.22-27
2. **Клімов, Ю.А.** (2022). Міцність хрестоподібних зварних з'єднань арматури класу А500С. *Будівельні конструкції: Теорія і практика, 11*, 4–17.https://doi.org/10.32347/2522-4182.11.2022.4-17
3. **Клімов, Ю.А.** (2022). Міцність стикового контактного зварного з'єднання арматури класу А500С. *Будівельні конструкції: Теорія і практика, 10*, 79–93. https://doi.org/10.32347/2522-4182.10.2022.79-93
4. **Kubicki, K.** (2023). Technical and economic aspects of load-bearing welded joints in reinforcing steel. *Construction of Optimized Energy Potential, 12*, 228–235. https://doi.org/10.17512/bozpe.2023.12.25
5. **Caprili, S., Salvatore, W. & Valentini, R.** (2021). Micro and macro structural investigations on welded joints of composite truss steel concrete beams. *Advances in Materials Science and Engineering*, 2021, 1–13 https://doi.org/10.1155/2021/6183178?urlappend=%3Futm_source%3Dresearchgate.net%26utm_medium%3Darticle
6. **Sharbatdar, M. K., Mohammadi Jafaria, O., & Karimi, M. S.** (2018). Experimental evaluation of splicing of longitudinal bars with forging welding in flexural reinforced concrete beams. *Advances in Concrete Construction, 6*(5), 509–525. https://doi.org/10.12989/acc.2018.6.5.509
7. **Бердник, О., Макаренко, В., & Амеліна, Н.** (2024). Дослідження взаємозв'язку між межею міцності і тривалою втомленістю сталевої арматури залізобетонних конструкцій тривалого терміну експлуатації в агресивних середовищах. *Будівельні конструкції: Теорія і практика, (14)*, 125–135.https://doi.org/10.32347/2522-4182.14.2024.125-135
8. **Knoedel, P., Gkatzogiannis, S., & Ummenhofer, T.** (2017). Practical aspects of welding residual stress simulation. *Journal of Constructional Steel Research, (132)*, 83–96. https://doi.org/10.1016/j.jcsr.2017.01.010
9. **Chattopadhyay, A., Glinka, G., El-Zein, M., Qian, J., & Formas, R.** (2011). Stress analysis and fatigue of welded structures. *Welding in the World, 55*, 2–21. https://doi.org/10.1007/BF03321303
10. **Hensel, J., Nitschke-Pagel, T., Tchoffo Ngoula, D., Beier, H.-Th., Tchuindjang, D., & Zerbst, U.** (2018). Welding residual stresses as needed for the prediction of fatigue crack propagation and fatigue strength. *Engineering Fracture Mechanics, 198*, 123–141. https://doi.org/10.1016/j.engfracmech.2017.10.024
11. **Gadallah, R., Osawa, N., Tanaka, S., & Tsutsumi, S. (**2018). Critical investigation on the influence of welding heat input and welding residual stress on stress intensity factor and fatigue crack propagation. *Engineering Failure Analysis, 89*, 200–221. https://doi.org/10.1016/j.engfailanal.2018.02.028
12. **Zhang, W., Jiang, W., Zhao, X., & Tu, S.-T.** (2018). Fatigue life of a dissimilar welded joint considering the weld residual stress: Experimental and finite element simulation. *International Journal of Fatigue, (109)*, 182–190. https://doi.org/10.1016/j.ijfatigue.2018.01.002
13. **Ferro, P., Berto, F., & James, M. N.** (2016). Asymptotic residual stresses in butt-welded joints under fatigue loading. *Theoretical and Applied Fracture Mechanics, (83)*, 114–124. https://doi.org/10.1016/j.tafmec.2016.02.002
14. **Madia, M., Schork, B., Bernhard, J., & Kaffenberger, M.** (2017). Multiple crack initiation and propagation in weldments under fatigue loading. *Procedia Structural Integrity, 7*, 423–430. https://doi.org/10.1016/j.prostr.2017.11.108
15. **Lewandowski, J., & Rozumek, D. (**2016). Cracks growth in S355 steel under cyclic bending with fillet welded joint. *Theoretical and Applied Fracture Mechanics, 86*, 342–350. https://doi.org/10.1016/j.tafmec.2016.09.003
16. **Naves, J. A., Carvalho, G., Rodrigues, A., Fernandes, M. S., Santos, F., & Medeiros, G.** (2017). Discontinuity detection in the shield metal arc welding process. *Sensors, 17*(1082). https://doi.org/10.3390/s17051082

17. **Araque, O., Arzola, N., & Hernández, E.** (2018). The effect of weld reinforcement and post-welding cooling cycles on fatigue strength of butt-welded joints under cyclic tensile loading. *Materials, 11*(4), 594. https://doi.org/10.3390/ma11040594
18. **Araque, O., & Arzola, N.** (2018). Weld magnification factor approach in cruciform joints considering post welding cooling medium and weld size. *Materials, 11*(1), 81. https://doi.org/10.3390/ma11010081
19. **Yang, Y., & Vormwald, M.** (2017). Fatigue crack growth simulation under cyclic non-proportional mixed mode loading. *International Journal of Fatigue, (102),* 37–47. https://doi.org/10.1016/j.ijfatigue.2017.04.014
20. **Kucharczyk, M., Madia, U., Zerbst, B., Schork, P., Gerwien, S., & Münstermann, S.** (2018). Fracture-mechanics based prediction of the fatigue strength of weldments: Material aspects. *Engineering Fracture Mechanics, 198*, 79–102. https://doi.org/10.1016/j.engfracmech.2017.09.010
21. **Kucharczyk, M., Madia, U., Zerbst, B., Schork, P., Gerwien, S., & Münstermann, S.** (2018). Fracture-mechanics based prediction of the fatigue strength of weldments: Material aspects. *Engineering Fracture Mechanics, 198*, 79–102. https://doi.org/10.1016/j.engfailanal.2014.12.021

REFERENCES

1. **Klimov, Yu. A. (**2017). *Teplova zvaryuvanist′ armatury klasu A500S*. *Budivel'ni konstruktsiyi: Teoriya i praktyka*, *1*, 22–27. [In Ukrainian] https://doi.org/10.32347/2522-4182.1.2017.22-27
2. **Klimov, Yu. A.** (2022). Mitsnist′ khrestopodibnykh zvarnykh z'yednan′ armatury klasu A500C. *Budivel'ni konstruktsiyi: Teoriya i praktyka, (11)*, 4–17. [In Ukrainian] https://doi.org/10.32347/2522-4182.11.2022.4-17
3. **Klimov, Yu. A. (2022).** Mitsnist′ stykovoho kontaktnoho zvarnoho z'yednannya armatury klasu A500C. *Budivel'ni konstruktsiyi: Teoriya i praktyka, (10)*, 79–93. [In Ukrainian] *https://doi.org/10.32347/2522-4182.10.2022.79-93*
4. **Kubicki, K.** (2023). Technical and economic aspects of load-bearing welded joints in reinforcing steel. *Construction of Optimized Energy Potential*, *12*, 228–235. https://doi.org/10.17512/bozpe.2023.12.25
5. **Caprili, S., Salvatore, W. & Valentini, R.** (2021). Micro and macro structural investigations on welded joints of composite truss steel concrete beams. *Advances in Materials Science and Engineering*, 2021, 1–13. https://doi.org/10.1155/2021/6183178?urlappend=%3Futm_source%3Dresearchgate.net%26utm_medium%3Darticle
6. **Sharbatdar, M. K., Mohammadi Jafaria, O., & Karimi, M. S.** (2018). Experimental evaluation of splicing of longitudinal bars with forging welding in flexural reinforced concrete beams. *Advances in Concrete Construction*, *6*(5), 509–525. *https://doi.org/10.12989/acc.2018.6.5.509*
7. **Berdnyk, O., Makarenko, V., & Amelina, N. (2024)**. Doslidzhennya vzayemozv'yazku mizh mezheyu mitsnosti i tryvaloyu vtomlenistyu stalevoyi armatury zalizobetonnykh konstruktsiy tryvaloho terminu ekspluatatsiyi v ahresyvnykh seredovyshchakh. *Budivel'ni konstruktsiyi: Teoriya i praktyka, 14, 125–135.* [In Ukrainian] https://doi.org/10.32347/2522-4182.14.2024.125-135
8. **Knoedel, P., Gkatzogiannis, S., & Ummenhofer, T.** (2017). Practical aspects of welding residual stress simulation. *Journal of Constructional Steel Research, (132),* 83–96. https://doi.org/10.1016/j.jcsr.2017.01.010
9. **Chattopadhyay, A., Glinka, G., El-Zein, M., Qian, J., & Formas, R.** (2011). Stress analysis and fatigue of welded structures. *Welding in the World*, *55*, 2–21. https://doi.org/10.1007/BF03321303
10. **Hensel, J., Nitschke-Pagel, T., Tchoffo Ngoula, D., Beier, H.-Th., Tchuindjang, D., & Zerbst, U.** (2018). Welding residual stresses as needed for the prediction of fatigue crack propagation and fatigue strength. *Engineering Fracture Mechanics*, *198*, 123–141. https://doi.org/10.1016/j.engfracmech.2017.10.024
11. **Madia, M., Schork, B., Bernhard, J., & Kaffenberger, M.** (2017). Multiple crack initiation and propagation in weldments under fatigue loading. *Procedia Structural Integrity*, *7*, 423–430. https://doi.org/10.1016/j.engfailanal.2018.02.028
12. **Zhang, W., Jiang, W., Zhao, X., & Tu, S.-T.** (2018). Fatigue life of a dissimilar welded joint considering the weld residual stress: Experimental and finite element simulation. *International Journal of Fatigue, (109)*, 182–190.

https://doi.org/10.1016/j.ijfatigue.2018.01.002

13. **Ferro, P., Berto, F., & James, M. N.** (2016). Asymptotic residual stresses in butt-welded joints under fatigue loading. *Theoretical and Applied Fracture Mechanics, (83)*, 114–124. https://doi.org/10.1016/j.tafmec.2016.02.002
14. **Madia, M., Schork, B., Bernhard, J., & Kaffenberger, M.** (2017). Multiple crack initiation and propagation in weldments under fatigue loading. *Procedia Structural Integrity, 7*, 423–430. https://doi.org/10.1016/j.prostr.2017.11.108
15. **Lewandowski, J., & Rozumek, D. (**2016). Cracks growth in S355 steel under cyclic bending with fillet welded joint. *Theoretical and Applied Fracture Mechanics, 86*, 342–350. https://doi.org/10.1016/j.tafmec.2016.09.003
16. **Naves, J. A., Carvalho, G., Rodrigues, A., Fernandes, M. S., Santos, F., & Medeiros, G.** (2017). Discontinuity detection in the shield metal arc welding process. *Sensors, 17*(1082). https://doi.org/10.3390/s17051082
17. **Araque, O., Arzola, N., & Hernández, E.** (2018). The effect of weld reinforcement and post-welding cooling cycles on fatigue strength of butt-welded joints under cyclic tensile loading. *Materials, 11*(4), 594. https://doi.org/10.3390/ma11040594
18. **Araque, O., & Arzola, N.** (2018). Weld magnification factor approach in cruciform joints considering post welding cooling medium and weld size. *Materials, 11*(1), 81. https://doi.org/10.3390/ma11010081
19. **Yang, Y., & Vormwald, M.** (2017). Fatigue crack growth simulation under cyclic non-proportional mixed mode loading. *International Journal of Fatigue, (102)*, 37–47. https://doi.org/10.1016/j.ijfatigue.2017.04.014
20. **Kucharczyk, M., Madia, U., Zerbst, B., Schork, P., Gerwien, S., & Münstermann, S.** (2018). Fracture-mechanics based prediction of the fatigue strength of weldments: Material aspects. *Engineering Fracture Mechanics, 198*, 79–102. https://doi.org/10.1016/j.engfracmech.2017.09.010
21. **Kucharczyk, M., Madia, U., Zerbst, B., Schork, P., Gerwien, S., & Münstermann, S.** (2018). Fracture-mechanics based prediction of the fatigue strength of weldments: Material aspects. *Engineering Fracture Mechanics, 198*, 79–102. https://doi.org/10.1016/j.engfailanal.2014.12.021

МІЦНІСТЬ ЗВАРНИХ З'ЄДНАНЬ АРМАТУРИ КЛАСУ А500С ПРИ МАЛОЦИКЛОВИХ ПОВТОРНИХ НАВАНТАЖЕННЯХ

Юлій КЛІМОВ

Анотація. Протягом останніх вже понад 25 років арматура класу А500С є найбільш широко використовуваною в залізобетонних конструкціях. Процес впровадження арматури класу А500С супроводжувався численними дослідженнями її механічних характеристик, зчеплення з бетоном, зварюваності та поведінки при повторних навантаженнях. Зокрема, отримано дані про діаграму стану, забезпеченість нормованих показників механічних характеристик, таких як межа текучості, опір розриву, відносне подовження при розриві, зчеплення з бетоном арматури з серпоподібним профілем, теплову зварюваність та міцність стикових і хрестоподібних зварних з'єднань. Водночас міцність як самої арматури класу А500С, так і її зварних з'єднань при малоциклових і багаторазово повторюваних навантаженнях залишається малодослідженою.

У роботі наведено результати експериментальних досліджень найбільш широко застосовуваних на практиці типів зварних з'єднань арматури класу А500С – стикового з'єднання контактним зварюванням типу С1-Ко та хрестоподібного з'єднання контактним зварюванням К1-Кт при малоциклових повторних навантаженнях.

Проведені дослідження включали випробування зразків арматури 20А500С зі сталі марки Ст3Гпс та 25А500С зі сталі марки 25Г2С у стані поставки, їх стикових зварних з'єднань С1-Ко на міцність при розтягуванні та хрестоподібних з'єднань К1-Кт з арматурою 10А500С і 12А500С на розм'якшення зварюванням при монотонно зростаючих і малоциклових повторних навантаженнях. Максимальні напруження циклу приймаються рівними 0,8σ_y, що становило 400 Н/мм^2 , мінімальні напруження циклу — 80 Н/мм^2. Розмах напружень і коефіцієнт асиметрії циклу при цьому відповідно становили $\Delta\sigma$ =320Н/мм² (МПа) і ρ=0,2. Кількість циклів повторних навантажень приймалася рівною 50, після яких зразки доводилися до руйнування монотонно зростаючим навантаженням.

Встановлено, що руйнування зварного з'єднання типу С1-Ко при монотонно зростаючому та малоцикловому повторному навантаженні відбувається в зоні термічного впливу. Під час випробувань монотонно зростаючим

навантаженням міцність на розтяг зварного з'єднання С1-Ко для арматури 20А500С становила 0,88–0,92, а для арматури 25А500С зі сталі марки 25Г2С – 0,89–0,90 міцності арматури у вихідному стані.

Руйнування зварного з'єднання типу К1-Кт при монотонно зростаючому навантаженні відбувалося по основному металу (табл. 8), а при малоциклових повторних навантаженнях — по основному металу або в зоні термічного впливу (табл. 9). Розміцнення зварюванням арматури класу А500С - 20А500С і 25А500С у зварному з'єднанні типу К1-Кт з арматурою, відповідно, 10А500С та 12А500С при монотонно зростаючому навантаженні не перевищувало 1..2% і знаходилося в межах похибки випробувань.

За результатами проведених випробувань малоциклове повторне навантаження не мало стійкого впливу на міцність зварних з'єднань С1-Кт і К1-Кт арматури 20 А500С та 25 А500С, розміцнення порівняно з випробуваннями монотонно зростаючим навантаженням не перевищувало 1…2%, перебувало в межах точності випробувань, як і при випробуваннях арматури в вихідному стані.

Ключові слова. зварювання; з’єднання; міцність; клас А500С; малоциклове повторне навантаження.

Received: *March 1, 2026.*
Revised: *April 3, 2026.*
Accepted: *May 28, 2026.*