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FATIGUE RESISTANCE OF STEEL WELDED JOINTS OF DIFFERENT STRENGTH WITH STEADY RESIDUAL STRESSES

V.A. DEGTYAREV
G.S. Pisarenko Institute for Problems of Strength of the NAS of Ukraine
2 Timiryazevskaya Str., 01014, Kyiv, Ukraine. E-mail: ips@ipp.kiev.ua

A work proposes a comparative analysis of the diagrams of cycle limiting stresses in welded joints of low-carbon and low-alloy steels of different strength under condition that they have the same level of steady residual stresses. By the example of testing of St3sp (killed), 09G2S and 14KhMNDFR steel butt welded joints it is shown that the welded joints with larger mechanical properties have higher endurance limits in all investigated range of change of the limiting steady residual stresses. It was found that the welded joints of stronger steels have also higher values of endurance limit at the same relative value of cycle average stress. They rise more intensively with increase of the relative values of cycle average stress. 10 Ref., 2 Tables, 5 Figures.

Keywords: *welded joint, cycle stress amplitude, cycle average stress, yield limit, steady residual stress, endurance limit, diagram of cycle limiting stresses*

Investigations carried in work [1] have determined that the diagrams of cycle limiting stresses (DCLS) of butt welded joints from low-carbon and low-alloy steels of different strength with high residual tension stresses (RS) in the field of limited life (to number of load cycles $N = 5\cdot10^5$) diverge with rise of a coefficient of cycle asymmetry R_σ, that shows advantage of higher strength steels. At that, they have similar endurance limit at symmetric stress cycle. DCLS of welded joint of different strength steels match at $N > 2\cdot10^6$ starting from symmetric cycle and up to specific positive value R_σ. This means that the diagram of stronger joints is continuation of one reflecting fatigue resistance of less strong joint. The results of investigations of other types of welded joints showed the same behavior of the diagrams of cycle limiting stress at $N > 2\cdot10^6$ [2]. Presentation of the investigation results in form of combined diagrams allowed determining the areas of reasonable application of steels of different strength in the elements of metal structures with non-processed welded joints that, undoubtedly, have large practical value. Analysis of publications carried in work [3] showed that each point on DCLS at different cycle average stresses σ_m or R_σ corresponds to endurance limit of welded joint with own value of limiting steady residual stress σ^s_{res}. Since it is well known [4] that initial residual stresses rise in proportion to yield limit of base material σ_y then their values are larger in welded joints of higher strength steels. Therefore, regardless similar received values of the endurance limits on matching section of the diagrams, i.e. at similar stresses from external load, welded joints of higher strength steels will have larger final RS. And taking into account that σ^s_{res} value at other conditions being equal plays an important role in reduction of fatigue resistance, the test results of the welded joints containing different level of σ^s_{res} are compared. Besides, it should be noted that the similar endurance limits for welded joints of different strength are received at different relationship of average stress to material yield limit, i.e. at different relative value of cycle average stress.

In this connection it is interesting to carry out the investigations which allow matching fatigue resistance of welded joints of different strength class steels containing similar level of limiting final RS and the same relative value of cycle average stress in R_σ range of changing, at which matching of the diagrams of cycle limiting stresses takes place.

Analysis of received results. The analysis carried out on the example of testing the butt welded joints of low-carbon steel St3sp (killed) (σ_y = 300 MPa), low-alloy steel 09G2S (σ_y = 340 MPa) and low-alloy high-strength steel 14KhMNDFR (σ_y = 600 MPa). The maximum initial tension RS according to work [4] depending on steel strength class are in the range of (0.75–0.85) σ_y, i.e. on average make 260, 290 and 450 MPa in the welded joints of St3sp (killed), 09G2S and 14KhMNDFR steels, respectively. Figure 1 shows the results of fatigue tests of butt welded joints with RS of low-carbon and low-alloy steels with different strength [4] in form of the combined diagrams of cycle limiting stresses. It can be seen that their endur-

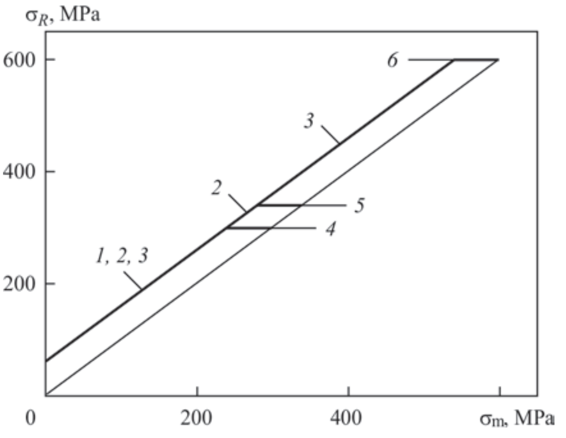

Figure 1. Diagrams of cycle limiting stresses in butt welded joints with RS of low-carbon (*1*), low-alloy (*2*) and low-alloy high-strength (*3*) steels, *4–6* — material yield limits

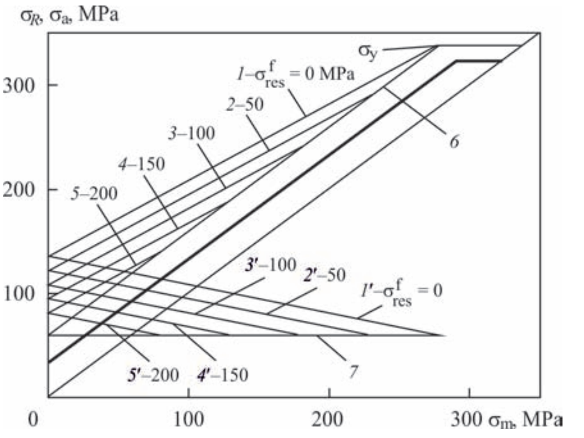

Figure 2. Diagrams of limiting stresses (*1–5*) and cycle limiting amplitudes (*1′–5′*) of butt welded joints of low-alloy steel 09G2S: *1*, *1′* — without RS; *2–5*, *2′–5′* — with steady RS; *6*, *7* — lines of limiting stresses and cycle minimum limiting amplitude, respectively

ance limits σ_R match in the range of R_σ changing from –1 to 0.6 or average cycle stress σ_m to 235 MPa. Since the stress limiting amplitude σ_a does not depend on σ_m, the diagrams of cycle limiting stresses of welded joints can be described in form of dependence

$$\sigma_R = \frac{2\sigma_{-1}}{1 - R_\sigma}, \quad (1)$$

where σ_{-1} = 65 MPa is the endurance limit of welded joint with RS at symmetric cycle of loading.

In present work an effect of theoretical coefficient of stress concentration was not considered by the reason of accepted in the references [5–7] determination of DCLS or diagrams of cycle limiting amplitudes (DCLA) only due to effect of nominal stresses. The effect of RS and stresses, caused by static loading, were supposed to be identical [8]. It also follows from the Figure analysis that the values of final RS as well as relationship of limiting stresses to material yield limit will be different at similar values of endurance limits in the welded joints of steels with various strength.

It is known that increase of average cycle stress under condition of reaching the maximum stresses (taking into account residual ones) of material yield limit provokes reduction of initial RS till the final level. The investigations [3] carried before allowed determining DCLS or DCLA of the joints with different value of σ^s_{res} using the results of tests of the welded joints without RS defined on formulae:

$$\sigma_R = \sigma_{-1m} + (1 - \psi_\sigma)\sigma_m - \psi_\sigma \cdot \sigma^s_{res}, \quad (2)$$

or

$$\sigma_a = \sigma_{-1m} - \psi_\sigma(\sigma_m + \sigma^s_{res}), \quad (3)$$

where σ_{-1m} is the endurance limit of the welded joint without residual stresses; ψ_σ is the coefficient of sensitivity to asymmetry of stress cycle.

Figure 2 shows as an example in general form such diagrams of butt welded joint from steel 09G2S with different level of σ^s_{res}. It can be seen that an inclined section of the diagram is shifted by $\Delta\sigma_a = \psi_a\sigma^s_{res}$ value parallel to the diagrams of welded joints without RS and with rise of σ^s_{res} each further diagram is placed below the previous one. They are ended on lines *6* and *7* where each point on these lines correspond to the cycle limiting stress or cycle minimum limiting amplitude σ^l_a of welded joint with own values of limiting ones σ^s_{res} that provides realizing of the limiting stress cycle. At that the average stress, which in this case is also the liming one, is shifted by $\Delta\sigma_m = \sigma^s_{res}$ value. Table 1 provides the necessary calculation values of the limiting stresses allowing determining the same diagrams of welded joints of other strength steels at different σ^f_{res} values. Following the limited number of experimental data [9] as well as reference data, given in work [10], it can be assumed that DCLS of 14KhMNDFR steel welded joints without RS can have parabolic nature. In this case ψ_σ will be variable value. Therefore, for convenience of calculations the

Table 1. Calculation limiting stresses (MPa) for different level of final RS in welded joints of steels St3sp and 14KhMNDFR

Steel	σ^s_{res}, MPa											
	0		50		100		200		300		400	
	σ_R	σ_m	σ_R	σ_m	σ_R	σ_m	σ_R	σ_m	σ_R	σ_m	σ_R	σ_m
St3sp (σ_{-1m} = 108 MPa, ψ_σ = 0.183)	300	235	250	185	200	135	100	35	–	–	–	–
14KhMNDFR (σ_{-1m} = 110 MPa, ψ_σ = 0.085)	600	535	–	–	500	435	400	335	300	235	200	135

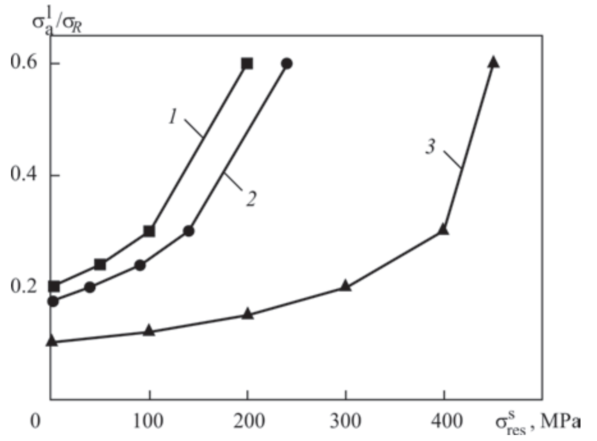

Figure 3. Dependencies between relationship of cycle minimum limiting amplitude to endurance limit and limiting steady RS in butt welded joints of steels St3sp (*1*), 09G2S (*2*) and 14KhMNDFR (*3*)

diagram was somewhat idealized and presented in from of a line.

Presentation of data in such a form allows coming to determination of cycle limiting stresses of the welded joints from researched steels at similar level of final RS. Sensitivity of the butt welded joints to σ^s_{res} value is shown in Figure 3. Taking into account experimental and calculation data, the Figure shows the dependencies between a relationship of stress limiting amplitude to corresponding endurance limit and value of final RS. In this case the most interesting characteristic, i.e. the cycle minimum limiting amplitude was considered. At that the single limiting stress cycle is realized. The analysis of received results shows that the similar values of σ^s_{res} in the welded joints of steels with higher mechanical properties are reached at lower σ^l_a/σ_R. And this difference rises with increase of σ^s_{res}. Also, it is not difficult to determine σ^s_{res} value at the same σ^l_a/σ_R relationship. For example, $\sigma^l_a/\sigma_R = 0.5$ in the welded joints of St3sp and 14KhMNDFR steels can be received at σ^s_{res} being equal 170 and 440 MPa, respectively. Using received data Figure 4 represents the dependencies of endurance limits of the welded joints from the investigated steels on limiting final RS under condition that different strength welded joints, as it was mentioned above, have similar endurance limit at symmetric cycle or similar minimum limiting amplitude of stresses on external load, that is the same, equal to 65 MPa. The analysis of presented results showed that rise of σ^s_{res} provokes reduction of endurance limits of welded joints from low-carbon and low-alloy steels of different strength. However, they remain increased in all investigated range of σ^s_{res} changing in welded joints with higher mechanical properties. For example, at change of σ^s_{res} from 50 to 200 MPa, σ_R of welded joint of low-alloy high-strength steel is higher 2.2 and 4.0 times, respectively, in comparison with low-carbon steel. If at σ^s_{res} equal to 200 MPa the endurance limit of low-carbon steel welded joint decreases 3 times than that for welded joint of high-strength steel is only 1.5 times. Thus, received results indicate the rise of endurance limits of welded joints with increase of strength of steels in investigated range of measurement of limiting steady RS.

Besides, if DCLS of welded joints shown in Figure 1 are presented in relative coordinates (Figure 5) it can be seen that they initially diverge at similar relative values of average stresses from external loading σ_m/σ_y. At that, welded joints of higher strength steels have larger relative values of the endurance limit, varying inclination angle of the diagram to larger extent. Presentation of data in such a form allows considering mechanical properties of researched steels, analyze obtained results in comparable test conditions. In general terms the equation for each line can be written as

$$\frac{\sigma_{Ri}}{\sigma_{-1}} = 1 + K\left(\frac{\sigma_m}{\sigma_y}\right), \qquad (4)$$

where $K = \sigma_{yi}/\sigma_{-1}$ is the angle of line inclination; σ_{yi} is the yield limit of the material of corresponding steel.

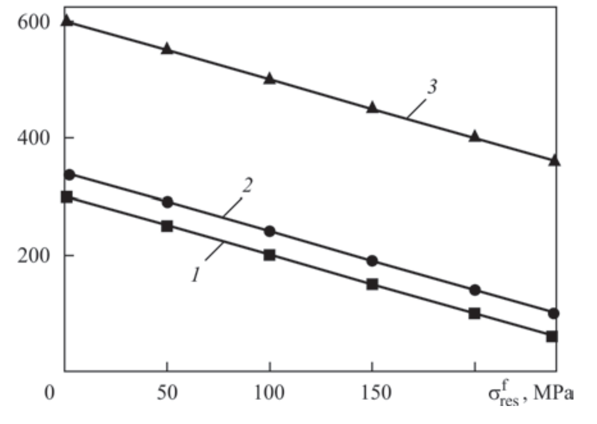

Figure 4. Dependencies of endurancies limits of butt welded joints of St3sp (*1*), 09G2S (*2*) and 14KhMNDFR (*3*) steels on limiting steady RS

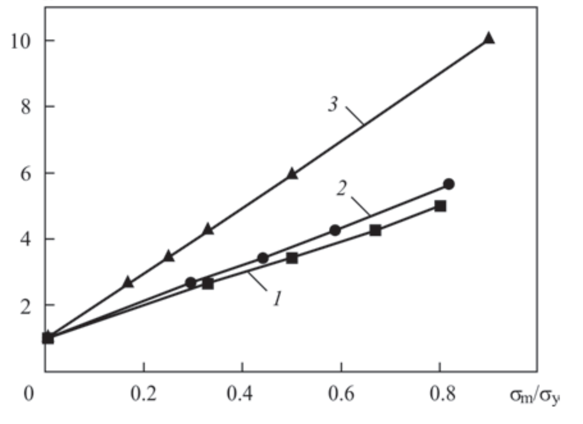

Figure 5. Dependencies between relative values of endurance limits of butt welded joints from St3sp (*1*), 09G2S (*2*) and 14KhMNDFR (*3*) steels and cycle average stresses

This provides the possibility for determination of DCLS of welded joints of investigated steels, knowing the equation for one of them. It is enough to write down an equation of diagram of cycle limiting stresses, for example, of welded joint of St3sp steel (line *1*) in form of

$$\frac{\sigma_{R1}}{\sigma_{-1}} = 1 + \frac{\sigma_{y1}}{\sigma_{-1}}\left(\frac{\sigma_m}{\sigma_y}\right) \quad (5)$$

and solving it relatively to σ_m/σ_y determine DCLS equation for welded joint of other strength steel, which will be in a form

$$\sigma_{Ri} = \sigma_{-1} + \frac{\sigma_{yi}}{\sigma_{y1}}(\sigma_{R1} - \sigma_{-1}). \quad (6)$$

As an example Table 2 gives, following formulae (5) and (6), the calculation values of endurance limits of welded joints from investigated steels at different values of σ_m/σ_y. The analysis of table data showed that the endurance limit of steel rises with increase of steel strength at similar relationship of σ_m/σ_y, i.e. in testing under comparable conditions. Moreover, increase of this relationship rises the difference between the endurance limits.

Using the data, given in Figures 4 and 5, it is possible to determine the values of cycle average stress, at which similar final RS and vice versa act in the welded joints of investigated steels. For example σ_m in the welded joints of St3sp, 09G2S and 14KhMNDRF steels equal 85, 120 and 380 MPa, respectively, at σ^s_{res} = 150 MPa. In turn, at σ_m/σ_y = 0.5 σ^s_{res} values in the welded joints make to 85, 100 and 230 MPa with improvement of mechanical properties of material. This corresponds to 0.28–0.38 of yield limit of corresponding steel. Besides, in the absence of full-scale investigations it is also not difficult to determine DCLS of the investigated welded joints. For this by means of combined solution of dependencies (2) and (4) for set value σ_m it is enough to determine the value of steady RS as

$$\sigma^s_{res} = \frac{\sigma_{-1m} - \sigma_{-1} - \psi_\sigma \sigma_m}{\psi_\sigma}, \quad (7)$$

and then using formula 2 the endurance limits of welded joints of investigated steels with available σ^s_{res} are determined.

Thus, received data allowed comparing the limiting stresses in welded joints of different strength steels at similar level of steady RS as well as relatively to acting stresses from external loading that can help in steel selection for known operation conditions.

Table 2. Endurance limits of welded joints from investigated steels

Steel	Endurance limits σ_R, MPa at different σ_m/σ_y				
	0	0.1	0.3	0.5	0.7
St3sp (killed)	65	95	155	215	275
09G2S	65	100	167	235	305
14KhMNDFR	65	125	245	365	485

Conclusions

1. The procedure was proposed for determination of diagrams of the cycle limiting stresses in butt welded joints of different strength class. It allows determining dependencies of change of endurance limits of welded joints at similar level of limiting steady residual stresses and relative stresses from external loading.

2. It is determined that the welded joints of stronger steels have larger steady residual stresses and higher values of endurance limit at similar relative value of cycle average stress. Increase of relative values of cycle average stresses promotes more intensive rise of endurance limits of the welded joints from stronger steels.

3. Increase of endurance limits of the welded joints with rise of steel strength in the investigated range of changes of limiting steady residual stresses is shown.

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