Strength of welded joint sunder quasi - brittle fracture

M V Shakhmatov[1], E A Usmanova[2]

[1]LLC, "Center of Preparation of Specialists" Welding and Control ", st. Ryileeva,11, 454087, Chelyabinsk, Russia
[2]South Ural State University, Lenin Ave., 76, Chelyabinsk, 454080, Russia

Abstract. In the study of the crack resistance of welded joints with constructive incomplete welds, which are regulated by welding GOSTs and have a wide practice of application, including for critical structures, it is necessary to keep in mind that these stress concentrators on the sharpness of their tops are significantly different from fatigue and operational cracks. Welding defects have the same difference: faulty welds, faulty fusions, undercuts. This paper shows that the strength of welded joints with structural faulty welds in addition to mechanical characteristics and the length of the faulty weld also depends on the radius at its top. Based on the ratios of fracture mechanics, a strain fracture criterion is proposed - the critical opening of the concentrator under consideration, depending on the radius at its top. At the same time, with the reduction of the radius at the top of the concentrator to a certain critical value, comparable to the radius at the top of the crack, the proposed criterion coincides with the material characteristic according to GOST 25.506-85 – the critical crack opening. Dependence for assessing the quasi-brittle strength of welded joints with faulty welds based on the critical disclosure of the concentrator under consideration satisfactorily corresponds to the experimental data on samples from the AMg6 alloy.
 Keywords: Welding joints, Quasi-brittle fracture, Stress concentrators, Crack resistance, Faulty welds, Plastic strains, Fracture mechanics.

1. Relevance, scientific significance

Most welded structures are made of materials (alloys and steels) with a fairly high plasticity resource. Such materials include low-carbon, low-alloyed, medium-alloyed steels, titanium and aluminum alloys, etc. When loading structures made of these materials, a fairly developed plastic flow takes place at the top of crack-like defects. In general, this reduces the risk of brittle fractures, since some of the energy is spent on the formation of plastic zones. In these zones, stresses and strains are no longer controlled by stress intensity factors K_{IC} [1], and are determined from the relations of the theory of plasticity. These fractures are usually called quasi-brittle (the prefix quasi denotes an approach to the brittle state). Thus, not all, but only a part of the net section of the welded joint is covered by plastic strain, therefore this circumstance must be taken into account when creating calculated estimates of the strength of welded joints. In the framework of fracture mechanics for models describing the behavior of materials beyond the elastic limit, a number of criteria are introduced: δ_C – critical crack openings [2], V_C –critical strain rate coefficient [3], J_C – critical value of the integral independent of the integration contour [4, 5], a two-parameter criterion based on a specific combination of the characteristics of crack resistance and plastic instability of the flow of metals [6]. These criteria and the practice of their application are most fully represented in the 4-volume directory of scientists edited by V.V. Panasyuk [7], in the works of Russian scientists: S.V. Serensen, V.P. Kogaeva, R.M.

Shnayderovich, N.A.Makhutov [8, 9, etc.]. With reference to the features of the fracture of welded joints and structures, the works of V.I. Makhnenko [10], L.A. Kopelman [11], G.P. Karzov [12], V.A. Vinokurov [13] and other scientists should be noted radius $\delta_C(\rho)$.

The purpose of this work is to further develop and apply the strain criteria of fracture for welded joints, taking into account their characteristic features.

2. Theoretical part

In the study of the crack resistance of welded joints with constructive incomplete welds, which are regulated by welding GOSTs [14, 15, 16 and others] and have a wide practice of application, including for critical structures, it is necessary to keep in mind that these stress concentrators on the sharpness of their tops are significantly different from fatigue and operational cracks. Welding defects have the same difference: faulty welds, faulty fusions, undercuts. In the framework of the formal approach, the direct use of fracture mechanics criteria for such concentrators leads to significant errors in assessing the quasi-brittle strength of welded joints [10]. In this regard, it is important to determine the effect of the severity of such concentrators on the stress-strain state in the zone of fracture. Following A. Kotrell [7], we take a certain radius ρ for sharpness at the top of welding concentrators and investigate its critical disclosure. For this purpose, we use the results of [3], where V_C ¬ critical coefficient of strain intensity, which takes into account the change in mechanical properties in the zone of the concentrator during the thermoplastic welding cycle and the radius at its top ρ. The value of the parameter V_C is equal to:

$$V_C = \varepsilon_{av} a_\varepsilon \sqrt{\rho} = \varepsilon_{1\,max} \varepsilon_{max}^* \sqrt{\rho} \tag{1}$$

Here ε_{av} is the average strain obtained at some base away from the concentrator; a_ε is the coefficient of concentration of strains at the top of the concentrator; ε_{1max} – maximum strain at its top.

To establish the relationship between the critical values of the parameters V_C, K_{1c}, δ_C and the radius at the top of the concentrator ρ we use the ratio of [3, 9]:

$$V_C = \frac{2K_{1C}}{\sqrt{\pi}E}, \tag{2}$$

$$\delta_C = \alpha \frac{K_{1C}^2}{E^* \sigma_T} \tag{3}$$

Here $E^* = E$ is the modulus of elasticity of the first kind for a welded joint in a plane stress state; $E^*=E/((1-\mu^2))$ – under plane strain; μ is the Poisson's ratio (transverse strain factor); σ_T – yield strength (ideal elastic-plastic model of the material is considered); α^* is a coefficient depending on the choice of correction for the plasticity zone near the concentrator.

It should be noted that the strain criterion δ_C is based on opening the crack edges to some constant critical values for the material under consideration, therefore this criterion was brought to the level of standardization [17]. Entering into the corresponding formulas the radius ρ and the value of the maximum strain ε_{21max}, we abstract from δ_C as from the characteristics of the material and proceed to some constructive characteristic - critical disclosure of the concentrator of the finite radius. $\delta_C(\rho)$. Taking into account (1-3), we obtain the following dependency:

$$\delta_{C(\rho)} = \alpha \frac{\pi E^*}{4\sigma_T} \rho \varepsilon_{1\,max}^2 \tag{4}$$

The value of the coefficient α^* depends on the shape of the plasticity zone at the crack top adopted in the calculation scheme. For example, in the Dagdale model [18], the plasticity zone coincides with the direction of the crack. In this regard, when solving a problem, we obtain $\alpha^* =1$. There is also data from numerical calculations in which it was obtained that $\alpha^* =1…4/\pi$ [19]. According to many authors [8, 9, 10, 19 and others], and also relying on experimental data for processes associated with the developed plasticity zone at the top of the concentrator, we take the value $\alpha^* =1$.

The resulting expression (4) allows to relate the critical opening of the concentrator of the finite radius $\delta_C(\rho)$ with a metal plasticity resource Λp in the fracture zone and at the same time determine the influence of the type of stress state in the zone of development of plastic strains [20]. This is possible due to the fact that both criteria (δ_C and Λp) determine the same moment: the moment of reaching the critical value of the resource plasticity of the metal Λp during plastic strain corresponds to the moment of reaching the critical opening of the concentrator $\delta_C(\rho)$ and as a result – fracture. For this we use the connection between the maximum strain in the area of fracture ε_{1Max} and a resource of metal plasticity Λp as follows [21]:

$$\Lambda_p = \frac{2}{\sqrt{3}} \varepsilon_{1\,max} \frac{\sqrt{3+v_\sigma^2}}{3-v_\sigma^2} \qquad (5)$$

where, $v_\sigma = \frac{2(\sigma_2-\sigma_3)}{(\sigma_1-\sigma_3)} - 1$ is an indicator of the type of stress state (indicator Lode - Nadai); σ_1 , σ_2 ,σ_3 are the principal stresses in the field of plastic strain.

Taking into account formulas (3–5), we obtain a formula for the critical disclosure of a concentrator of the finite radius $\delta_C(\rho)$:

$$\delta_{C(\rho)} = \frac{\pi}{48} \frac{(3-v_\sigma)^2}{3+v_\sigma^2} \frac{E^*}{\sigma_T} \Lambda_p^2 \rho \qquad (6)$$

With decreasing of ρ the value $\delta_C(\rho)$ decreases and at some critical values $\rho = \rho_e$ achieves fatigue crack values. At the same time $\delta_C(\rho) = \delta_C$. In view of (6), we can write:

$$\delta_{C(\rho)} = \delta_C \frac{\rho}{\rho_e} \qquad (7)$$

where ρ_e is the effective radius of the concentrator equivalent to the radius at the top of the fatigue crack:

$$\rho_e = \frac{48}{\pi} \frac{3+v_\sigma^2}{(3-v_\sigma)^2} \left(\frac{\sigma_T \delta_c}{E^* \Lambda_p^2}\right). \qquad (8)$$

If the concentrator has a radius $\rho \leq \rho_e$, the fracture process does not depend on this parameter, the fracture occurs during the critical opening of the concentrator (crack) equal to δ_C. The effective radius ρe is an important microstructural characteristic and is determined not only by the properties of the material, but also by its stress state.

Based on the criterion $\delta_C(\rho)$ in [22, 23] there are proposed formulas for assessing the quasi-brittle strength of welded joints from plates $v_\sigma= 0$ (plate strain at flat stress state) For plates with structural faulty welds, critical stresses σk are equal to:

$$\sigma_k = \sqrt{\frac{E\sigma_B \delta_{C(\rho)}}{0,89\pi l}} \cos \frac{\pi l}{2B} \qquad (9)$$
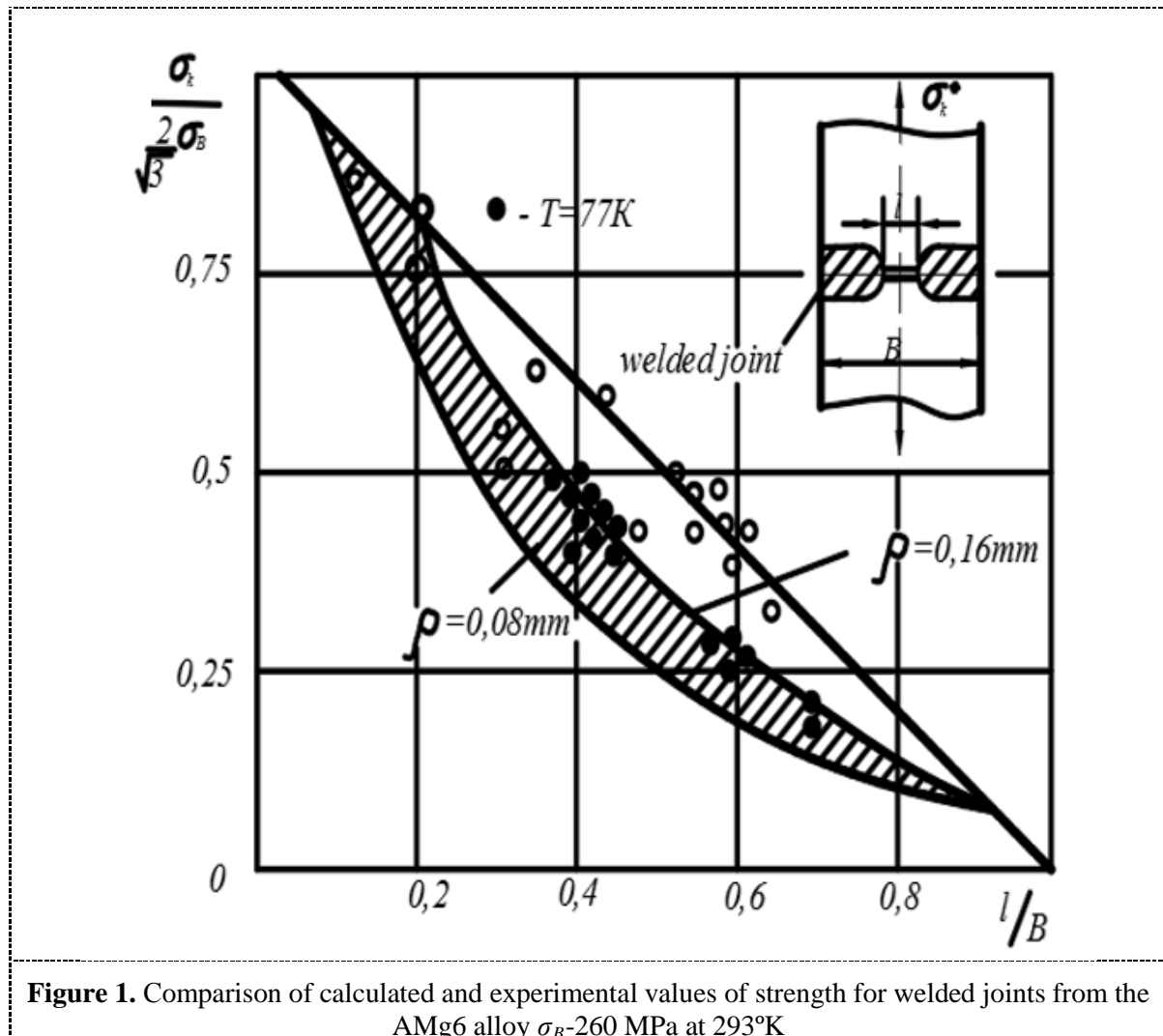
where l is the length of constructive incomplete weld; B is the weld width; σ_B is the temporary resistance of the weld metal. (Since an elastic-plastic model of a material was considered ideally, the corresponding real diagram of the material stretching was approximated by an ideally elastic-plastic to the level of the values of the temporal resistance σ_B [23, 24]).

3. Results of experimental studies

Figure 1, 2 shows the results of the experiment for welded joints from the AMg6 alloy. The straight line in Figure 1, 2 corresponds to the viscous nature of the fracture, the static strength of the samples decreases in proportion to the decrease in net sample cross section $\sigma_k = \sigma_B$ *(1-l/B)*. At the same time the gap $\Delta = 2\rho= 1$ *mm* between end (connected) surfaces was created with spec Dial templates.

Experimental data corresponding to the viscous nature of fracture are shown in Figure 1, 2 in white circles.

By reducing the radii at the top of the faulty weld to $\rho = 0.08 - 0.16$ mm, at a test temperature of 77K, quasi-brittle fractures were obtained (Figure 1 the calculated curves using formula (9) and experimental data are filled circles). With a decrease in radii to a value of $\rho = 0.02$-0.04 mm, quasi-brittle fractures (triangles in Figure 2) were obtained already at a normal test temperature of 293 K (+20$^{\text{o}}$C).
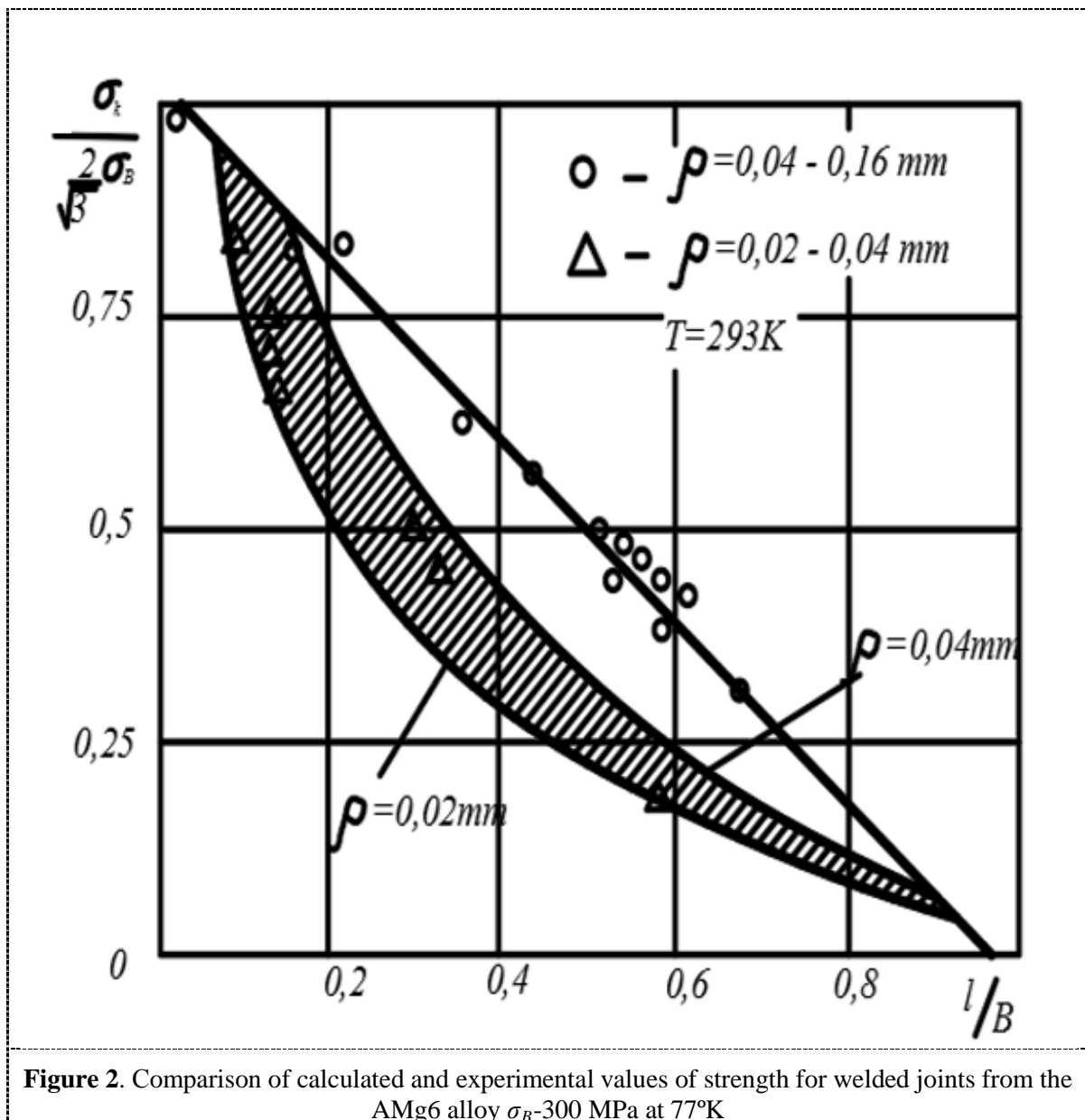

Figure 1. Comparison of calculated and experimental values of strength for welded joints from the AMg6 alloy σ_B-260 MPa at 293°K

Figure 2. Comparison of calculated and experimental values of strength for welded joints from the AMg6 alloy σ_B-300 MPa at 77ºK

The value of the radii ρ = 0.02–0.16mm was obtained on the basis of the state of the joined surfaces, which were evaluated by the roughness class R_Z (R_Z ¬ height of the roughness profile of the surface). With a dense imposition of surfaces on each other and subsequent welding, the parameter of the top of the penetration $\Delta = 2\rho = 2R_Z$. As a result of measurements, it was obtained that for a batch of samples with processing according to the second roughness class (R_Z =80…160 um) ρ = 0,08…0,16 mm; for the fourth class (R_Z = 20…40 um) ρ = 0,02…0,04 mm. The material characteristic - the critical crack opening δ_C was determined experimentally with reference to the standard [17]. At normal test temperature δ_C = 0,022 mm; at 77K δ_C = 0,0074 mm. To calculate the effective radius ρ_e plasticity diagrams were constructed according to the method [20], of which, with the stress state value Π = 3,08 the value Λp =0,12 at normal temperature; at 77K – Λp =0,06…0,065. The calculation of the effective radius by the formula (8) for the weld metal from the AMg6 alloy showed approximately the same value ρ_e = 0,023mm regardless of the temperature of the test, which indirectly indicates that ρ_e – microstructural characteristics of the material.

4. Conclusion

The strength of welded joints with structural faulty welds depends on the mechanical characteristics of the material, the length of the faulty weld, as well as on the radius at its top. Based on the ratios of fracture mechanics, a strain fracture criterion is proposed: the critical opening of the concentrator depending on the radius at its top. At the same time, with the reduction of the radius at the top of the concentrator to a certain critical value comparable to the radius at the crack top, the proposed criterion coincides with the material characteristic according to GOST 25.506-85 – the critical crack opening. The dependency for assessing the quasi-brittle strength of welded joints with incomplete welds based on the critical disclosure of the concentrator under consideration satisfactorily corresponds to the experimental data on samples from the AMg6 alloy.

5. References

[1] Panasyuk V V 1968 The ultimate equilibrium of brittle bodies with cracks (Kiev: Naukova Dumka) 246

[2] Leonov M Ya, Panasyuk V V 1959 Development of the smallest cracks in a solid *Applied Mechanics* **4** 391-401

[3] Vinokurov V A 1977 Using the provisions of fracture mechanics to assess the properties of welded joints *Welding production* **5** 2-4

[4] Rice J 1980 The mechanics of earthquake rupfure Amsterdam, 1980

[5] Cherepanov G P 1974 Mechanics of brittle fracture (Moscow: Nauka) 640

[6] Morozov E M, Parton V Z 1974 Mechanics of elastoplastic fracture (Moscow: Nauka) 416

[7] Fracture mechanics and strength of materials: Reference manual in 4 volumes 1988 under the general editorship of Academician of the Ukrainian Academy of Sciences Panasyuk V V (Kiev: Naukova Dumka)

[8] Serensen S V, Kogaev V P, Sheyderovich R M 1975 Carrying capacity and calculation of machine parts for durability. Manual and reference manual (Moscow: Mashinostroenie) 488

[9] Makhutov N A 1981 Strain criteria for fracture and calculation of structural elements for strength, (Moscow: Mashinostroenie) 272

[10] Makhnenko V I 2006 Resource safe operation of welded joints and components of modern design (Kiev: Naukova Dumka) 617

[11] Kopelman L A 1978 Resilience of welded knots to brittle fracture (Leningrad: Mashinostroenie) 232

[12] Karzov G P, Margolin B Z, Shvetsova V A 1993 Physico-mechanical modeling of the processes of fracture (Saint-Petersburg: Politekhnik) 930

[13] Vinokurov V A 1968 Welding strains and stresses(Moscow: Mashinostroenie) 235

[14] GOST 5264-80. Manual arc welding. Welded joints. The main types of structural elements and dimensions 1981 (Moscow: Publishing house of standards)

[15] GOST 8713-79. Submerged arc welding. Welded joints. The main types of structural elements and dimensions 1993 (Moscow: Publishing house of standards)

[16] GOST 16037-80. Welded steel pipe joints. The main types of structural elements and dimensions 1999 (Moscow: Publishing house of standards)

[17] GOST 25.506-85. Determination of the characteristics of crack resistance (fracture toughness) under static loading 1985 (Moscow: Publishing house of standards)

[18] Shakhmatov MV, Usmanova EA, Khmarova LI 2019 Calculated-experimental estimation of residual pipeline resource for long-term operation In: Radionov A, Kravchenko O, Guzeev V, Rozhdestvenskiy Y (eds) Proc. of the 4th Int. Conf. on Industrial Engineering. ICIE 2018. Lecture Notes in Mechanical Engineering. Springer, Cham

[19] Broek D 1980 Fundamentals of fracture mechanics (Moscow: Vysshaya shkola) 368

[20] Kolmogorov V L 1977 Plasticity and fracture (Moscow: Metallurgy) 335

[21] Smirnov-Alyaev G A 1978 Resistance of metals to plastic strain (Leningrad: Mashinostroenie) 368

[22]   Shakhmatov M V , Erofeev V V 1983 On the issue of rationing the admissibility of welding defects of the type of faulty welds according to the criteria of fracture mechanics *Welding production* **1** 8-10

[23]   Shakhmatov M V, Shakhmatov D M 2009 Strength of mechanically inhomogeneous welded joints (Chelyabinsk: "TsPS Welding and Control") 223

[24]   Shakhmatov M V , Usmanova E A 2017 Safety Evaluation of Pipelines Based on Probabilistic Approaches *Proc. Eng.* **206** 16–20