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# INFLUENCE OF THE RATIO OF DYNAMIC AND STATIC STRESSES ON BRITTLE FRACTURE RESISTANCE OF LOW-ALLOYED STEEL WELDED JOINTS

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Results of experimental studies of the influence of the ratio of static and dynamic stresses on limit stresses and second critical brittleness temperature of butt welded joints with a crack on 09G2 and 12GN2MFAYu steels under the conditions of room and low (to –80 °C) temperatures are analyzed. It is found that at the specified temperature the dynamic component of critical stress decreases linearly with increase of static stress. It is shown that decrease of limit stresses and increase of the second critical brittleness temperature take place at increase of the dynamic factor. Critical brittleness temperatures of welded joints of steel with higher mechanical properties are significantly lower. It is found that ignoring the dynamic stresses leads to underestimated values of limit stress and overestimated values of second critical brittleness temperature. Presented analysis of research allows a more substantiated approach to assessment of brittle fracture resistance of structural elements made from the studied materials, and determination of their safety margins. 7 Ref., 1 Table, 7 Figures.

***Keywords:*** *welded joint, critical brittleness temperature, limit stress diagram, yield point*

Increase of reliability and reduction of the number of failures of metal structure elements during winter operation period is a highly urgent task [1–3]. Transition of quasibrittle to brittle fracture is characterized by second critical brittleness temperature, $T_{cr2}$. For structures, exposed to static or just dynamic impact, it is determined at static or dynamic loading of samples [4]. In practice, however, the absolute majority of structural elements operate under the conditions of simultaneous impact of static and dynamic loads. Therefore, if $T_{cr2}$ is determined at static loading, it can yield underestimated values, if it is done at dynamic load the values can be overestimated. Only combined loading, allowing for the real ratio of static and dynamic stresses, enables application of welded joints with maximum effectiveness. Known is the work [5], where change of static stresses and critical brittleness temperature of samples with a crack from low-carbon and low-alloyed steels was studied at combined loading. The sample was statically stretched by application of stepwise increasing load with subsequent impact of a transverse shock pulse, the magnitude of which was not determined. An essential lowering of static nominal breaking stresses and increase of critical brittleness temperatures was noted. However, no publications were found in literature, in which dependencies of breaking stresses and critical brittleness temperatures of welded joints on different ratios of static and dynamic loads are studied. It is known that brittle fracture resistance of metal structure elements depends on a number of factors, in particular, on temperature, deformation rate, as well as their cross-sectional dimensions and defects present in them.



In this connection, structural strength and second critical brittleness temperatures of welded joints containing defects of the type of fatigue cracks were studied in this work, depending on temperature and nature of applied forces.

**Equipment, materials and testing procedure**. Butt welded joints of low-alloyed steels 09G2 ($\sigma_t$ = = 518 MPa, $\sigma_y$ = 330 MPa), and 12GN2MFAYu ($\sigma_t$ = = 710 MPa, $\sigma_y$ = 620 MPa) were used as research material. Samples of 400×48×24 mm size were cut out of a plate 24 mm thick in as-delivered condition with the butt weld, directed normal to the rolling direction. Thickness selection is due to the need to determine the studied characteristics for structures, made from rolled stock of the above thicknesses. The initiating notch in the sample was made so that the fatigue crack grown afterwards, was in the plane running through the line of fusion of weld metal with base metal. Therefore, test results belonged to the heat-affected zone (HAZ) metal. Initial fatigue cracks were grown from the notch up to sample mid-height, in keeping with the requirements of GOST 25.506–85 [6] at zero-to-tension loading cycle. For observation of the cracks weld reinforcement was milled, and the anticipated crack growth site was polished. Diagram of loading the cracked sample in the unit developed for these studies based on repeated impact drop-hammer DSO-1 [7], is given in Figure 1. The unit consists of static loading mechanism, sample attachment assembly and shock loading mechanism. Sample *4*, mounted on two stationary supports *3* and *5*, was statically loaded by weights *7* through lever *8* and rod 9 with support *10*. Compared to three-point loading, console loading allows testing samples with much larger cross-sectional dimensions. Dynamic loading was performed by free-falling load *1* of 10 kg weight, mounted in guiding ball-bearings *2*. At sample testing under the conditions of just dynamic loading support *10* was stationary fixed. Load raising height was controllable.

Thus, testing of welded samples with pre-grown fatigue cracks was conducted at static, dynamic and combined loading in a broad range of climatic temperatures. The latter kind of loading was carried out by sample bending under constant static load up to specified nominal stress $\sigma^{st}$ with subsequent application of dynamic load, which was increased to the specified degree, increasing the load drop height, and, thus, dynamic stress $\sigma^{d}$. Their measurements and respective values of notch edge displacement *V*, measured by a sensor, specially made in the form of a cramp, were used to plot deformation diagrams with «*P*–*V*» coordinates, on which limit load $P_{st}$ was noted, corresponding either to the moment of appearance of a tear in the blunted crack tip on the sample side surface, that was indicative of the start of crack movement through its entire thickness, or to brittle fracture of the sample. Use of a standard two-console sensor at dynamic loading was not possible, as the arising force of inertia caused additional sagging of its elastic elements, and this led to a significant error in measurement of the notch edge displacement. It was applied at static loading of samples.

Commercial TV system PTU-61 was used for observation of crack growth and formation of a plastic zone in its tip. To increase measurement accuracy, the TV camera was connected to MBS-1 microscope through a special transition piece that allowed magnifying the observed object 109 times. Low-temperature testing was performed using a system of cooling and automatic maintenance of sample temperature in the range of 20– –100 °C [3]. To reduce heat losses, the sample was placed into a specially prepared chamber.

Reaction $R^{d}$ of support *10* to the impact of dynamic load was determined by strain gauge *6*, glued to the lower plane of the sample, and reaction $R^{st}$ of the same support to the action of static load — by the weight of calibrated loads *7* and known value of the ratio of the arms of the lever of 2nd kind, equal to 1:50.

Critical stress at combined loading in sample net section was defined as

$$\sigma_{cr} = \sigma^{st} + \sigma^{d} = \frac{6(R^{st} + R^{d})L}{t(b-l)^2}, \qquad (1)$$

where *l* is the length of fatigue crack, determined after sample fracture as the mean arithmetic by three points on the crack contour [6]; *t* is the sample width. Other designations are given in the Figure.

Let us designate limit stress at static loading as $\sigma_0^{st}$, and that at dynamic loading as $\sigma_0^{d}$.

**Analysis of investigation results.** According to experimental data (Table), Figure 2 presents in relative coordinates the limit stress diagrams (LSD) of butt welded joints of steel 09G2 (*a*), determined at

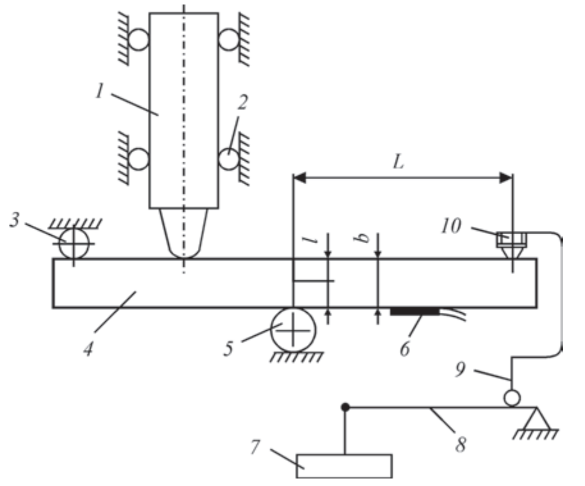


**Figure 1.** Schematic of welded sample loading (for description see the text)

temperatures of 20, –20, –60 °C and 12GN2MFAYu (*b*) at 0, –40 and –80 °C, respectively. Several samples were tested at each temperature, assigning different $\sigma^{st}$, and the correspondence of limit breaking $\sigma^{d}$ and critical stresses $\sigma_{cr}$ was determined. Limit stresses not only at static $\sigma_0^{st}$, but also at dynamic $\sigma_0^{d}$ loading were found at the same temperatures. Considering the experience of earlier full-scale investigations of samples from 09G2 steel, which are indicative of linear dependence between $\sigma^{d}$ and $\sigma^{st}$ at different temperatures, this work required a smaller number of samples of welded joints of these steels, confirming the availability of the above dependence. At 20 °C temperature for joints of 09G2 steel, and at 0 °C for those of 12GN2MFAYu steel, $\sigma_0^{d}$ turned out to be higher than $\sigma_0^{st}$. Therefore, the experimental points are not given on the ordinate axis. The derived stresses at specified temperature were used at determination of ratios $\sigma^{d}/\sigma_0^{st}$ and $\sigma^{st}/\sigma_0^{st}$. Therefore, for any temperature the relative value of critical stress at static loading is equal to a unity. Analysis of the results, given in the Figure, showed that mainly a linear dependence is observed between static $\sigma^{st}$ and breaking dynamic $\sigma^{d}$ components of crit-

Limit stresses in butt welded joints of 09G2 and 12GN2MFAYu steels at different temperatures (20– –80 °C)

| Temperature, °C | $\sigma^{st}$, MPa | $\sigma^{d}$, MPa | $\sigma_{cr}$, MPa |
|---|---|---|---|
| (20)0 | (799) 1056<br>(0) 1045<br>(363) 525<br>0 | (0) 0<br>(848) 0<br>(475) 671<br>1264 | (799) 1056<br>(848) 1045<br>(838) 1196<br>1264 |
| (–20) –40 | (749) 1160<br>(525) 517<br>(0) 0<br>(369) | (0) 0<br>(75) 618<br>(459) 1144<br>(224) | (749) 1160<br>(600) 1135<br>(459) 1144<br>(593) |
| (–60) –80 | (752) 942<br>(350) 453<br>(463) 0<br>(0) | (0) 0<br>(110) 81<br>(47) 658<br>(295) | (752) 942<br>(460) 734<br>(510) 658<br>(295) |

*Note.* Data pertaining to welded joints of steel 09G2, are given in brackets.

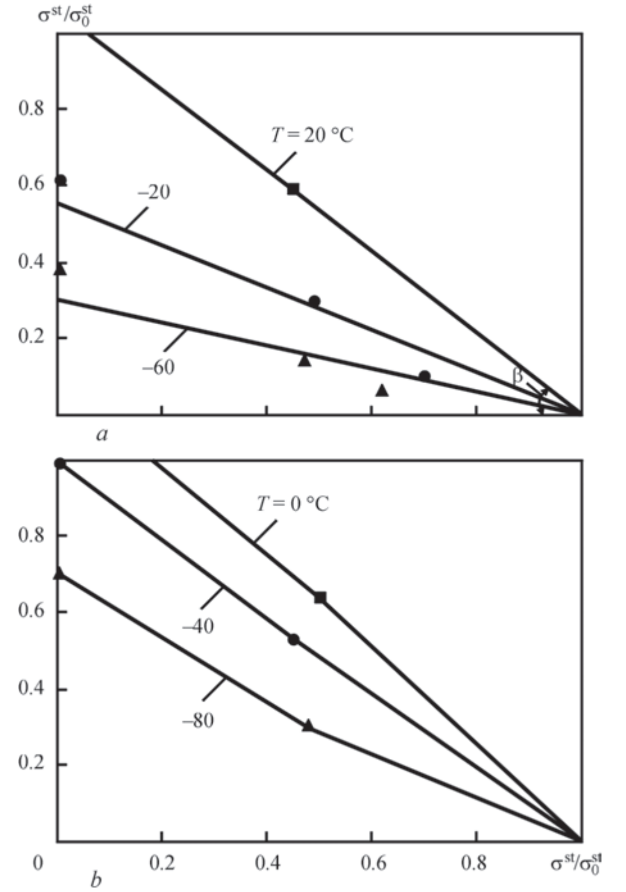


**Figure 2.** Diagrams of limit stresses of welded joints of 09G2 (*a*) and 12GN2MFAYu (*b*) steels under the conditions of combined loading at room and low temperatures

ical stress $\sigma_{cr}$, except for the results of testing 09G2 steel welded joints at –60 °C. With increase of static stresses, limit dynamic stresses decrease, and critical stresses increase. A certain lowering of $\sigma_{cr}$ is observed for welded joints of 09G2 steel only at room temperature and at 0 °C for those of 12GN2MFAYu steel. It can be noted that if by static stresses we mean residual stresses, then the admissible level of dynamic loads can always be assessed by the derived limit stress diagrams. Moreover, in absence of impact drop-hammers with high impact energy, it is possible to determine

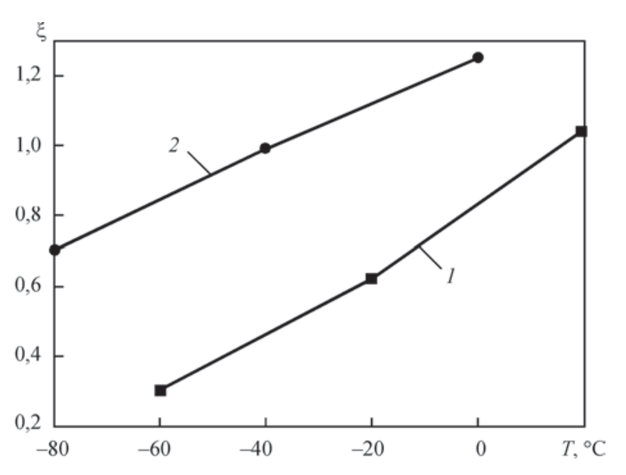


**Figure 3.** Temperature dependence of the coefficient of proportionality of welded joints of 09G2 (*1*) and 12GN2MFAYu (*2*) steels

the breaking stress at dynamic loading by the results of testing at static and combined loading.

Points of LSD intersection with axes of ordinates and abscissas correspond to relative values of $\sigma_0^d$ and $\sigma_0^{st}$, respectively. In this case, the tangent of the angle of LSD inclination to the abscissa axis at specified temperature, is defined as

$$\mathrm{tg}\,\beta = \xi = \frac{\sigma_0^d}{\sigma_0^{st}} = \frac{\sigma^d}{\sigma_0^{st} - \sigma^{st}}, \qquad (2)$$

and critical stress at combined loading is

$$\sigma_{cr} = \sigma_0^d + (1 - \xi)\sigma^{st}, \qquad (3)$$

where $\xi$ is the coefficient of proportionality, depending on the ratio of stresses, induced by static and dynamic loads at combined loading of welded joints.

Analysis of the Figure showed that the angle of LSD inclination largely depends on temperature. Relative $\sigma^d/\sigma_0^{st}$ value decreases noticeably with temperature lowering, but critical stress changes only slightly here. $\xi$ dependence on temperature for the studied welded joints is shown in Figure 3. One can see that it decreases with testing temperature lowering. Here, the value of the coefficient of proportionality for butt joint of 09G2 steel (curve *1*) is essentially lower, that is indicative of higher crack resistance of 12GN2MFAYu steel welded joint that is confirmed by operating practice of these steels application.

In those cases, when dynamic loads are random, and are not taken into account in strength analysis, we will use static component $\sigma^{st}$ of critical stress $\sigma_{cr}$, by analogy with the method of evaluation of load-carrying capacity of a sample, accepted in work [5], as limit stress at combined loading. In this case, we will designate the ratio of dynamic and static stresses at combined loading, numerically characterizing the degree of dynamic overload, as dynamic overload factor $K_{ov} = \sigma^d/\sigma^{st}$. Then, the limit static and breaking dynamic stresses at specified temperature and dynamic overload factor, allowing for dependence (2), can be found as

$$\sigma^{st} = \frac{\xi}{K_{ov} + \xi}\sigma_0^{st} \qquad (4)$$

or

$$\sigma^d = \frac{\xi K_{ov}}{K_{ov} + \xi}\sigma_0^{st}. \qquad (5)$$

Derived equations and dependencies, presented in Figure 3, allow determination of LSD of the studied welded joints at any temperature in the considered range, in the absence of direct experimental studies. For this purpose, it is sufficient to assign the value of $K_{ov}$ and determine $\sigma_0^{st}$ at static loading.

Temperature dependencies of limit static stress $\sigma^{st}$ for welded joints of steels 09G2 (*a*) and 12GN2MFAYu (*b*) at certain values of dynamic overloading factor are given in Figure 4. Curve $K_{ov} = 0$ characterizes the dependence of limit stress $\sigma_0^{st}$ on temperature at static loading. All the other curves characterize the results of studies at combined loading. At $K_{ov}$ = 1 stresses induced by static and dynamic loads, are the same. The same Figure gives temperature dependencies of the studied material yield point at tension $\sigma_y$ and bending $\sigma_y^b$. Yield point $\sigma_y^b$ was determined by three-point bending of smooth (uncracked) samples, the thickness of which (see Figure 1) is equal to thickness of net-section of the cracked sample. This means that the gradient of nominal stresses of smooth samples and the cracked samples was the same. At room temperature it was 480 and 970 MPa for 09G2 and 12GNMFAYu steels, respectively. Temperature dependencies of $\sigma_y$ and $\sigma_y^b$ of the studied materials were established by calculation [4]. Points of intersection of graphs $\sigma^{st} = f(T)$ at the set dynamic overload factor and $\sigma_y = f(T)$ or $\sigma_y^b = f(T)$ are exactly what determines $T_{cr2}$ values. The data given in the Figure show that stresses induced by dynamic load essentially affect both $\sigma^{st}$ and $T_{cr2}$. With increase of $K_{ov}$ limit stresses in the studied welded joints decrease at static loading, and the second critical brittleness temperature rises.

Welded joint sensitivity to dynamic load can be assessed by the ratio of the value of decrease of static stress $\Delta\sigma = \sigma_0^{st} - \sigma^{st}$ at the set ratio of dynamic stress to breaking static stress $\sigma_0^{st}$. As an example, Figure 5 gives temperature dependencies of sensitivity of the studied welded joints at $\sigma^d$ = 200 MPa. Figure analysis showed that in the studied temperature range the welded joint of 09G2 steel (curve *1*) is more sensitive to dynamic load. This difference becomes greater with temperature lowering and at –60 °C it increases approximately three times. It follows that during strength analysis at sample testing under combined loading not only static, but also dynamic stresses should be measured and taken into account. In this case, $T_{cr2}$ should be more reliably determined by intersection of temperature dependencies of critical maximum stress $\sigma_{cr}$ and yield point of the considered material. Dynamic factor $K_d = \sigma^d/\sigma_{cr}$, which is connected by relationship $K_d = K_{ov}/1 + K_{ov}$ with dynamic overload factor, was used as loading mode characteristic. Using experimental data (see Table), Figure 6 gives temperature dependencies for welded joints of steels 09G2 (*a*) and 12GN2MFAYu (*b*) at certain values of dynamic coefficient. Curve $\sigma_{cr} = f(T)$ determined at $K_d$ = 0, characterizes temperature dependence of critical stress, equal to limit stress $\sigma_0^{st}$, derived under the conditions of just static loading, and $K_d$ = 1 — that at dynamic loading $\sigma_0^d$. With known values $\sigma_0^{st}$, ξ, and $K_d$, critical stress $\sigma_{cr}$ for specified temperature can be determined by the following formula:

$$\sigma_{cr} = \frac{\xi}{K_{ov} + \xi(1 - K_{ov})}\sigma_0^{st}. \quad (6)$$

Dependencies, given in the Figure, show that with $K_d$ increase, critical stresses in the studied welded joints decrease, and the second critical brittleness temperature increases, i.e. the nature of variation of maximum stresses and critical brittleness temperature is analogous to those given in Figure 4, except for their absolute values.

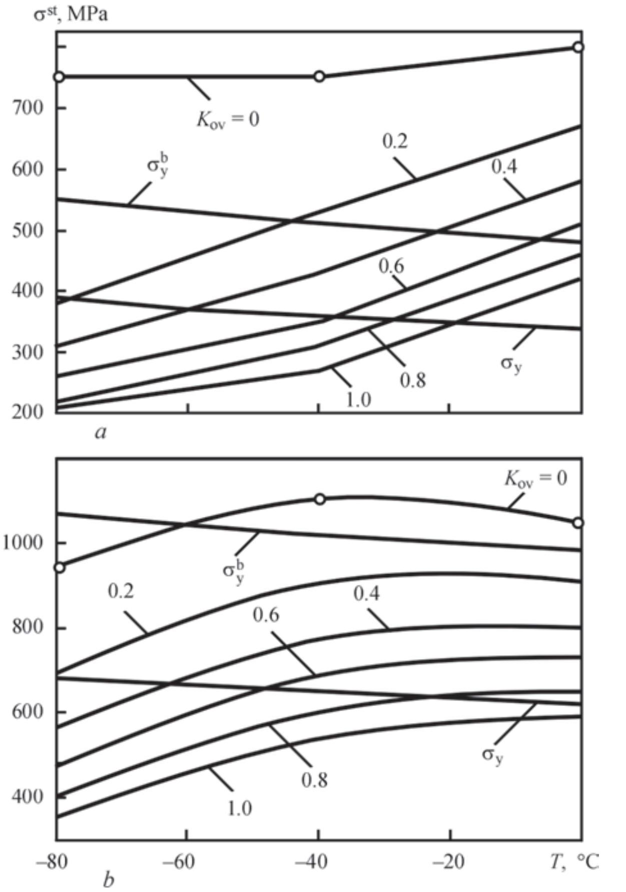


**Figure 4.** Influence of temperature and dynamic overload factor on limit static stresses in welded samples of 09G2 (*a*) and 12GN2MFAYu (*b*) steels: $\sigma^y$, $\sigma_y^b$ — yield point at tension and bending, respectively

Influence of dynamic overload factor (curves *1*, *3*) and dynamic factor (curves *2*, *4*) on second critical brittleness temperatures of welded joints of steels 09G2 (*1*, *2*) and 12GN2MFAYu (*3, 4)* is show in Figure 7. Points of intersection of temperature dependencies of $\sigma^{st}$ with $\sigma_y = f(T)$ (Figure 4), and for curves *2*, *4* — temperature dependencies of $\sigma_{cr}$ with $\sigma_y = f(T)$

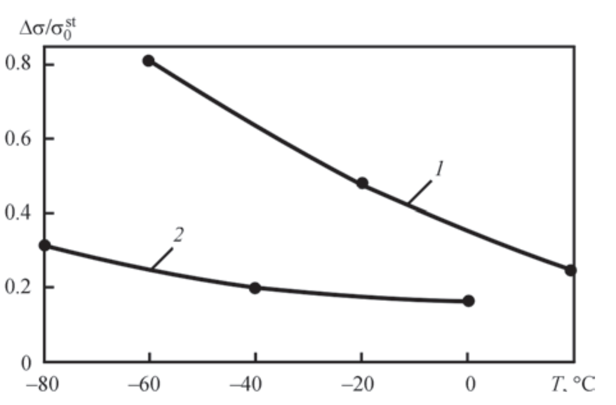


**Figure 5.** Dependence of sensitivity of welded joints of 09G2 (*1*) and 12GN2MFAYu (*2*) steels on temperature at specified value of dynamic stress $\sigma^d$ = 200 MPa

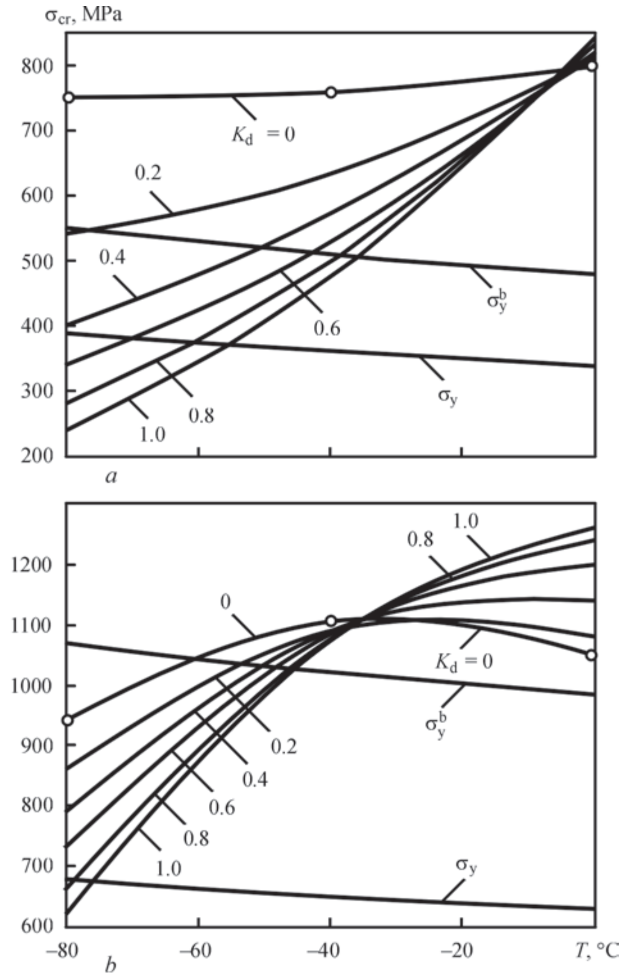


**Figure 6.** Influence of temperature and dynamic factor on critical stresses in welded samples from 09G2 (*a*) and 12GN2MFAYu (*b*) steels

(Figure 6) were used to plot curves *1, 3*. Comparison of obtained results shows that $T_{cr2}$ is much lower at evaluation of welded joint load level by the dynamic factor, than at its evaluation by dynamic overload factor. With increase of the factors the difference between the second critical brittleness temperatures determined by $\sigma^{st}$ and $\sigma_{cr}$, tends to increase. It can be stated that evaluation of second critical brittleness temperatures of the studied welded joints by maximum stresses at combined loading (curves *2, 4*) is more valid than that allowing for the impact of just the static stresses. Moreover, one can see that at the same values of $K_{ov}$ or $K_d$ the second critical brittleness temperatures of welded joints of 12GN2MFAYu steel are essentially lower. For instance, at $K_{ov}$ = 0.4, the difference of critical brittleness temperatures between the studied welded joints is equal to 23 °C, and at $K_d$ = 0.8 it is 39 °C.

Thus, performed investigations of welded joints of steels of different strength, having a defect in the form of a fatigue crack at different ratios of dynamic and static stresses in a broad range of variation of climatic temperatures and presented analysis of the data pro-

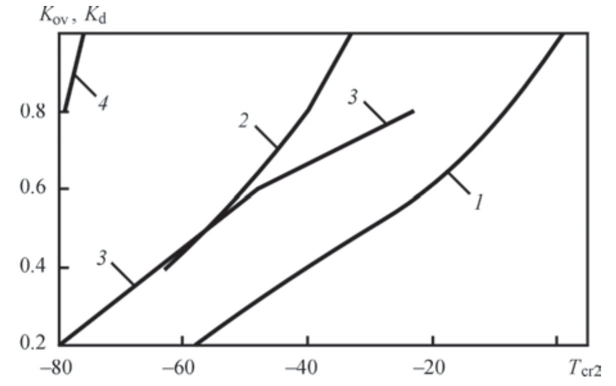


**Figure 7.** Influence of dynamic overload (*1, 3*) and dynamic (*2, 4*) factors under combined loading conditions on second critical brittleness temperatures of welded joints of 09G2 (*1, 2*) and 12GN2MFAYu (*3, 4*) steels

vide a better substantiated approach to determination of strength margins of metal structure elements, produced from the studied materials.

## Conclusions

1. Limit stress and second critical brittleness temperature at combined loading of the studied welded joints depend on the ratio of static and dynamic stresses. At increase of dynamic overload and dynamic factors limit stress decreases, and the second critical brittleness temperature rises.

2. It is shown that ignoring the dynamic stresses leads to lower values of limit stress and overestimated values of second critical brittleness temperature.

3. It is found that second critical brittleness temperatures of welded joints of steel 12GN2MFAYu and their sensitivity to dynamic load are lower in the entire range of studied temperatures.

4. Limit stresses and second brittleness temperature should be determined under the conditions of combined loading at the same dynamic factor, at which metal structure element operates.


1. Grigoriev, R.S., Larionov, V.P., Urzhumtsev, Yu.S. (1987) *Methods of increase of serviceability of equipment in North version*. Novosibirsk: Nauka. Siberian section.
2. Telushkin, V.D., Vinokurov, V.A., Ryakhin, V.A. et al. (1978) *Road-building machines for regions with cold climate*. Moscow: Mashinostroenie.
3. Sleptsov, O.I., Shulginov, B.S., Mikhajlov, V.E. et al. (2012) *Improvement of strength of welded metal structures of mining and transport engineering under conditions of North*. Novosibirsk: Nauka.
4. Makhutov, N.A. (1973) *Resistance of structure elements to brittle fracture*. Moscow: Mashinostroenie.
5. Trufyakov, V.I. (1973) *Fatigue of welded joints*. Kiev: Naukova Dumka.
6. (1985) *GOST 25.506–85*: Methods of mechanical tests of metals. Determination of characteristics of crack resistance (fracture toughness) under static loading. Moscow: Standart.
7. Degtyaryov, V.A. (1982) Units of DSO type for fatigue testing under repeated impact loading with different cycle asymmetry. *Problemy Prochnosti*, **10**, 110–113.


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