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Fatigue Endurance of Welded Joints, Residual Stresses and Fatigue Improvement Treatments

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Abstract

Under certain conditions residual welding stresses greatly effect fatigue performance. Residual tensile stresses reduce the fatigue life of welded joints in the region of multi-cycle loading by two to three times and more. The effect of tensile residual stresses on the fatigue limit of symmetrically loaded (R = minus 1) welded joints is equal to that of stress concentration factor. With an increase of the external load level the effect of the residual welding stresses decreases and at the stress level $S = S_y/K_t$ the fatigue resistance of welded joints with and without residual stresses become identical. Residual stresses play an important role in welded attachments such as stiffness, ribs, diaphragms and also in welded joints with defects.

A method of calculating the effect of residual stresses on the cyclic endurance of the welded joints, which makes it possible to estimate with an accuracy sufficient to practice the role of residual stresses in fatigue process in relation to the type of weld, mechanical properties of base metal and external loading parameters was developed.

A new ultrasonic impact peening treatment is introduced. The fatigue improvement treatment is based on introduction of compressive residual stresses into areas of high stress concentration, reduction in stress concentration associated with welds local geometry and plastic deformation strengthening of surface metal layer.

A quantitative assessment of effectiveness of fatigue improvement treatments was developed. This paper briefly describes this assessment.

Comparison of the calculated values with the experimental data indicates satisfactory agreement (difference does not exceed 10%).

Introduction

The fatigue resistance of a welded joint is inferior to that of base material. In low carbon steel the fatigue limit is approximately 50% for butt joints and 15 - 25% for lap joints. This phenomenon deals mainly with the combined effect of stress concentration and particularly residual stresses: the higher the mechanical properties - the higher the level of harmful tensile residual stresses [1,2].

One of the efficient ways to increase the fatigue strength of welded structure is the application of improvement treatments of welded joints during fabrication, repairs and service life. In order to make a decision to treat or not to treat the welded structure, it is very important to know the role of welding residual stresses in fatigue process.

Effect of Welding Tensile Residual Stresses

Figure l,a gives the results of tenting the low-carbon steel plates of 200 mm width and 26 mm thickness with a polished area and a hole in the middle. In one batch of the specimens the spot heating up to 530 degrees C was made by the resistance welding machine for inducing the residual tensile stresses in proper places at the hole edge. The rest of the specimens were not heated, there were no residual stresses in them. The specimens were tested at a plane banding and symmetric cycle of stresses up to the initiation of 2-3 mm fatigue crack. On the base of 2 million cycles the fatigue limit of specimens without heating was above 120 MPa, while that of heated specimens was only 60 MPa. The observed reduction can be explained only by effect of the residual tensile stresses.

The same phenomenon was observed in testing butt joints at plane bending and symmetric cycle of stresses (Fig. l,b). The specimens of series VI were cut out of the common welded plate. As the measurements showed these specimens had the residual stresses of a small value. The additional longitudinal deposits in specimens of series VII created high tensile residual stresses in the middle part, not increasing the stress concentration in the butt weld. In each specimen of series VIII first the longitudinal deposition was made then it was cut into two halves, which were further butt welded. Due to a small length of this weld the transverse residual stresses in these specimens were approximately the same as in specimens of series VI. The specimens of series VI and VIII showed practically the same fatigue life at the corresponding levels of loading. The fatigue limit of all those specimens was approximately 120-130 MPa. At the same time the fatigue limit of specimens of series VII with high residual stresses is equal only to 70 MPa.

In experiments with specimens, having holes (Fig.1,a) and butt joints (Fig. 1,b) the same regularities were observed: at nominal stresses ±190 - 200 MPa, i.e. close to the yield strength of metal (specimens were made of low-carbon steel) the cyclic fatigue life of the specimens with high and low residual stresses was practically similar. With a decrease of the alternating stresses the residual stress effects are intensified thus leading to the drastic reduction of the fatigue limit of specimens with high tensile residual stresses. In this case the effect of these stresses is similar to that of the stress concentration.

Ultrasonic Impact Peening Treatment

The E.O. Paton Welding Institute recently developed high-production fatigue performance improvement treatment based on an ultrasonic impact process [3,4,5,6,8]. Weld toes, where fatigue crack initiation is usually observed, are locations to be treated. Unlike grinding and thermal stress relieving, only a 4mm to 7mm wide zone adjacent to weld toe is subject to ultrasonic impact peening. Application parameters are carefully chosen depending upon the type of joint, base material strength, and nature of the in-service cyclic loading. One of the important attributes of ultrasonic peening is that it can be applied to weldments with weld reinforcement and to complexly shaped weldments. The treatment can be used in the prefabrication stage at plants and on-site during erection and operation.

The equipment consists of a magnetoconstriction transducer, an ultrasonic wave transmitter and a tool with holder (see Figure 2). The tool converts oscillations from the transducer to an ultrasonic impulse action at the surface being treated. The working component of this tool, either a single 16mm ball element or multiple needles, vibrates at 27KHz with maximum axial amplitude up to 30 microns. The treatment is performed in a single pass by the operator pushing the tool and holder (3.5 Kg weight) toward the weld toe with the force of approximately 3 Kg, and moving along the weld toe at about 0.5M/min. The tool holder isolates the operator from the vibration and there is a little audible sound during the treatment. The ultrasonic tool also impresses a radius into the surface at the weld toe about the same as the tool component used. An increase in fatigue performance of welded joints treated by this method is achieved due to a number of factors:

1. A decrease in stress concentration associated with working (live) stresses. This is due to the removal of abrupt transitions from base metal to weld metal and the removal of small undercuts. This typically decreases the stress concentration in welded joints with transverse fillet welds from the range of 4.43 to 4.83 down to the range of 2.98 to 3.0 [7].

2. The formation of favorable compressive residual stresses in the region of the stress concentration. For high-strength steel the compressive residual stresses can reach 900 MPa [7], and occur in the surface layer and just below as a result of the ultrasonic impact peening treatment.

3. Plastic deformation strain hardening in the surface layer. The depth of the cold-worked layer after the ultrasonic impact peening treatment can amount to 0.5mm to 0.7mm [7].

Studies carried out at the E.O. Paton Institute have shown that all specimens with complete joint penetration welds that were subjected to the ultrasonic impact peening treatment, fractured during fatigue tenting in the base metal and sustained a larger number of cycles under higher stresses, as compared to those left untreated. All untreated specimens fractured in the HAZ when tested in a similar manner.

The results obtained are given in Figures 3 and 4. The treatment improves the cyclic life of butt and overlap joints by 5 to 10 times as compared to the initial untreated state, and the fatigue strength being increased by 50% to 200%. Other studies, made by the French Institute of Welding [7], on high-strength steel joints fabricated with transverse fillet welds confirmed the effectiveness of the ultrasonic impact peening treatment.

The treatment does not reduce the toughness of welded structures operating in low temperature environments. The negligible anisotropy of plastic properties, caused by the local deformation of the surface layer, does not lead to a reduction of the low temperature fracture toughness in welded joints, as characterized by the CTOD testing results.

The ultrasonic impact peening treatment process has been used by the shipbuilding industry and is also used for bridge and other heavy construction in CIS (Confederation of Independent States). The main advantage of the technology is higher efficiency and effectiveness, as well as lower energy consumption.

Calculation of the Effect of Welding Residual Stresses

The development of the method of calculation was based on the comprehensive studies of the regularities of redistribution of residual stresses in the zones of stress raisers in welded joints with a different concentration of stresses in the process of a cyclic loading [1,2]. Until recently such studies were complicated by the lack of a reliable method of their multiple measuring in the zone being studied. The solution of this problem became considerably easier after the development of the non-destructive ultrasonic method of measuring the residual stresses [9]. With its help it is possible to measure the residual stresses in the process of testing many times and to study in detail the kinetics of their changing caused by the stress concentration, level of stresses, value of initial residual stresses and number of loading cycles.

The studies [10-13] showed that within the interval of nominal stresses, corresponding to the multi-cycle region of loading of welded joints, the change of residual stresses occurs, mainly at the first cycle. The next cycles of loading cause considerably less changes and the level of the residual stresses can be considered practically steady (Fig. 5).

The established regularity of the cycle-by-cycle changing of the residual stresses is typical for the whole studied range of values of the theoretical coefficient of stress concentration ($1.3 < K_t < 4.0$). The steady level of residual stresses depends upon the value and nature of distribution of the initial residual stresses, amplitude of stresses and asymmetry of cycle external loading as well as stress concentration, caused by the shape of a weld or a joint. The more detailed concept about the level of steady residual stresses in the zone of stress raisers of welded joints is given by three-dimensional diagram (Fig. 6). This diagram is plotted by the results of the multiple measurements of the residual stresses in the zone of stress raisers of the low-carbon steel welded joints after 10^4 cycles of loading.

There are approaches for the estimation of the effect of stress concentration on the redistribution of residual stresses in welded joints after effect of the external loading. It should be noted that such methods of calculation are, as a rule, rather complicated and not always convenient for the solution of problems connected with the estimation of the fatigue life of the welded structures. It seems, however, that with respect to the solution of the engineering problems, the estimation of effect of stress concentration can be performed on the basis of a simpler approach [14], from which it follows that in the conditions of a multi-cycle loading (S_{max}/S_y 0.5) the steady level of the residual stresses in the zones of stress raisers of welded joints with a sufficient accuracy for the practical application is determined by the estimated relation:

$$S_{res} = S_y - S_{max} \times K_t \tag{1}$$

Here, as was noted, the cycle of changing stresses at which their maximum level reaches the value of material yield strength will be realized independent of asymmetry of cycle of the external loading in the zones of stress raisers of the welded joints [15].

The fatigue limit of the welded joint, taking into account the residual stresses, for instance, at symmetric cycles of loading, can be assumed equal to the amplitude of limiting stresses of welded specimens without the residual stresses, at which the limiting cycle of stresses is realized in the zones of stress raisers in the process of a cyclic loading [2,16] i.e. the following condition is fulfilled:

$$S^c_{max} = S_y \tag{2}$$

Coming from the estimated diagram (Fig. 7) illustrating the above mentioned statement the equation was obtained for the determination of the amplitude of limiting stresses of the welded joint with high tensile residual stress

$$S^l_a = \frac{S_u - S_y/K_t}{S_u/S_f^{-1} - 1} \tag{3}$$

As the amplitude of the limiting stresses of welded joints in the initial state does not depend upon the asymmetry of external loading cycle [1,2] (line 3 in Fig. 7), the level of maximum limiting stresses in this case may be determined from the relation

$$S^l_{max} = \frac{S\ 2S^l_a}{1 - R} \tag{4}$$

and

$$S^l_{max} = S^l_a + S_m \tag{5}$$

The determination of characteristics of fatigue strength of welded joints in the region of a limited life is usually carried out on the basis of equations [1, 2].

$$S = a + b \times \lg N \tag{6}$$

$$S^m \times N = C \tag{7}$$

Relationship (6) in a half-logarithmic system of coordinates (lgN, S) and relationship (7) in a logarithmic system (lgN, lgS) are linear. It gives an opportunity to determine the parameters of fatigue curve for both cases in coordinates of two points. For welded joints with high tensile residual stresses the first point (point D in Fig. 8) with coordinates (N_3, S_3), characterizes the value of fatigue limit of welded joint with high residual tensile stresses. The value is determined by calculations using a known value of fatigue limit of welded joint without the residual stress S_f [17]:

$$S^l_f = \frac{S_u - S_y/K_t}{S_u/S_f - 1} \tag{8}$$

The coordinates of the second point C (N4, S4) are determined coming from the following. With a growth of the external loading level the effect of residual welding stresses on the cyclic life of welded joints is decreased [1], it being associated with the reduction of the level of residual stresses at the increase of the external loading. At some level of the external loading the value of residual welding stresses in the zones of stress raisers is decreased down to the zero values. In this case the cyclic life of welded joints with residual stresses and without them will be equal between each other. The value of the external loading, at which the level of residual welding stresses in the zone of stress concentrators reaches zero values is determined from the equation (1).

By the known coordinates of two points D and C it is not difficult to determine the parameters of equation of the sloped region of the fatigue curve of the welded joint with high residual tensile stresses. In a final form the estimated relations for the determination of a cyclic life of the welded joint taking into consideration the residual welding stresses on the basis of equations of fatigue curve (6) and (7) has the form, respectively:

$$\lg(N_{res}/N_i) = \frac{\left[S_{max}(S_u/S_f - 1) - S_u - S_y/K_t\right] \times \left(S_y/K_t^{-a-b \times LgN1}\right)}{b \times S_u\left[S_y/(S_f \times K_t) - 1\right]} \qquad (9)$$

and

$$\lg(N_{res}/N_i) = S_{max} - \frac{S_u - S_y/K_t}{S_u/S_f - 1} \times \frac{\lg[C \times (K_t/S_y)^m \times N_1^{-1}}{\lg\left[\frac{S_y \times (S_u/S_f - 1)}{K_t \times (S_u - S_y/K_t)}\right]} \qquad (10)$$

where a,b,c, m are the parameters of equations of fatigue curves of welded joints without the residual stresses.

On the basis of the above given equations the estimations have been made about the effect of residual welding stresses on fatigue limit and cyclic life of butt and cruciform joints. The characteristics of fatigue resistance of welded joints without residual stresses served the initial data for calculations [1]. Fig. 9 gives the diagram of limiting stresses of the considered type of welded joints without residual stresses and with high tensile residual stresses, plotted in accordance with equations (3), (4) and (5).

On the basis of equation (10) the estimation was made about the effect of residual welding stresses in the region of limited life cruciform welded joints of steel (S_y = 464 MPa and S_u = 593 MPa) at R =1/4. The parameters of equations of fatigue curves of welded specimens without the residual stresses serve the initial data for the calculations.

Fig. 10 gives the fatigue curves of welded specimens with residual stresses, plotted in accordance with equations (10).

The results of calculations and experimental data, presented in Fig. 10 show that the tensile residual stresses can lead to the reduction of cyclic life of the welded joints in the region of a multi-cyclic loading by 2 ... 3 times. With a growth of the external loading level the effect of the residual welding stresses is decreased and at the level of stresses $S_{max} = S_y/K_t$ the resistance of welded joints to the fatigue fractures becomes similar both with the presence of the residual stresses and without them.

Estimation of Effectiveness of Strengthening Treatments

The E.O. Paton Electric Welding Institute has developed the method of estimation of the effectiveness of strengthening treatment based on the artificial regulation of the residual stresses. This method, as well as the above described method of calculation of effect of the residual welding stresses, is based on the analysis of the diagram of limiting stresses and stressed state of the welded joints in the initial state and after the strengthening treatment. The value of fatigue limit of the treated welded joint S^{tr}_f is determined depending upon the level of residual stresses after treatment S_{res}, coefficient of asymmetry of external loading cycle K_t, mechanical characteristics of used material (yield strength S_y. and ultimate strength S_u).

$$s_f^{tr} = \frac{2s_a^1}{1 - R} \qquad \text{at } S_{res} \geq S^1{}_{res} \quad (11)$$

$$s_f^{tr} = \frac{s_u - s_{res}/k_t}{(1-R) \times (s_u - s_y/k_t)/2s_a^1 + 1} \qquad \text{at } S^{1c}{}_{res} < S_{res} < S^1{}_{res} \quad (12)$$

$$S_f^{tr} = \frac{S_u + S_y/K_t}{(1-R) \times (S_u - S_y/K_t)/2S_a^1 + 1} \qquad \text{at } S_{res} \leq S^{1c}{}_{res} \quad (13)$$

where:

$$s_{res}^1 = s_y - \frac{2k_t \times s_a^1}{1 - R}$$

$$S_{res}^{1c} = -\left\{S_y + \frac{2K_t \times R \times (S_u + S_y/K_t)}{(1-R) \times [(S_u - S_y/K_t)/2S_a^1 + 2]}\right\}$$

If the level of residual stresses in welded joint after the strengthening treatment satisfies the condition

$$S_{res} \geq S_{res}^1$$

then such redistribution of residual stresses will not lead to the increase of the joint fatigue strength. It is explained by that in the zones of concentrators of the treated welded joint at cyclic loading as well as in the untreated joint the limiting cycle of stresses will be realized. The value of fatigue limit of the treated welded joint for this case depending upon the asymmetry of the external loading cycle both for the joints with high tensile residual stresses should be determined from the estimated relation (11).

If the level of residual stresses after the strengthening treatment satisfies the condition

$$S^{1}_{res} > S_{res} > S^{1c}_{res}$$

then the value of the fatigue limit of the treated joint should be determined on the basis of the estimated relation (12). The mentioned relation permits to determine the value of the fatigue limit of the welded joint both at the presence of tensile and compressive residual stresses in the zones of stress raisers. The value of residual stresses should be put into the mentioned equation regarding its sign.

If the level of residual stresses after the strengthening treatment satisfies the condition

$$s_{res} \leq s^{1c}_{res}$$

then the value of fatigue limit of the welded joint should be determined from the estimated relation (13). The value of the amplitude of limiting stresses in this case as well as for the welded joints with high tensile residual stresses does not depend upon the asymmetry of the external loading cycle. It is stipulated by the fact that in presence of high, by value, the compressive residual stresses the limiting compressive cycle of the stresses will be realized under the action of the external loading in the zones of stress raisers of welded joints.

Below some examples of calculation of fatigue limits of treated welded joints are given. In the first case the redistribution of residual stresses in welded butt joints was made by the overloading of specimens. The level of residual stresses after the overloading was determined in accordance with the estimated relationship (1). The comparison of experimental data as a result of calculation by the suggested method displays a good correlation (Fig. 11).

The above given data refer to the case when the artificial redistribution of the residual welding stresses led only to their partial reduction. The checking of the suggested estimated method of prediction of the effectiveness of increasing the fatigue strength of welded joints by the inducing compressive residual stresses in the zone of stress raisers was carried out for the welded specimens passed the ultrasonic impact treatment (Fig. 3). As was already noted such treatment leads to the formation of the residual compressive stresses in the zones of stress raisers of the welded joints, whose value reaches the value of the material yield strength.

The comparison of the obtained experimental data and results of calculation by the suggested equations showed, as in the first case, a good correlation (Fig. 12). The error of estimated determination of fatigue limits of treated welded joints in both cases did not exceed 5 .... 10%.

The above given estimated relations permit to determine both the value of the fatigue limit of the strengthened welded joint at a fixed value of the asymmetry coefficient of the external loading cycle and also the nature of dependence of value of limiting stresses on R, i.e. diagram of limiting stresses of joints subjected to the definite kind of treatment. It gives a concept about the quantitative parameters of the effectiveness, and about the rational field of application of either type of the strengthening treatment. Fig. 13 presents the diagrams of the cycle limiting stresses of welded butt joints of low-carbon, low-alloy and high-strength steels in as-welded and as-ultrasonic impact treated conditions. It follows from the given generalized diagrams and results of multiple tests of welded joints of steels of different classes of steel, that the ultrasonic impact treatment provides the increase in fatigue limit of joints of low-carbon steel by 1.5-1.6 times; low-alloy - by 1.7-1.9 times; high strength - 2.5-2.9 times. The given diagrams show that the ultrasonic impact treatment permits maximum realization of the advantages of the high-strength steels in fabrication of welded structures, since the fatigue resistance of welded joints of steels of different classes of strength in the welded conditions are practically similar.

Conclusion

The residual stresses, occurring during the process of welding can, at certain conditions, remarkably change the fatigue strength of the welded joints. They manifest their effect at the presence of stress raisers. The highest decrease in strength under the action of the residual tensile stresses is observed at alternating cycles of stresses and in the region of the alternating compression. At the symmetric cycle of loading the effect of influence of residual-tensile stresses in joints with butt and fillet welds can be compared with an effect of stress concentration.

The application of ultrasonic impact treatment provides the 5... 10 and more times increase in cyclic life of welded joints and 50 ... 200% increase in their fatigue limit, depending on the mechanical characteristics of materials used, type of joint and parameters of external loading. The strengthening effect is achieved, mainly due to formation of high residual compressive stresses, decrease in stress concentration and surface strengthening of metal in the zone of treatment.

The quantitative estimation of the role of residual stresses and effectiveness of the strengthening treatment can be made with the help of the suggested method of calculation, taking into account the effect of stress concentration on the redistribution of residual stresses during cyclic loading of the joint. This results can be used to predict the fatigue limit and cyclic life of the treated joints.

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Notation

S = nominal stress

S_m, S_{max}, S_{min} = mean, maximum and minimum stresses of cycle

S_a = amplitude of cycle stresses

R = coefficient of asymmetry of stress cycle; stress ratio

S_y = material yield strength

S_u = material ultimate strength

S_f = fatigue limit

s^{-1}_f ; s^0_f = fatigue limit at R=-1 and R=0

N = fatigue limit

N_{res} = fatigue life of welded joints with high residual tensile stresses

K_t = theoretical coefficient of stress concentration

s^c_{max}; s^c_{min} = maximum and minimum cycle stresses in the zone of stress raiser

S_{res} = residual stress

S^{st}_{res} = modified residual stresses (steady)

s^1_a; s^1_f = limiting amplitude of cycle stresses and fatigue limited of welded joint with high residual tensile stresses

s^{tr}_f = fatigue limit of welded joint after strengthening treatment

s^1_{res}; s^{1c}_{res} = residual stresses, at which s^c_{max} and s^c_{min} reach the values of yield strength of material in tension and compression, respectively

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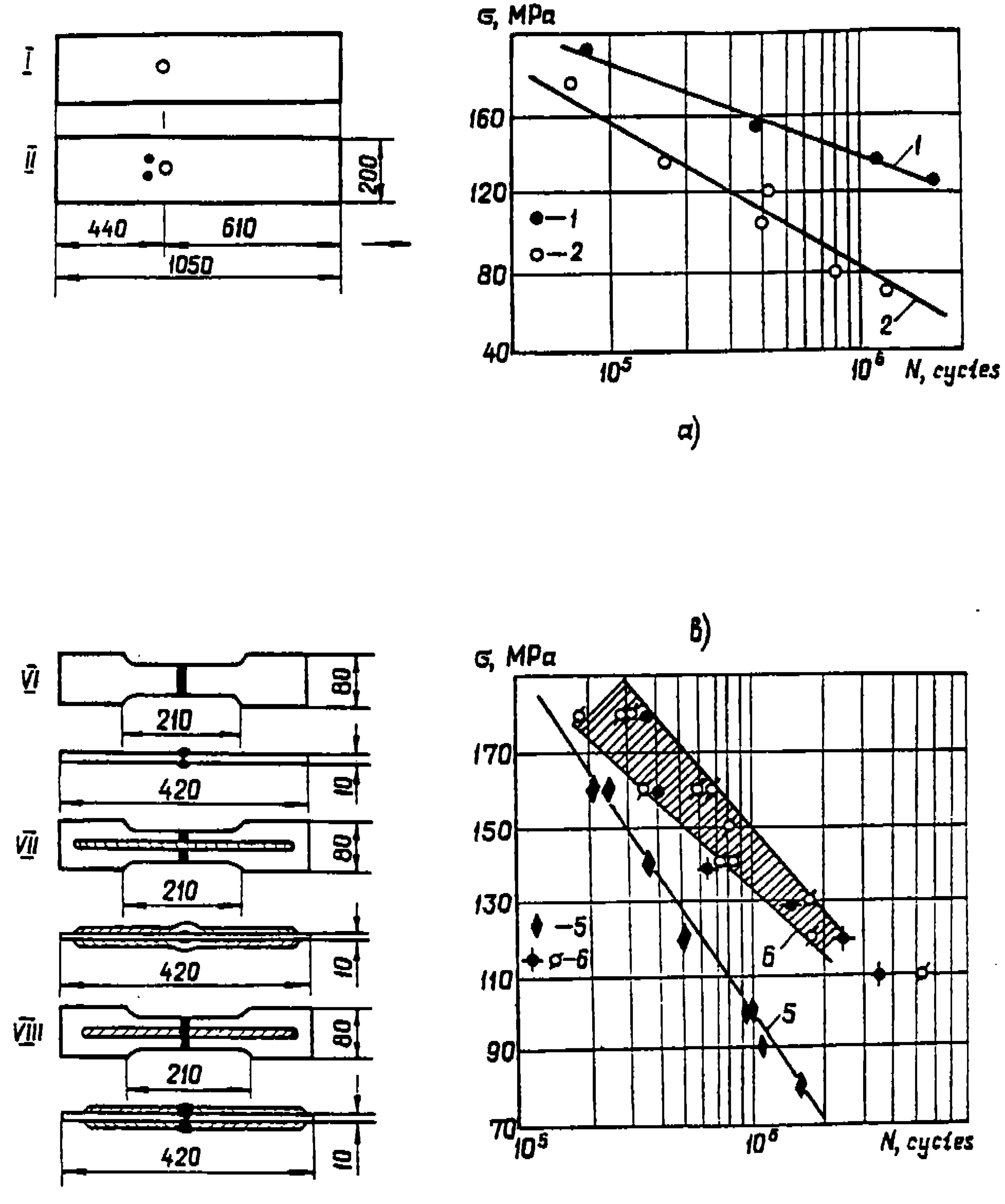

Figure 1

Reduction of Fatigue Strength Under the Effect of Tensile Residual Stresses: II, VII - Specimens with High Tensile Residual Stresses; I, VI, VIII - Specimens without Residual Stresses; 1, 2 - Test Results of Specimens I and II, Respectively; 5 - Specimens VII; 6 - Specimens VI and VIII.

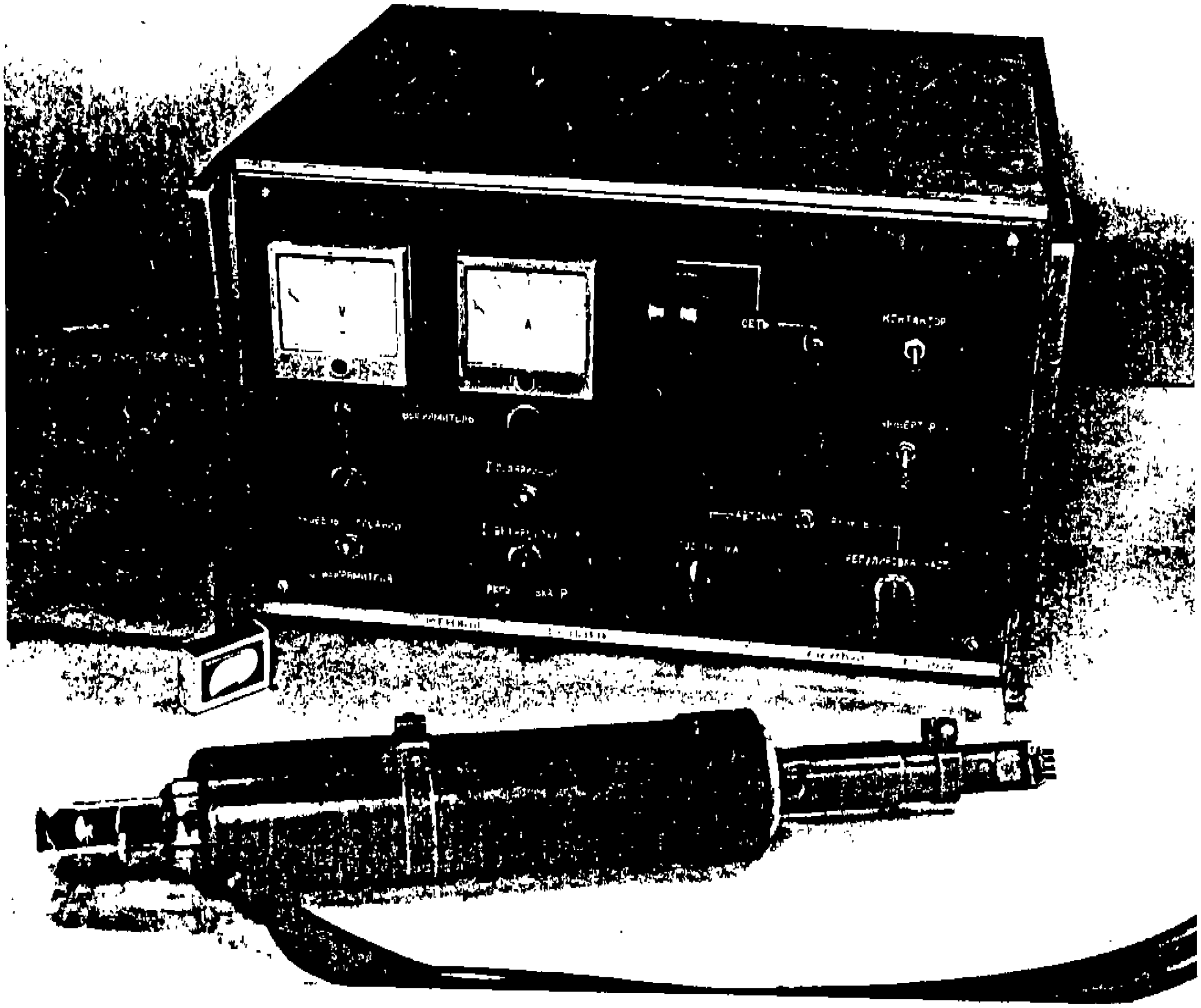

Figure 2
Tool that Converts Oscillations from a Transducer to an Ultrasonic Impulse

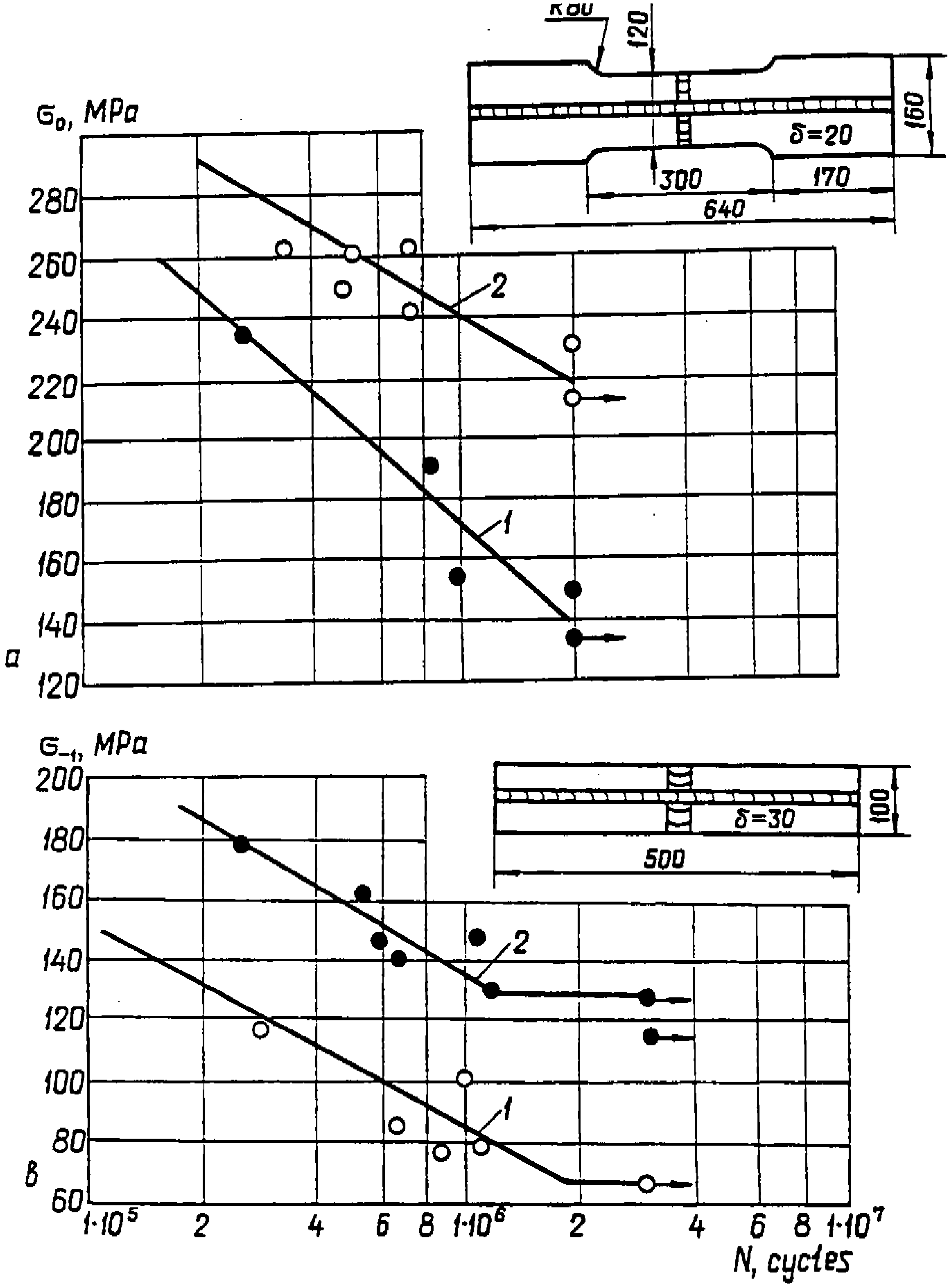

Figure 3
Results of Fatigue Tests of Butt Joints of Low-Carbon Steel:
1 - in Initial State; 2 - after Ultrasonic Impact Treatment

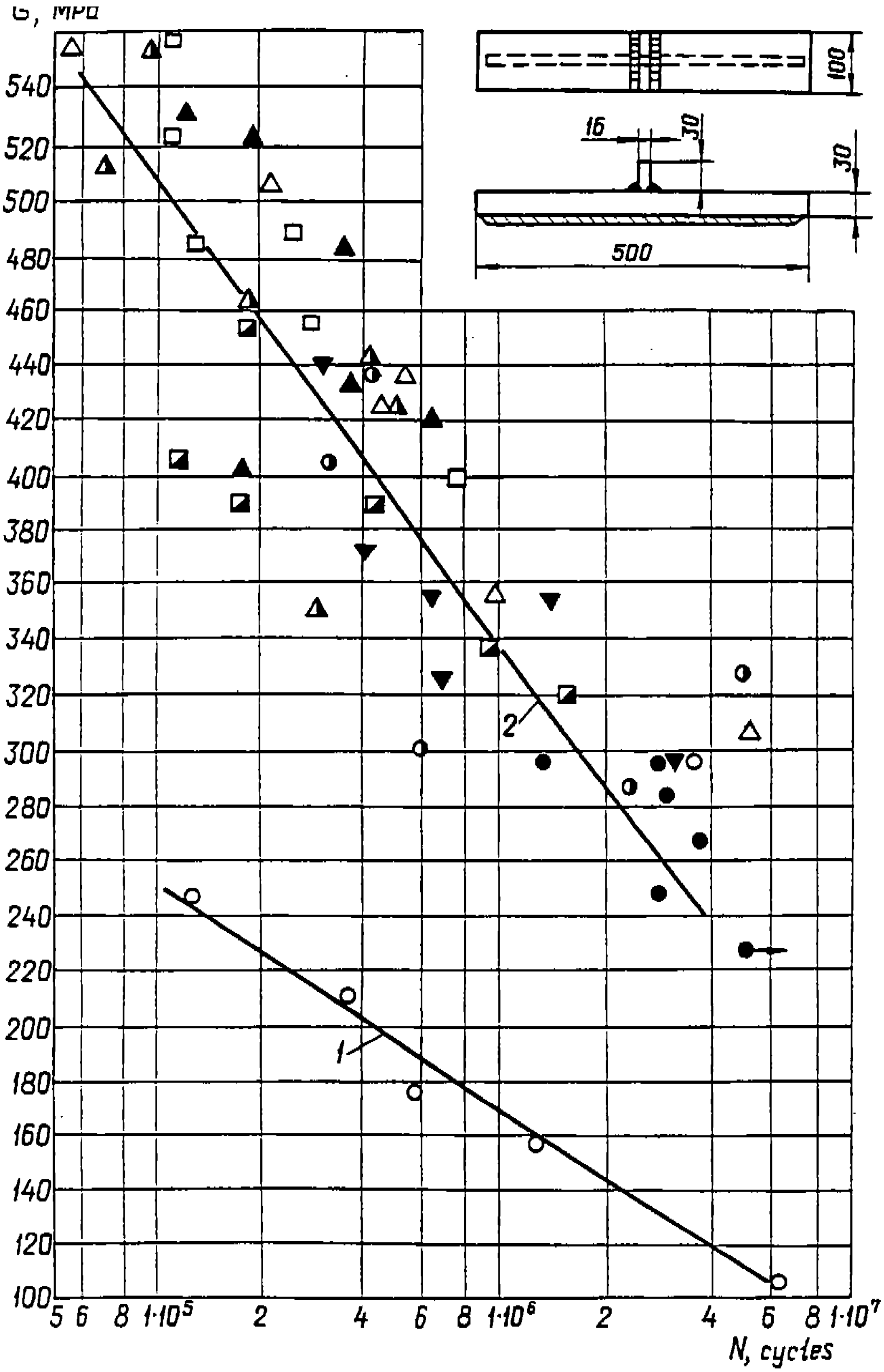

Figure 4

Results of Fatigue Tests of T-Joints of High-Strength Steel:
1 - in Initial State; 2 - after Ultrasonic Impact Treatment

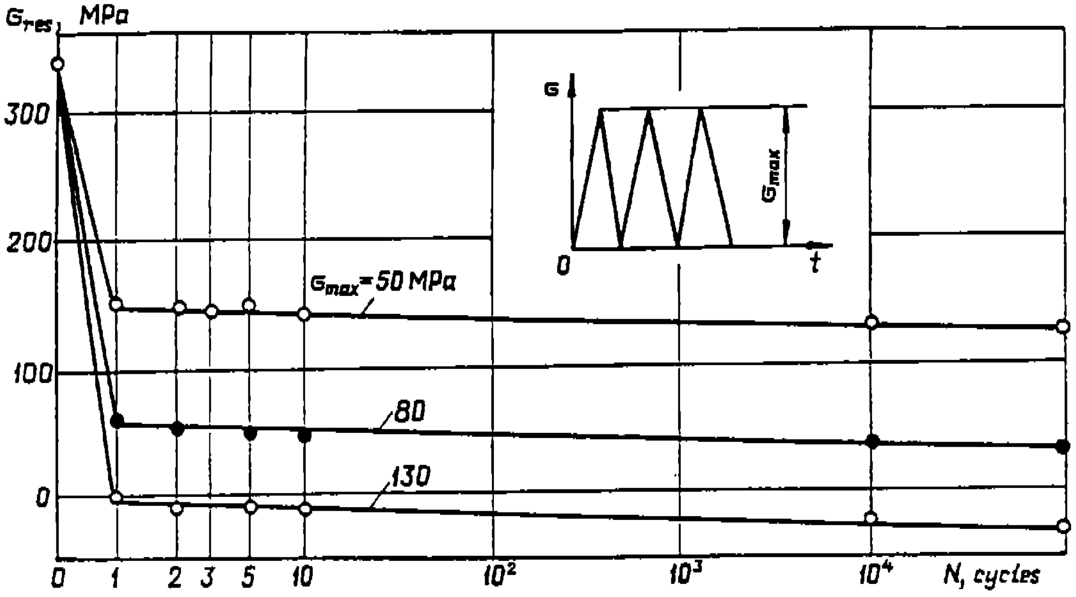

Figure 5
Variation of Residual Stresses in the Zones of Stress Raisers ($K_t = 2.5$), Depending Upon the Number of Loading Cycles and Values of Maximum Stresses

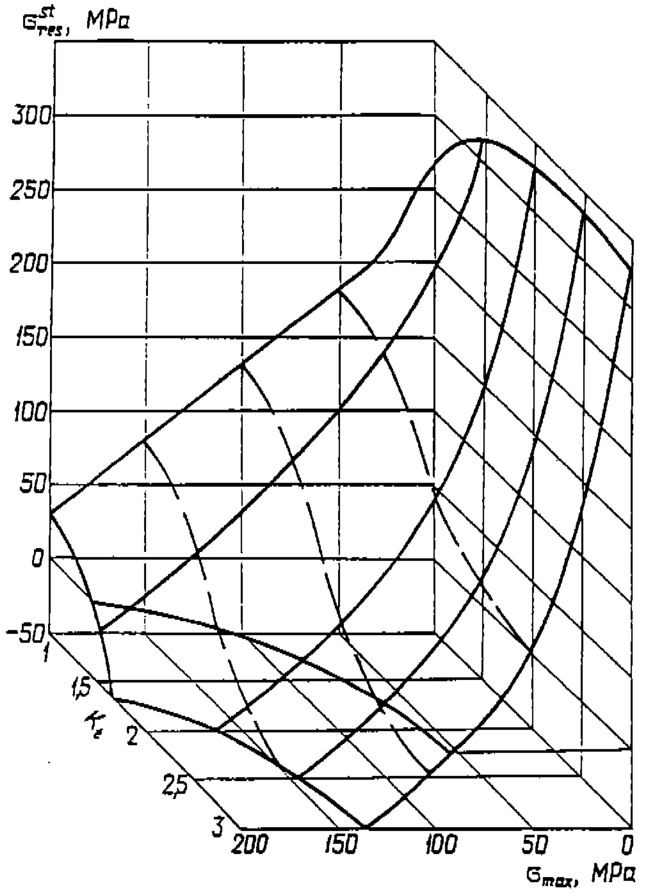

Figure 6
Three-Dimensional Diagram of the Stabilized Residual Stresses in Coordinates S_{max}, K_t, S^{st}_{res}

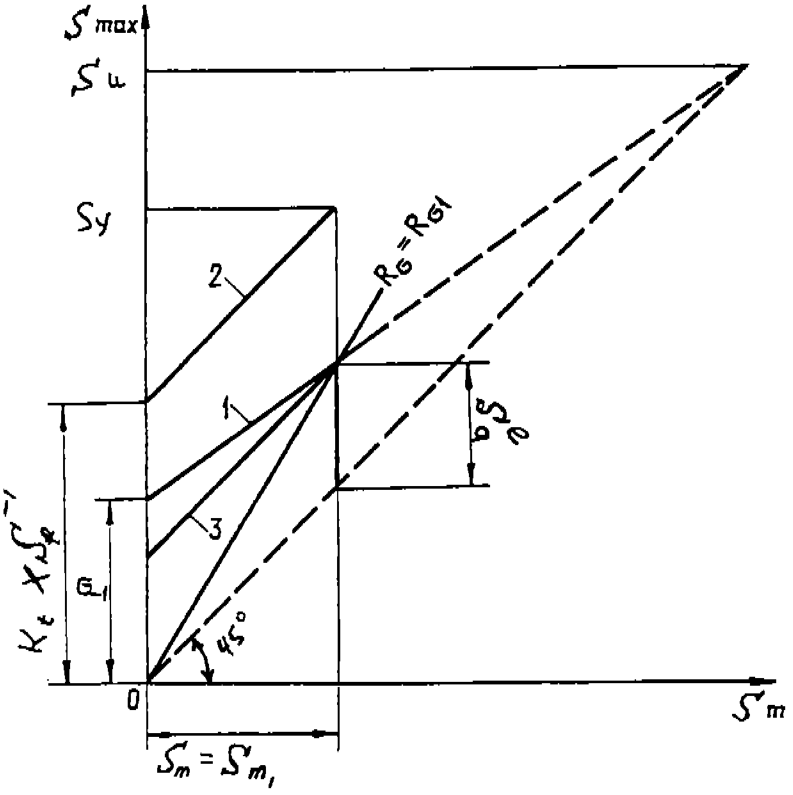

Figure 7

Relationships between the Maximum Cycle Limiting Stresses of Welded Joints and Level of Cycle Mean Stresses of the External Loading; 1, 3 - Welded Joints without and with High Tensile Residual Stresses; 2 - Maximum Stresses in the Zone of Stress Raiser of Welded Joint without Residual Stresses.

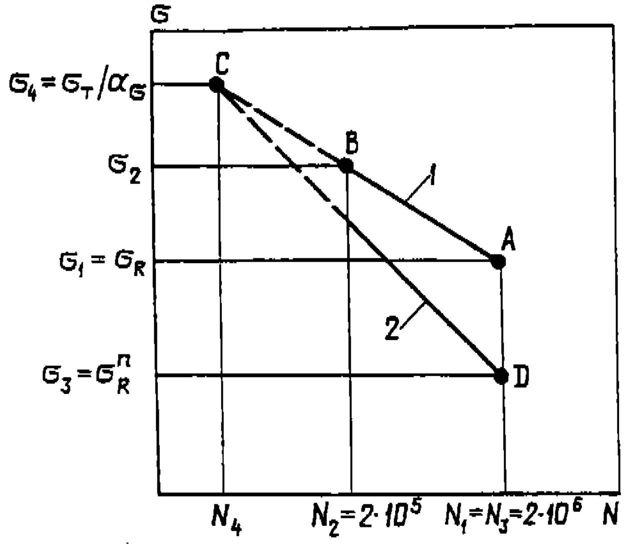

Figure 8

Sloped Region of Fatigue Curve of Welded Joint: 1 - without Residual Stresses; 2 - with High Tensile Residual Stresses

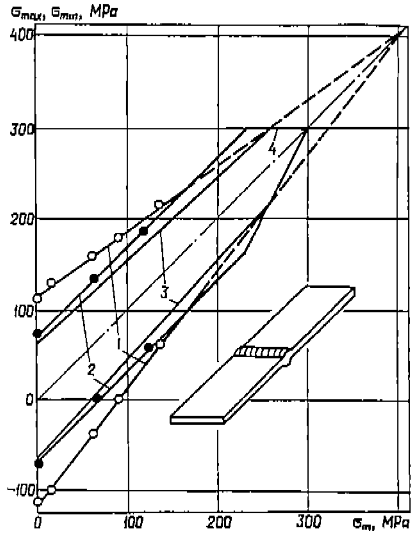

Figure 9

Diagram of Cycle Limiting Stresses of Butt Joints (K_t=1, 32; S_y=300 MPa; S_u=410 MPa) 1 - without Residual Stresses; 2, 3, - with High Tensile Residual Stresses from Proposed Equations (2) and Relations (3) 4 - Limiting Static Stresses; - Experimental Data [1]

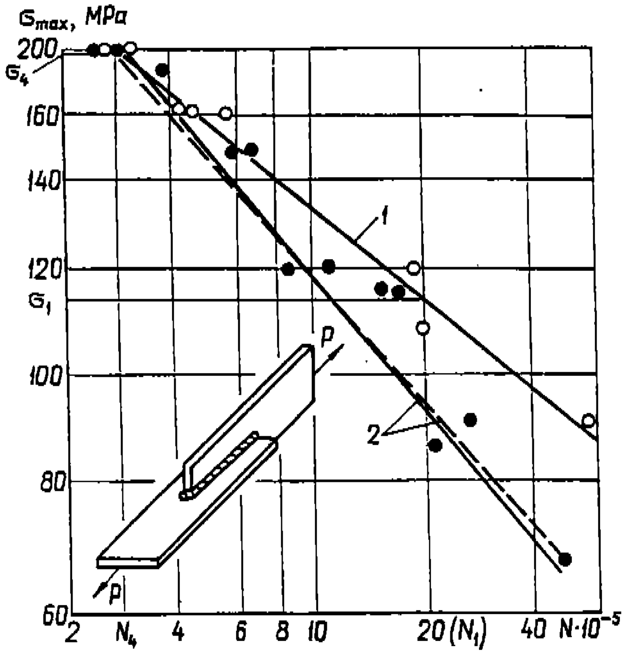

Figure 10
Relationship between the Cyclic Life of Welded Joint (R=0.25) and the Level of Applied Stresses; 1 - without Residual Stresses; 2 - with Residual Stresses;- - - by Equation (10);- - - by Experimental Data

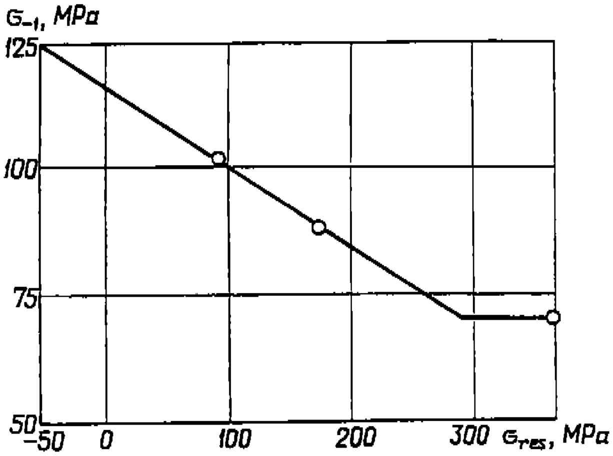

Figure 11
Calculated Relationship between the Values of Fatigue Limit (S^{-1}_f) of Welded Butt Joint of Carbon Steel at R=-1 and the Level of Residual Stresses (0 - Experimental Data)

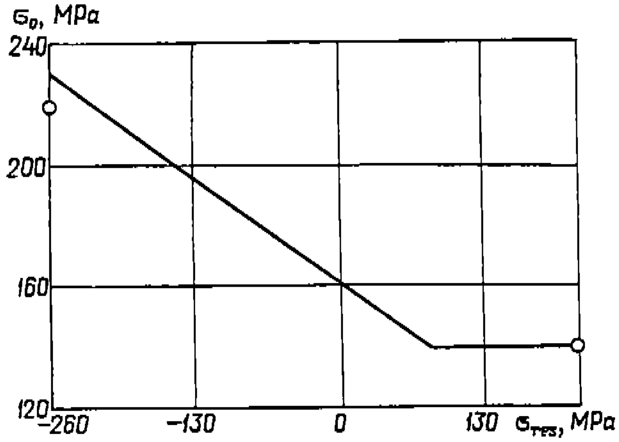

Figure 12
Calculated Relationship between Values of Fatigue Limit S^0_f of Welded Butt Joint of Carbon Steel at R=0 and the Level of Residual Stresses (0 - Experimental Data)

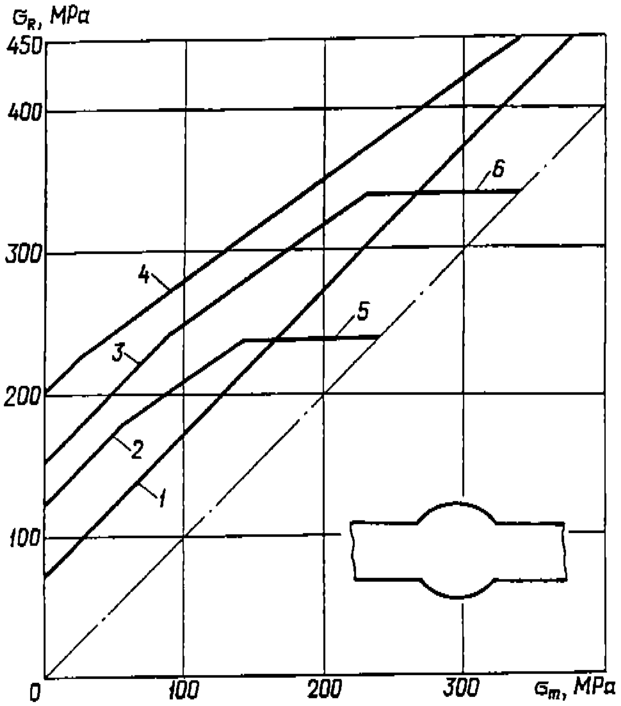

Figure 13
Diagram of Cycle Limiting Stresses of Welded Butt Joints: 1 - As-Welded Conditions; 2, 3, 4 - After Ultrasonic Impact Treatment of Joints of Low-Carbon, Low-Alloy and High-Strength Steels, Respectively; 5, 6 - Limiting Static Stresses of Low-Carbon and Low-Alloy Steels, Respectively