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KINETICS OF SOLID-PHASE INTERACTION BETWEEN DISSIMILAR CRYSTALLINE MATERIALS UNDER AN APPLIED LOAD IN A WIDE TEMPERATURE RANGE

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Abstract: In the paper, a functional dependence of the kinetics of plastic strain and the change in shape of copper microprotrusions under the action of an applied load in a wide temperature range was obtained. The equations obtained in the paper can further find wide practical application for calculating the microstresses of the 2nd kind arising at the interface of a metal - an inorganic material (for example, iron carbide, oxides, nitrides, etc.) during plastic strain, and will also allow estimating the intensity of the processes of the first stage of a solid-phase topochemical reaction between dissimilar crystalline materials with sharply different creep resistance, leading to the formation of a real and physical contact between the surfaces. Synthetic monocrystalline corundum was chosen as such a response material in the paper.

Keywords: kinetics, plastic strain, contact interaction, applied load in a wide temperature range, correlation-regression analysis, microstresses of the 2nd kind, relay transmission of strain

КИНЕТИКА ТВЕРДОФАЗНОГО ВЗАИМОДЕЙСТВИЯ МЕЖДУ РАЗНОРОДНЫМИ КРИСТАЛЛИЧЕСКИМИ МАТЕРИАЛАМИ ПОД ДЕЙСТВИЕМ ПРИЛОЖЕННОЙ НАГРУЗКИ В ШИРОКОМ ДИАПАЗОНЕ ТЕМПЕРАТУР

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Аннотация: В работе получена функциональная зависимость кинетики пластической деформации и формоизменения микровыступов меди под действием приложенной нагрузки в широком диапазоне температур. Полученные в работе уравнения в дальнейшем могут найти широкое применение на практике для расчета микронапряжений 2-ого рода, возникающих на границе раздела металла - неорганический материал (например, карбид железа, оксиды, нитриды и т.п.) при пластической деформации, а также позволят оценить интенсивность протекания процессов первой стадии твердофазной топохимической реакции между разнородными кристаллическими материалами с резко различной сопротивляемостью ползучести, приводящих к образованию действительного и физического контакта между поверхностями. В качестве такого ответного материала в работе был выбран синтетический монокристаллический корунд.

Ключевые слова: кинетика, пластическая деформация, контактное взаимодействие, приложенная нагрузка в широком диапазоне температур, корреляционно-регрессионный анализ, микронапряжения второго рода, эстафетная передача деформации

INTRODUCTION

Continuing the series of papers devoted to the study of solid-phase interaction under the influence of applied load in a wide range of temperatures, in particular the kinetics of contact formation between dissimilar crystalline materials using copper-corundum as an example, this paper is devoted to obtaining the dependence of the kinetics of plastic strain of microprotrusions at different levels of applied loads in a wide range of temperatures. A microprotrusion corresponds to the size of one grain of metal.

The need for research

Establishing the kinetics of plastic strain of microprotrusions (a microprotrusion corresponds to the size and structure of one grain) is a very important issue in the process of obtaining a precision detachable or permanent connection - a smoothing process that allows obtaining high-frequency metal surfaces with controlled and adjustable mechanical properties or obtaining a permanent precision connection (welding) when establishing physical contact between the surfaces.

The objective of the paper is to establish the dependence of the formation of plastic strain of copper microprotrusions ε_m, determined in %, on time *t,* determined in seconds, in a wide range of temperatures from room temperature to pre-melting (from 293 K to 973 K) and nominal pressures from 5 to 30 MPa. Of interest is the kinetics of the process of plastic strain of microprotrusions and the influence of temperature and nominal pressure on its course, since in metal under the action of a variable applied load in a wide range of temperatures there is a transition from elastic to elastic-plastic and plastic contact, which must be taken into account in real calculations. In this case, the formulas for calculating strains under elastic mechanical contact cannot be applied. Also, under plastic strain of metal grain, microstresses of the 2nd kind arise, responsible for the relay transmission of strains from soft to hard using the example of copper-corundum or ferrite-cementite Fe_3C contact.

METHODS

Experimental study

The papers [1, 2, 3] describe in detail the experiment and its methodology.

The data considered in the paper were obtained using experimental processing of changes in the roughness indices of the study of contact surfaces of copper grade MB and synthetic single-crystal corundum (sapphire) α-Al_2O_3, 60^{O}-orientation, carried out using a profilograph-profilometer mod. 201 with a special computer program of the information computing complex (ICC) [4, 5-9].

The experiment was carried out for a wide range of temperatures T from 293 K to 973 K and nominal pressures σ_n from 5 MPa to 30 MPa, the height of the processing microprotrusions R_z was within the range: 3.2 ... 6.3 ... 10 µm and 40-80 µm. The data obtained as a result of the experiment are presented in Table 1.

Table 1. Experimental values of plastic strain ε_m, between copper grade MB and synthetic single-crystal corundum (sapphire) α-Al_2O_3

σ_n, MPa	*t*, s	ε_m, %							
		T=293, K	*T*=373, K	*T*=743, K	*T*=573, K	*T*=673, K	*T*=773, K	*T*=873, K	*T*=973, K
5	30	3.9	5.7	11.5	12.3	17.7	15.7	19.7	21.7
	150	7.8	8	15.3	16.4	21.5	23	26.4	28
	330	8	9.5	17.1	17.7	24.2	24.3	28.8	29.9
	570	8.9	9.8	17.3	17.8	25.9	25.4	29.9	31.1
	870					27	25.9	32	32.2
	1170	10.2	10.5	18.7	20.3	28	27.5	32.2	33.4
	1470					28.5	29	33.1	34.2
	2070	10.7	11.5	20.2	22	29.8	30.8	35.1	36.1

σ_n, MPa	t, s	ε_m, %							
		T=293, K	T=373, K	T=743, K	T=573, K	T=673, K	T=773, K	T=873, K	T=973, K
10	30	6.8	8.5	12.7	14.4	17.5	18.3	21.1	22.6
	150	11.5	13	16	17.4	20.9	23.1	26.2	29.8
	330	13.4	14.7	18	19.7	23.9	26.1	29.8	34.2
	570	13.8	15.6	19.2	20.5	25.7	28	30.5	36.7
	870					26	29.3	32	37.9
	1170	15.4	16.7	19.3	21	26.4	29.8	33	39
	1470					27	30.2	33.5	39.4
	2070	17.3	18.3	20.8	22.8	28.2	31.2	34.7	40.3
15	30	9.1	11.5	13.8	14.5	17.7	19	21.6	26.4
	150	12	13.4	16	18.3	21.5	23.7	27	32.2
	330	13.4	15.2	18	20	24.2	27.3	29.6	36.1
	570	14.1	16	19	21	25.9	28.5	30.8	39
	870					27	29	31.9	39.6
	1170	14.8	16.7	19.7	22	28	30.2	32.8	40.2
	1470					28.5	31	33.7	41.2
	2070	16.3	17.7	21.3	23	29.8	33.1	35.9	42.2
20	30	10.30	11.90	14.10	15.60	19.00	20.60	23.70	29.00
	150	12.30	13.80	16.30	18.30	21.90	25.10	28.50	35.50
	330	13.40	15.20	19.00	21.00	25.90	28.50	32.00	39.40
	570	14.10	16.00	20.00	21.60	27.20	30.00	33.80	41.20
	870					27.50	30.50	34.50	41.80
	1170	14.80	16.70	20.30	22.50	28.00	31.00	35.00	
	1470					28.50	31.50	35.50	42.60
	2070	16.30	18.00	21.30	23.70	29.00	32.20	36.00	43.50
30	30	11	13	16	17	19.3	20.7	24.8	31
	150	13	15.6	18.7	20.3	23.3	21.9	31.7	34.2
	330	14.2	16.7	20.6	21.9	26.4	25.6	35	38.3
	570	14.8	17.4	21.9	22.7	28.5	31.3	35.9	41.2
	870					29	32.4	37.1	42.8
	1170	15.2	17.7	22.5	23.7	29.6	33.6	39.6	44.5
	1470					30	35	40.3	46.2
	2070	16	18.7	23	24.2	31.5	37.1	42.2	47.5

RESULTS AND DISCUSSION

Obtaining kinetic equations for plastic strain of copper microprotrusions under the action of an applied load in a wide temperature range

Based on the analysis of the data in Table 1, a one-to-one correspondence was obtained and substantiated using correlation-regression analysis methods, allowing one to obtain a specific value of plastic strain ε_m arising in copper depending on the contact time t.

The analysis carried out in the paper allowed us to establish that the kinetics of plastic strain of copper microprotrusions obeys the logarithmic law

$$\varepsilon_m = a + b\ln(t)\,. \quad (1)$$

In accordance with formulas (2), the coefficients a and b of the equation for determining plastic strain (1) were determined

$$a = \overline{\varepsilon_m} - b\overline{X}, \quad b = \frac{\overline{\varepsilon_m X} - \overline{\varepsilon_m} \cdot \overline{X}}{\overline{X^2} - \left(\overline{X}\right)^2}, \qquad (2)$$

where $X = \ln t$; the overline in formulas (2) denotes the average values.

Table 2 presents the obtained equations for calculating the kinetics of plastic strain in copper under the action of variable load in a wide temperature range.

Table 2. Values of the coefficients a and b included in equation (1) for temperatures T from 293 K to 973 K and nominal pressures σ_n = 5, 10, 15, 20 and 30 MPa

σ_n, MPa	5		10		15		20		30	
T, K	*a*	*b*	*a*	*b*	*a*	*b*	*a*	*b*	*a*	*b*
293	-0.9161	1.5599	-0.839	2.3608	3.6918	1.6323	5.5765	1.3541	7.1514	1.1712
373	1.2949	1.3396	1.3314	2.2354	6.3405	1.4879	6.933	1.4182	8.8503	1.3047
473	5.1083	1.9699	6.5898	1.8851	7.6295	1.7592	8.1104	1.768	10.265	1.7332
573	4.998	2.1701	7.9196	1.9367	8.0523	1.9992	9.0525	1.9396	11.472	1.7292
673	7.5722	2.8797	8.8366	2.5327	7.5722	2.8797	10.506	2.493	9.4443	2.8802
773	5.3888	3.2136	7.8274	3.11	8.1487	3.1755	11.493	2.787	3.8381	4.1951
873	8.4701	3.4356	10.406	3.1947	10.91	3.1635	13.833	3.0077	11.546	3.9383
973	11.281	3.1703	8.5363	4.2907	13.63	3.8092	18.143	3.4553	15.521	4.0863

For all obtained equations type (1) of the kinetics of plastic strain of copper with coefficients a and b (Table 2), the coefficient of determination R^2 was calculated in accordance with formula (3), showing the quality of the equations

$$R^2 = 1 - \frac{\sum_{t=1}^{n}\left(\varepsilon_{m_t} - \hat{\varepsilon}_{m_t}\right)^2}{\sum_{t=1}^{n}\left(\varepsilon_{m_t} - \overline{\varepsilon_m}\right)^2} \qquad (3)$$

where ε_{m_t} is the value of plastic strain of copper microprotrusions at time *t*, obtained as a result of the experiment (in %), $\hat{\varepsilon}_{m_t}$ is the value of plastic strain of copper microprotrusions at time *t*, calculated using formula (1) (in %), $\overline{\varepsilon_m}$ is the average value of plastic strain of copper microprotrusions (in %).

The values of the determination coefficient obtained in accordance with formula (3) are presented in Table 3.

It is evident from Table 3 that all values of the coefficient of determination exceed 0.9, from which it follows that the equations obtained in Table 2 describe the kinetics of plastic strain in copper under the action of variable load in a wide temperature range with an accuracy of more than 90%. This makes it possible to apply these equations in practice for calculating plastic strains occurring in copper in a wide range of temperatures and pressures.

Table 3. Values of the coefficient of determination R^2 for kinetic equations (Table 2) for T from 293 K to 973 K and σ_n = 5, 10, 15, 20, 30 MPa

σ_n, MPa / T, K	5	10	15	20	30
293	0.960	0.984	0.990	0.987	0.988
373	0.987	0.987	0.989	0.991	0.979
473	0.984	0.973	0.987	0.961	0.977
573	0.975	0.982	0.989	0.981	0.983
673	0.996	0.985	0.996	0.964	0.989
773	0.962	0.994	0.987	0.980	0.908
873	0.989	0.994	0.990	0.981	0.988
973	0.987	0.988	0.988	0.967	0.966

An example of the application of the obtained formulas in practice

The formulas obtained in the paper will allow modeling the kinetics of plastic strain of copper microprotrusions under the action of variable load in a wide temperature range at each stage of contact formation [2].

The process of contact formation can be conditionally divided into three stages, each of which is characterized by its own physical and mechanical features of the behavior and activity of atoms in the near-contact volume of microprotrusions and is controlled by a certain mechanism of plastic strain at each stage of the kinetic curve [5, 6, 9].

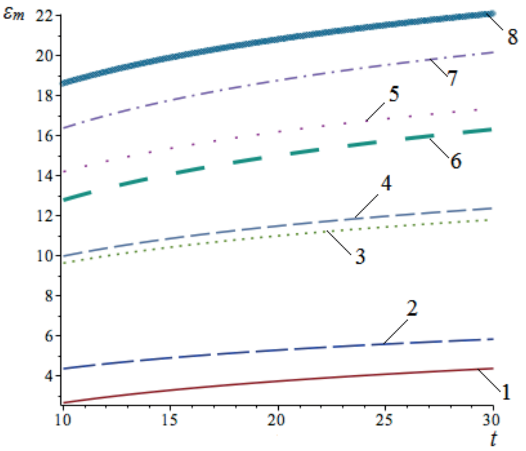
As an example, we will consider the period of active strain or the loading period corresponding to a time *t* from 10 to 30 seconds. Let us construct kinetic curves of plastic strain of copper microprotrusions for the temperature range *T* considered in the paper from 293 K to 973 K and nominal pressures σ_n = 5, 10, 15, 20 and 30 MPa (Figure 1).

In Figure 1 (a-e), the curves are designated by numbers: 1 – T=293 K, 2 – T=373 K, 3 – T=473 K, 4 – T=573 K, 5 – T=673 K, 6 – T=773 K, 7 – T=873 K, 8 – T=973 K.

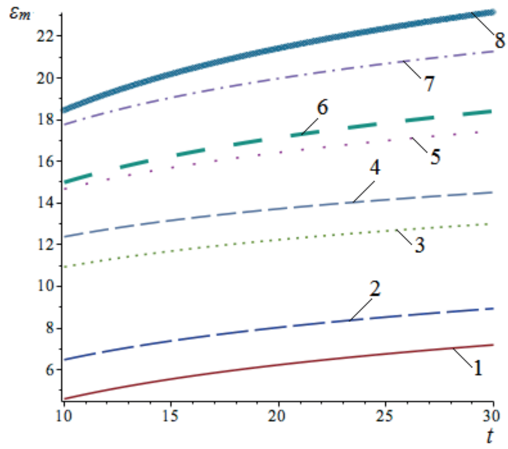
Using the graphs in Figure 1, it is possible to determine the value of plastic strain in copper with an accuracy of 90% during the period of active strain for a specific *t* from 10 to 30 s. Taking into account the formulas obtained in the paper (Table 2), it is possible to determine plastic strain at any other stage (formation of contact of transient and steady creep) with the stated accuracy.

The modeling results obtained in the paper can be confirmed by studies of copper microhardness H_μ (Figure 2).

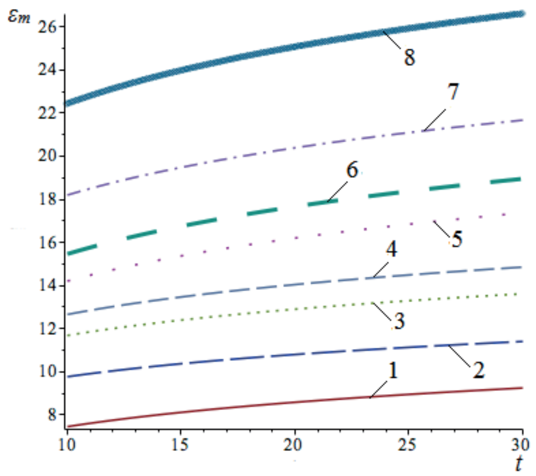
The greatest hardening of copper corresponds to the period of active strain (corresponding to a time *t* from 10 to 30 seconds) and the stage of unsteady creep (6-8 minutes). After completion, the process of changing hardness stabilizes, i.e. corresponds to the stage of steady creep.



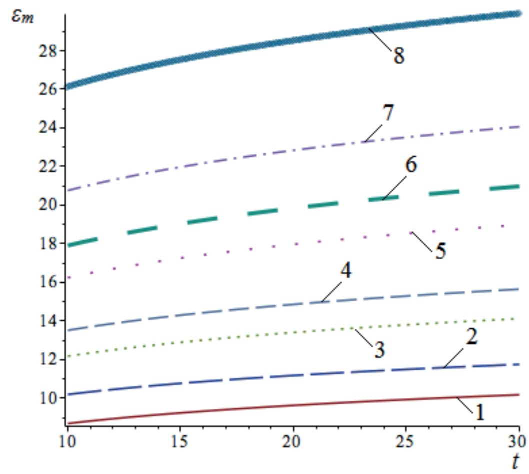
(a) σ_n = 5 MPa



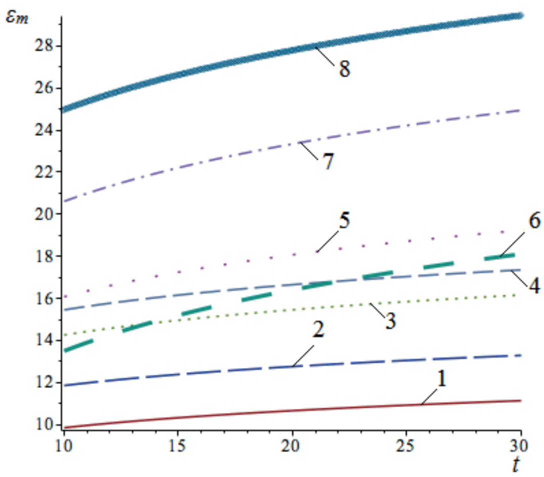
(b) σ_n = 10 MPa



(c) σ_n = 15 MPa

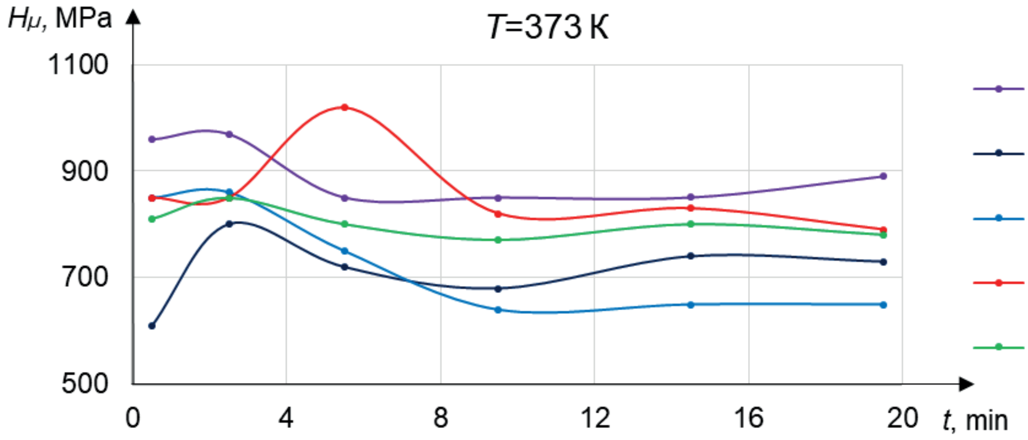


(d) σ_n = 20 MPa

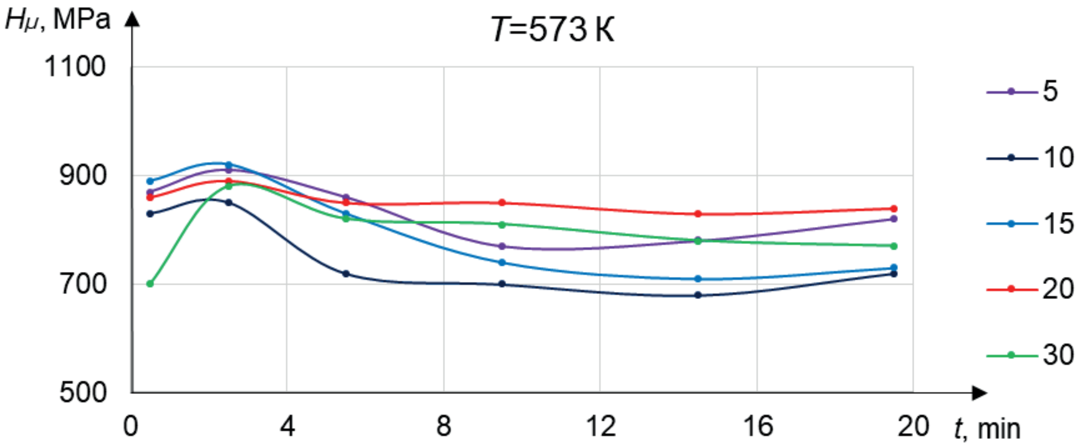


(e) σ_n = 30 MPa

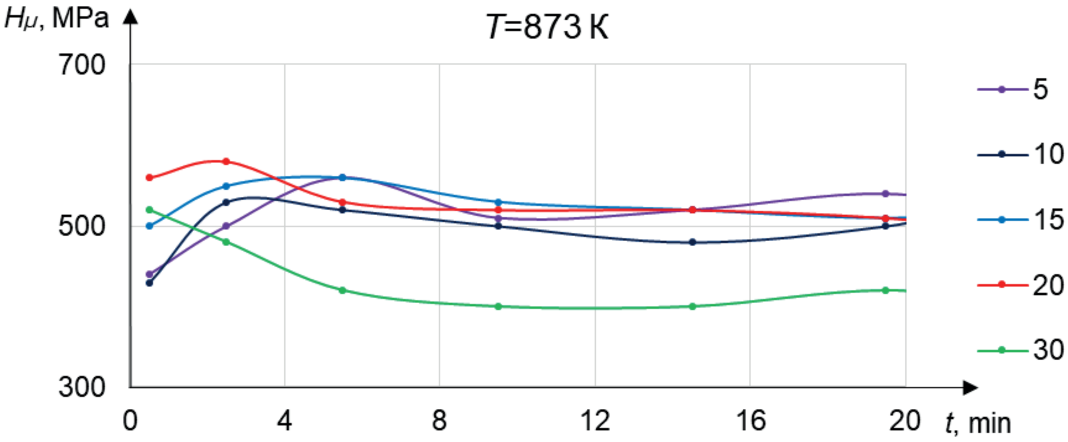
Figure 1. Kinetics of plastic strain of copper microprotrusions, t=10-30 s, T=293, 373, 473, 573, 673, 773, 873, 973 K: (a) σ_n = 5 MPa, (b). σ_n = 10 MPa, (c) σ_n = 15 MPa, (d) σ_n = 20 MPa, (e) σ_n = 30 MPa



(a)



(b)



(c)

Figure 2. Effect of pressure (σ_n = 5…30 MPa) and temperature (a): T =373 K, (b) T = 573 K, (c) T =873 K on the magnitude and nature of the change in hardness (H_μ) on the surface of the contact pads of copper microprotrusions

CONCLUSION

The paper presents kinetic equations that can be used to determine plastic strains of copper microprotrusions under the influence of applied load in a wide range of temperatures, starting with the period of active strain and ending with the stage of steady-state creep.

Knowledge of the patterns of contact formation due to plastic strain of microprotrusions and their shape change at each stage of the solid-phase topochemical reaction in the contact volumes of the metal allows for a more complete justification of the technological process for obtaining a precision detachable or permanent connection, to manage it and actively control its flow. In addition, the established patterns allow for the calculation of the level of acting normal and tangential microstresses of the 2nd kind in the contact volume of the metal and to explain the mechanism of relay transmission of strains from a soft metal to a harder material and activate its contact surfaces (e.g., semiconductors, inorganic dielectrics, etc. materials) or the destruction of inclusions in steels (carbides, oxides, nitrides) and the subsequent sudden catastrophic destruction of welded metal structures [3]. The established mechanism of relay transmission of strain under the action of microstresses of the 2nd kind combines macroscopic concepts of the mechanics of deformation of solids with microscopic ones, considered from the standpoint of dislocation theory [7, 10]. Knowing these features, it is possible to control the process of obtaining high-purity metal surfaces necessary for high-tech industries such as aviation and radio electronics, nuclear power engineering, as well as the theory of sudden brittle failure of welded metal structures [5, 6, 11].

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