



Identification of fatigue and mechanical characteristics of explosively welded steel - titanium composite

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ABSTRACT. Paper presents results of fatigue tests performed on S355J2 steel - titanium Grade 1 composite produced in explosive welding technology. Specimens were subjected to cyclic tension-compression loading with zero mean value and controlled force. Also mechanical properties were investigated.

KEYWORDS. Welding; Explosive; Fatigue; Bimetal; Steel; Titanium.



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INTRODUCTION

Technology of the explosive welding is based on principles of joining dissimilar materials with the energy from explosive detonation. Phenomena of the explosive material joining was observed for the first time during the first world war, but from the commercial point of view technology became appreciated in the 1950's [7]. Explosive welding is defined as a solid state process. Bond between materials results from the impact effects during detonation. Stable joint between materials is attained if energy of the detonation cause hydrodynamic behavior of the material [7,8,16]. Characteristic feature of the interface lines is their wavy shape (Fig. 1). Bond and strength parameters are influenced by basic welding parameters: detonation velocity, standoff distance and welding angle [1,2]. Research on welding parameters and overall properties of multilayer material influenced on range of their industrial application. Especially in industry branches demanding universal properties of the construction materials for example: high strength and chemical resistance. At the present time explosively welded composites are used in industrial areas such as: chemical and nuclear engineering in example: tube sheets, heat exchangers. In the literature explosively welded multilayer materials are mainly investigated in terms of operational and design aspects like welding parameters and their impact on microstructure changes[2-4,6,9]. Influence of the heat treatment on overall properties of the material is also examined [5]. However, although the fatigue phenomenon which is very important from a design calculation and operational point of view [13, 14] is rarely investigated.

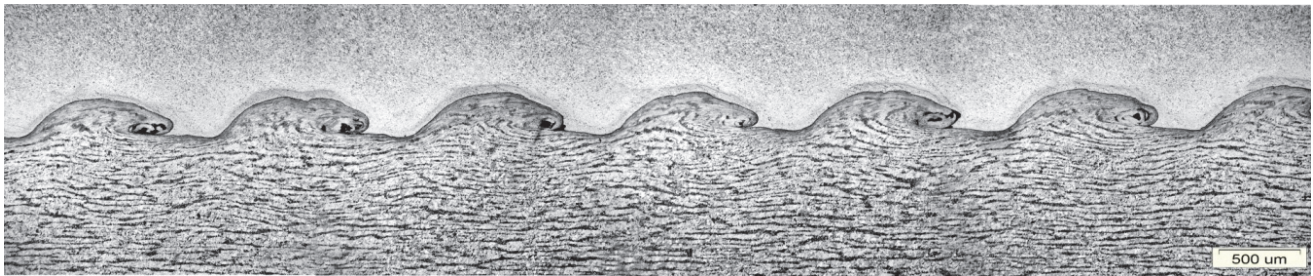


Figure 1: Wavy interface line in steel – titanium bimetal.

Fatigue properties of clad materials are subject of the lower number of studies than other topics combined with explosive technology. Some scientific and technical information concerning fatigue resistance and behavior can be found in following papers [10,11,15]. Fatigue curves for bimetallic materials are presented in [11,12]. In the case of building fatigue curves for multilayer materials difficulty can be related to stress inhomogeneity caused by different Young’s modulus of joint metals. Problem can be extended to the uniformity of mechanical properties in the particular layers of joined materials. Studies performed on steel titanium bimetallic plates exhibited inhomogeneity of basic mechanical properties [17]. Taking into account some assumption which will be described later bimetallic material can be split on following sections: sections of base and clad materials and the interface section zone characterized by substitute mechanical properties (Fig. 2).

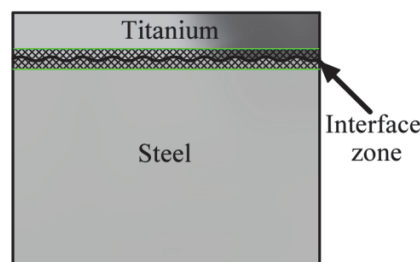


Figure 2: Interface zone location

Stresses calculated on the basis of mechanical properties of each section can be used in finite element method or in characterization of fatigue properties. The main aim of this paper is presentation of experimental fatigue test results carried out on specimens made of steel-titanium bimetal subjected to cyclic tension-compression loading. The experimental research results in presentation of mechanical properties and demonstration of strain based fatigue characteristics.

MATERIAL PROPERTIES

Specimens used in study were cut from the bimetal plate carried out in the explosive welding process of the S355J steel and the titanium Grade 1. Material was heat-treated after the welding process. Heating took place for 90 minutes at 600°C and then the material and a furnace were cooled to 300°C (at cooling velocity 100°C/h). The final cooling stage was carried out in the calm air. Mechanical properties and of joined materials are presented in Tab. 1.

| Material | Mechanical properties | | | | | |
|----------|-----------------------|-------------|--------|--------|-----------|-------|
| | R_e , MPa | R_m , MPa | E, MPa | G, MPa | ν , - | A5, % |
| S355J2 | 382-395 | 598-605 | 220000 | 84000 | 0.3 | 24-34 |
| Grade 1 | 189-215 (R02) | 308-324 | 100000 | 38000 | 0.39 | 43-56 |

Table 1: Mechanical properties of steel S355J2 and titanium Grade 1.

Example microstructure is shown on Fig. 2. Microstructure observations revealed local melting zones in the interface line. In the steel layer, decarburization occurred near interface line. On the other hand, in the titanium layer, recrystallization induced by the heat treatment appeared.

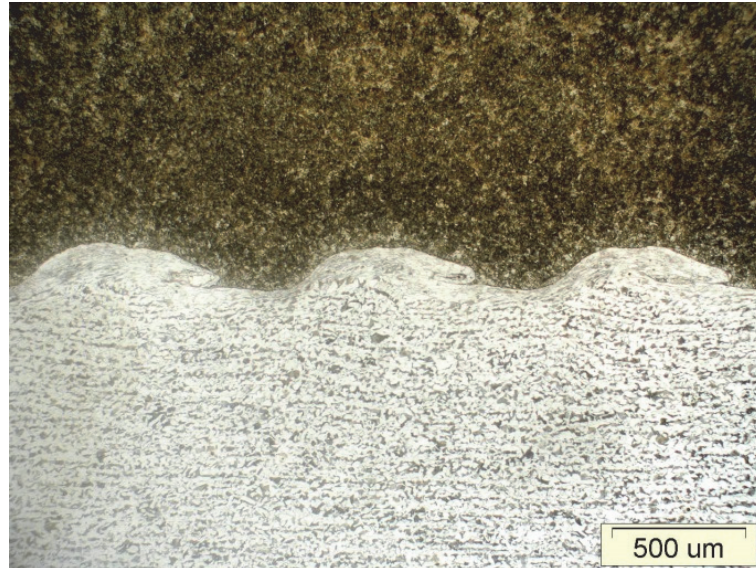


Figure 2: Interface zone location

Mechanical properties of the interface layer in steel-titanium bimetal were obtained on the basis of following assumptions: near the interface zone mechanical properties of joined materials undergo a strong change, and calculation of stress in each material layer located near interface line is impossible, properties of the interface zone can be described taking into account behavior of the thick substitute layer. For the identification of interface layer mechanical properties specimens were carry out using water jet technology. Application of water abrasive technology has prevented introduction of the residual stress and microstructure changes caused by cutting process. Shape and dimension of the specimen are presented on Fig. 3.

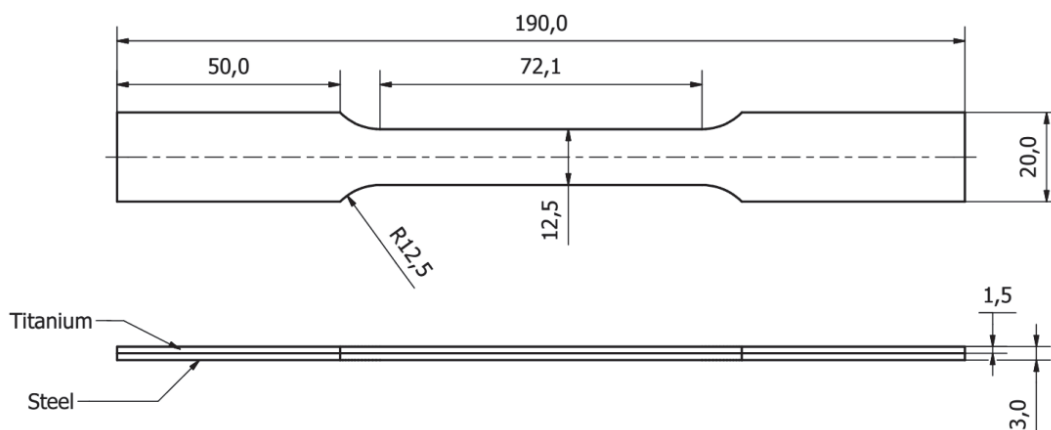


Figure 3: Shape and dimensions of the interface zone specimens

Results were presented in form of the table including test details (Tab. 2).

Interface layer was characterized by averaged properties $E_{int}=157 \text{ GPa}$, $\nu_{int}=0,27$. Stresses existing in material layers can be calculated taking into account following assumptions: homogeneous strain distribution throughout the specimen cross section (resulting from the displacement of the specimen grips), no defects, elastic deformation range, flat interface line, uniaxial stress state. Analytical expressions for stress in steel, titanium and substitute interface zones:

| Specimen | Dimensions, mm | | F _m , kN | F _u , kN | F _{p02} , kN | ν _{sub} , - | E _{sub} , GPa |
|----------|----------------|------|---------------------|---------------------|-----------------------|----------------------|------------------------|
| | w | h | | | | | |
| B1 | 12.2 | 3.3 | 20.0 | 16.2 | 12.8 | 0.27 | 151 |
| B2 | 12 | 2.95 | 17.6 | 14.5 | 15.5 | 0.27 | 158 |
| B3 | 11.98 | 2.96 | 18.0 | 14.5 | 12.2 | 0.27 | 157 |
| B4 | 12.3 | 3.0 | 18.2 | 14.7 | 13.5 | 0.27 | 161 |
| B5 | 12.5 | 2.95 | 17.7 | 15.1 | 11.1 | 0.27 | 155 |
| B6 | 12.1 | 2.85 | 18.1 | 14.9 | 14.2 | 0.28 | 160 |
| B7 | 12.1 | 2.92 | 17.7 | 14.6 | 13.0 | 0.27 | 155 |
| B8 | 11.88 | 3.05 | 18.3 | 16.0 | 14.7 | 0.28 | 156 |
| Averaged | | | | | | 0.27 | 157 |

where: w, h –specimen section dimensions , E_{sub} – substitute Young modulus, ν_{sub} – substitute Poisson ratio, F_m – maximum force, F_u –Breaking force, F_{p02} – force at 0.2% strain.

Table 2: Mechanical properties of the interface zone.

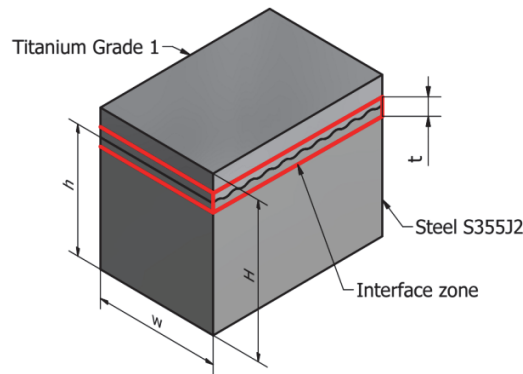


Figure 4: Dimensions of specimen cross section.

$$\sigma_{ti} = \frac{E_{ti} F}{E_{int} t w - E_{ti} w \left(b - H + \frac{t}{2} \right) + E_{st} w \left(b - \frac{t}{2} \right)} \quad (1)$$

$$\sigma_{int} = \frac{E_{int} F}{E_{int} t w - E_{ti} w \left(b - H + \frac{t}{2} \right) + E_{st} w \left(b - \frac{t}{2} \right)} \quad (2)$$

$$\sigma_{st} = \frac{E_{st} F}{E_{int} t w - E_{ti} w \left(b - H + \frac{t}{2} \right) + E_{st} w \left(b - \frac{t}{2} \right)} \quad (3)$$

Where: E_{ti} , E_{int}, E_{st} – Young Modulus of titanium, interface and steel layers respectively, F – force, w, H, b, t – characteristic dimensions of the composite.

Among the specimens not used during the study phenomenon of residual stresses relaxation in titanium layer was observed. Relaxation progressed gradually in about 2 weeks after cut (Fig. 5).

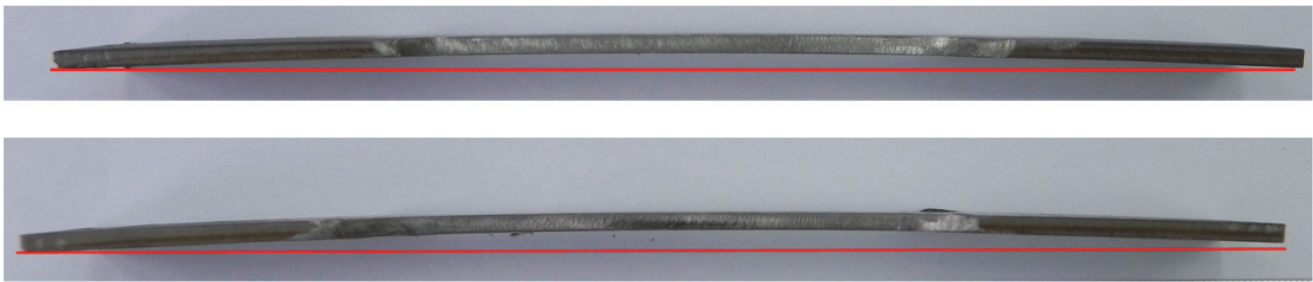


Figure 5: Deformation of samples caused by residual stress relaxation.

FATIGUE TESTS

Fatigue tests were performed using hydraulic testing machine equipped with a force and a displacement sensors. Strain was registered by extensometer mounted on the specimen (steel side). A Force control was used in all of fatigue tests. Loadings applied to specimens were generated up to the formula $F(t)=F_s \sin(2\pi ft)$. Tests were performed at various frequencies f from 2 to 12Hz. A moment of total material interruption was considered as the specimen destruction. Because of limited research range of a fatigue testing machine, each specimen were milled to 9 mm total thickness (Fig. 6).

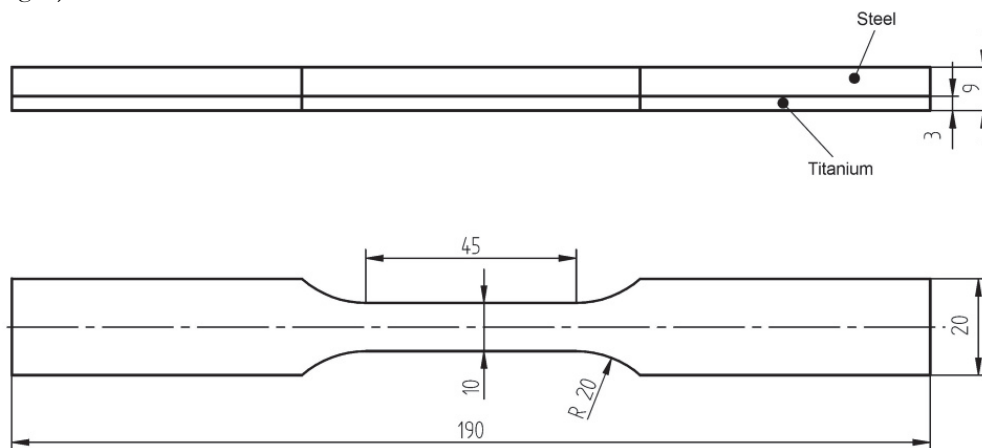


Figure 6: Shape and dimensions of the fatigue specimens.

Result and parameters of tests were presented in Tab. 3.

During the fatigue tests loading and strain were registered. The dependence between those two parameters is very important and contain an information about changes which proceed in the material. In fatigue tests with controlled force only the strain amplitude can undergo a change, an amplitude of loading force remain constant. In case of increasing strain amplitude tested material is classified as cyclic softening. Non uniform properties of welded materials cause that description of material behavior in case of bimetal is more complicated. Lack of an information about cyclic elastic-plastic properties of joined materials and in particular of the created interface zone makes determining a curve of dependence between stresses and strains difficult. It is, however, possible to obtain the dependence between the registered force F and strain ε . Strains occurring in particular layers are homogeneous because displacement generated by holder of a testing machine is forced and identical as displacement of specimen grips. In case of the elastic strain the ε - F dependence is a straight line, appearance of a hysteresis loop indicates the plastic strain. Registered ε - F loops (Fig. 7) identify stability of the bimetal (softening or hardening). Hysteresis loops were created for selected load cycles. Parameter n used in figure signify the damage amount, which is quotient of the actual number of cycles to the total number of cycles. Characteristic feature of tested bimetals is quick transition from the elastic range (no hysteresis loops) to the plastic strain range. In next cycles of the fatigue loading a ratcheting phenomenon appears (Fig. 8). Ratcheting is defined as phenomenon of accumulation of plastic strains in the direction of stretching).

| Specimen | w, mm | H, mm | F _a , kN | Stress, MPa | | | N _{exp} , cycles |
|----------|----------|----------|---------------------|---------------|----------------|---------------|------------------------------|
| | | | | σ_{ti} | σ_{int} | σ_{st} | |
| P01 | 10 | 9 | 24 | 155.3 | 233.0 | 326.2 | 6650 |
| P02 | 10 | 9 | 21.5 | 139.2 | 208.7 | 292.2 | 98310 |
| P03 | 9.7 | 9 | 19.9 | 132.8 | 199.2 | 278.9 | 895970 |
| P04 | 9.62 | 9.02 | 23 | 154.5 | 231.8 | 324.6 | 34390 |
| P05 | 9.54 | 8.74 | 24.5 | 169.1 | 253.6 | 355.0 | 26570 |
| P06 | 9.46 | 8.96 | 22 | 150.9 | 226.4 | 316.9 | 104820 |
| P07 | 9.76 | 9.02 | 23.1 | 153.0 | 229.5 | 321.3 | 22980 |
| P08 | 9.84 | 9 | 21.1 | 138.8 | 208.2 | 291.5 | 134850 |
| P09 | 9.7 | 9.08 | 23.1 | 153.3 | 230.0 | 322.0 | 28860 |
| P10 | 9.7 | 9 | 19.6 | 130.8 | 196.2 | 274.6 | 263540 |
| P11 | 9.82 | 9 | 21 | 138.4 | 207.6 | 290.7 | 117640 |
| P13 | 10.08 | 9.08 | 25 | 159.7 | 239.6 | 335.4 | 132600 |
| P14 | 9.9 | 9 | 25 | 163.4 | 245.2 | 343.2 | 195050 |
| P15 | 9.85 | 8.93 | 28 | 184.8 | 277.2 | 388.1 | 31100 |
| P16 | 9.85 | 8.93 | 30 | 198.0 | 297.0 | 415.9 | 9100 |
| P17 | 9.85 | 8.85 | 33 | 219.0 | 328.5 | 459.8 | 2710 |

where: w, h –specimen section dimensions , σ_{ti} – stress in titanium layer, σ_{int} – stress in interface zone, σ_{st} – stress in steel layer F_a – force amplitude.

Table 3: Results of the fatigue tests.

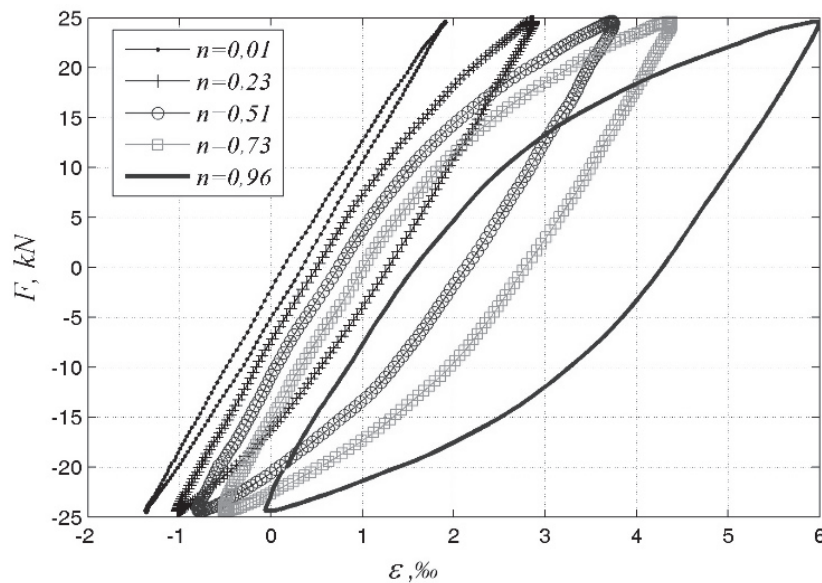


Figure 7: Hysteresis loops recorded during fatigue tests.

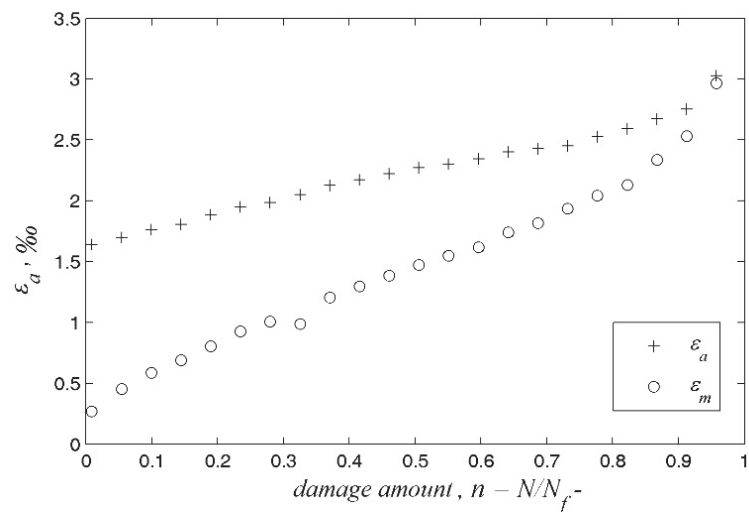


Figure 8: Amplitude and mean value of strain during fatigue test, where: ϵ_z – strain amplitude.

Results of performed experiments are presented as experimental points on the background of S355J2 steel fatigue characteristic (Fig. 9). According to the ASTM Standard E2207-08 [18] recommends to build fatigue characteristics for strain amplitudes registered in the middle of the fatigue test, i.e. for $n=0.5$.

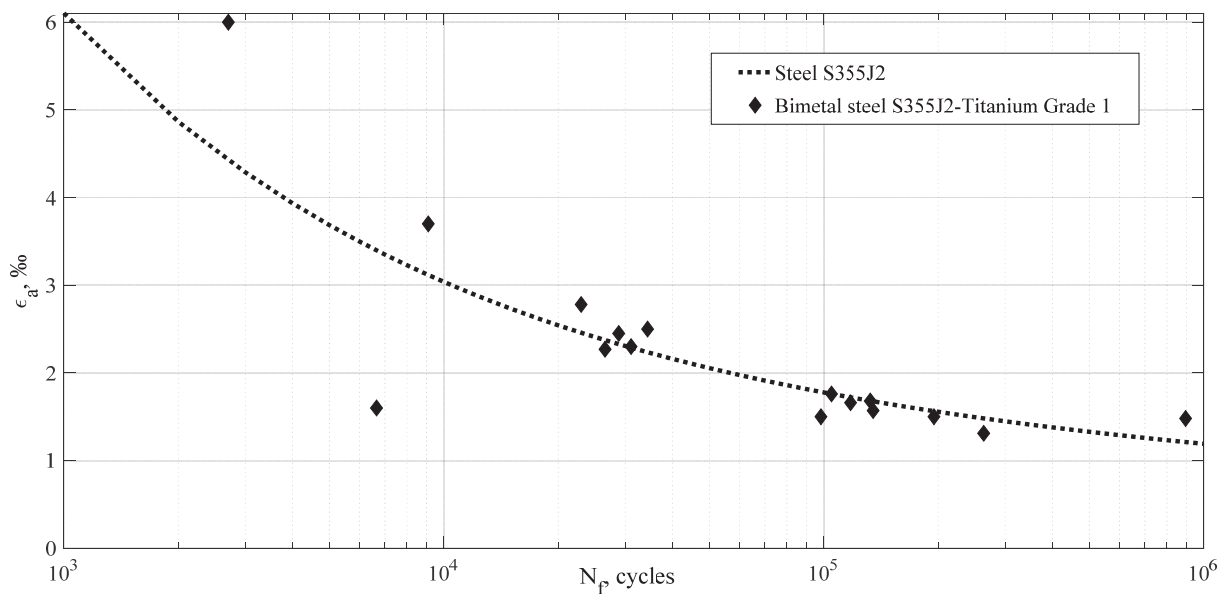


Figure 9: Experimental points (steel – titanium specimens) and fatigue characteristic of S355J2 steel.

CONCLUSIONS

As a result of the performed fatigue tests, the following conclusions were drawn. Substitute mechanical properties obtained during identification of mechanical properties are close to the average of the elasticity coefficients for materials before welding (approximately 157GPa). In the case of the Poisson ratio, substitute value (0.27) is close to the value of factor for the steel before welding process. Obtained substitute mechanical properties of the interface zone can be supplement to material data for numerical analysis. Fatigue tests have shown the cyclic instability of steel-titanium composite. In case of bimetal, cyclical instability (softening) combined with cyclical flow of material has been observed (for some specimens from the first load cycles). These phenomena were characterized by increasing amplitude values of deformation ϵ_a and mean values of deformation ϵ_m . Residual stress relaxation phenomena was also observed.



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