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Electrical double layer and adhesive force in fatigue strength of metals coated with plastics

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ABSTRACT

Purpose: Literature consists a lot of information concerning the issues of the fatigue endurance of metals coated with plastics. However few studies explicitly explain, what mechanisms decide on the increased fatigue endurance of metals coated with plastics. Therefore an expression is a purpose of the work on what a way increasing this fatigue endurance permanence is taking a place.

Design/methodology/approach: In hereby article they discussed issues concerning the fatigue endurance of metals coated with plastic. Authors are putting the thesis on the basis of an analysis of literature and own examinations, that metals coated with material are characterized by an increased fatigue endurance.

Findings: On the basis of results conclusions concerning raising the fatigue endurance permanence of some coated metals were deduced from an experiment with material.

Research limitations/implications: Examinations were concentrated only on determining the influence of the electrode potential and power of adhesion on metal samples (steel 20 and 45) covered with different coatings. To the purpose of demonstrating the increased fatigue endurance permanence of analyzed samples they limited themselves to experiments taking into consideration the strength to turning and bending.

Practical implications: Get results of research are broadening their knowledge of the scope of changes of the fatigue strength of metals coated with plastic.

Originality/value: Authors are making a demand that the considerable increase of the fatigue endurance permanence of tested samples is caused with influence of electric double layer by adhesive force of the coating to metal.

Keywords: Electrical properties; Durability of fatigue; Adhesion; Double electric layer

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PROPERTIES

1. Introduction

Plastic layers coated on metals increase their fatigue strength regardless of the type of metal, plastic or applied load. A partially crystalline structure characterizes the plastics. Moreover, they are able to create the natural Electric Double Layer (EDL) on the metal-plastic boundary, which mirrors a charged electrical condenser [1, 2, 3]. Some experimental studies proved the existence of two types of EDL, which have dissimilar electric charges deployment. As an example, in a polyvinyl chloride (PVC) layer there is an excess of electrons (negative charge), whereas in a layer of Epidian 5 more positive charges were found comparing to the quantity of positive charges in the proximity of the metal base. Considering the fatigue strength of the combined materials it must be noticed that the increased fatigue strength is caused by the EDL phenomenon, yet not by the polarization of the Electric Double Layer electric charges.

On the basis of some literature survey and hitherto research [4, 5, 6], which focus on metals coated with plastics, it can be observed that the increased metal fatigue strength is conditional upon many factors. Although a key factor is the thickness of a plastic layer the authors of this paper suggest that the thickness influences the fatigue strength mainly in its initial increment phase. Further, the increase of the fatigue strength depends on a range of factors, which must be considered by a comprehensive approach and treated as a system rather than individuality. Basing on the authors' long-term experience, research and a survey of literature the observations regarding the subject were put forward [4, 7, 8, 9, 10].

Finally, the authors investigated how great the influence of undergoing process is on the fatigue strength of the metals coated with plastics.

2. Fatigue strength of plastic-coated metals

The influence of the plastic layers on the metals fatigue strength was limited only to the plastics which have a direct effect on the fatigue strength rise, i.e.: synthetic rubber, epoxy resins, PVC and polyamide. A comprehensive review of the subject [11, 12, 13, 14] as well as the authors' personal work [2, 4, 15] enabled them to form a list (Table 1) containing the materials which explicitly increase the fatigue strength of the coated metals.

The percentage increase of the fatigue strength was calculated using the following formula:

a) for the unlimited fatigue strength range, where the Wöhler curve has a partially horizontal run:

Torsion:

$$W_{\sigma_s} - \frac{Z_{sop} - Z_{so}}{Z_{so}} \cdot 100\% \quad (1)$$

Bending:

$$W_{\sigma_g} - \frac{Z_{gop} - Z_{go}}{Z_{go}} \cdot 100\% \quad (2)$$

where:

Z_{so} – fatigue strength for uncoated samples, *bending*;

Z_{sop} – fatigue strength for coated samples, *torsion*;
Z_{gop} – fatigue strength for coated samples, *bending*;
Z_{go} – fatigue strength for uncoated samples, torsion.

b) for the limited fatigue strength range, where the Wöhler curve is a straight line without a horizontal run:

Torsion:

$$W_{p_s} - \frac{\overline{N}_{ps} - \overline{N}_{ns}}{\overline{N}_{ns}} \cdot 100\% \quad (3)$$

Bending:

$$W_{p_g} - \frac{\overline{N}_{pg} - \overline{N}_{ng}}{\overline{N}_{ng}} \cdot 100\% \quad (4)$$

where:

$\overline{N}_{ps}$ – average number of cycles for coated samples leading to scrap on adequate stress level, *torsion*;

$\overline{N}_{pg}$ – average number of cycles for coated samples leading to scrap on adequate stress level, *bending*;

$\overline{N}_{ns}$ – average number of cycles for uncoated samples leading to scrap on adequate stress level, *torsion*;

$\overline{N}_{ng}$ – average number of cycles for uncoated samples leading to scrap on adequate stress level, *bending*.

As it was mentioned before, the layer thickness is crucial for the fatigue strength of the analyzed samples. Basing on the experiments, the authors concluded that the samples fatigue life in function of the layer thickness (Fig. 1) is characterized as a nonlinear run [4]. Some examples of the research are depicted in Figure 1-2.

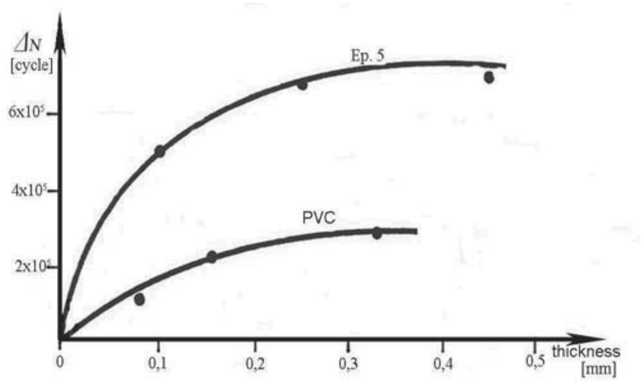

Fig. 1. Influence of the layer thickness on samples life for steel 20; bilateral torsion σ = 186.3 MPa

Table 1.
Value of fatigue strength increase [%] for coated samples [2]

Set number	Sample material	Layer material	Load type	Fatigue strength range	Fatigue strength increase [%]
1.	Steel 14.05	Epoxy resins	oscillatory bending	unlimited	20.0
2.	Aluminum ABT-1	Synthetic rubber	in-plane bending	limited	300-500
3.	Aluminum ABT-1	Synthetic rubber	oscillatory bending	unlimited	35.8
4.	Steel 45A	Epidian 5	rotary bending	limited	114-558
5.	Brass M63	Polyamide M	rotary bending	limited	433-1680
6.	Steel 20	Epidian 5	bilateral torsion	unlimited	16.2
7.	Steel 20	Epidian 5	bilateral torsion	limited	182-351
8.	Steel 20	PVC	bilateral torsion	unlimited	9.6
9.	Steel 20	PVC	bilateral torsion	limited	116.8-136.5
10.	Steel 45	Epidian 5	in-plane bending	unlimited	7.0
11.	Steel 45	Epidian 5	in-plane bending	limited	300-666.6
12.	Steel 45	PVC	in-plane bending	unlimited	5.5
13.	Steel 45	PVC	in-plane bending	limited	171.4-369.5
14.	Steel E235A	Epoxy-phenol lacquer	rotary bending	limited	20-70
15.	Steel E235A	Epoxy-phenol lacquer	rotary bending	unlimited	4.3
16.	Steel 45	Capron (polyamide)	rotary bending	unlimited	4.3

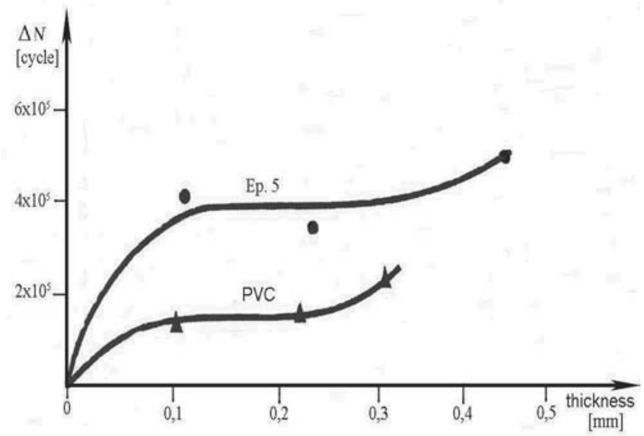

Fig. 2. Influence of the layer thickness on samples life for steel 45; bilateral in-plane bending σ = 353.2 MPa

It can be noticed that the greatest increase of the fatigue strength have been obtained for the minimal thickness of the plastic layers (Epidian 5 and PVC) used for the coating. The graphs of the fatigue strength in the function of thickness (Fig. 1-2) become horizontal or almost horizontal and further they tend to rise. Initially, the curves representing the variation of the fatigue strength appear to be steep, thus the maximum increment of the fatigue strength is for the 0.1 mm thick layer.

Furthermore, to demonstrate the above analysis, Figure 3 depicts the experimental values in contrast to the value obtained from the theoretical calculations- basing on the fatigue strength increments ΔN for each layer which thickness increases gradually by 0.01 mm. It was assumed that the value of the moment (bending or torsional), loading the both coated and uncoated samples, is constant. Additionally, the mechanical properties of the layers were also taken into consideration except from their adhesion.

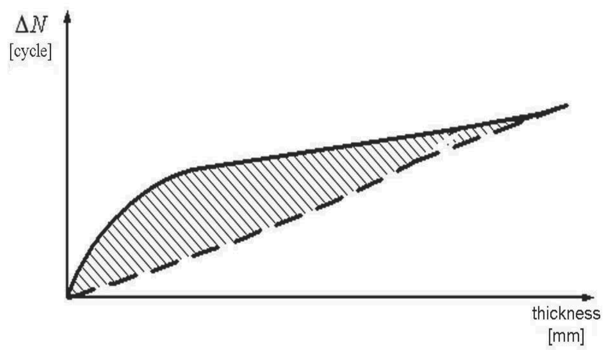

Fig. 3. Changes in the fatigue life vs. thickness of the layers

The authors' main task was to compare the curves plotted in Figure 3 hence the values are not listed. Clearly, the curves do not overlap each over, which proves that some other factors, beside the mechanical properties, have an influence on the fatigue strength of the samples. Therefore, to find which factors have an influence on the run of the curves (Fig. 3.), the authors focused on the following phenomenon: the electrode potential, layer to metal adhesion and Electric Double Layer.

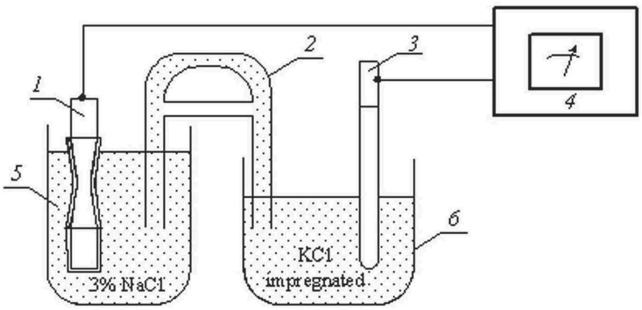

Fig. 4. Schematic diagram of the meter circuit for the electrode potential measurements: 1 – investigated sample, 2 – electrolytic bridge, 3 – calomel electrode, 4 – measuring bridge, 5 – electrolytic cell with 3% NaCl solution, 6 – electrolytic cell with KCl saturated solution

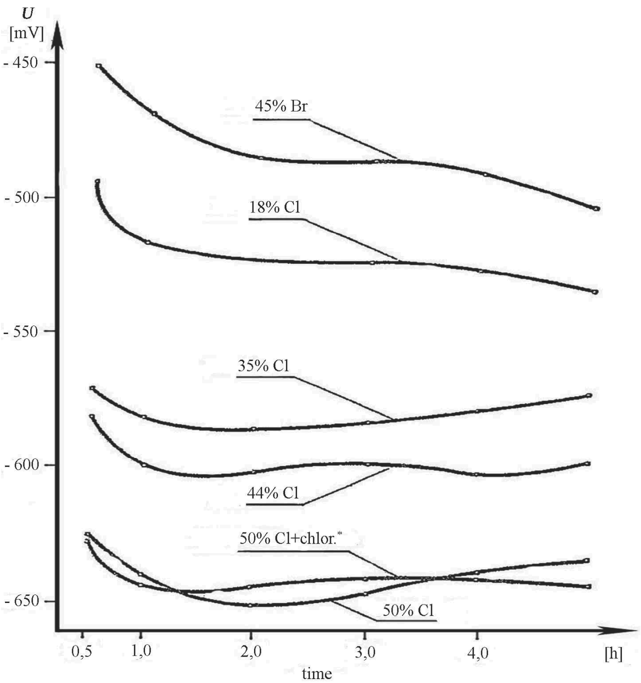

Fig. 5. Electric potential graphs for the chlorite and boron polyethylene electrode made of E235A steel [2]

2.1. Electrode potential of plastic-coated metals

In order to verify the issues regarding to the position of the electrode potential some experiments were carried out. The potential of a metal electrode coated with a suitable plastic was measured. Subsequently, the obtained results were compared with a standard calomel electrode during the assumed 5-hour time. The meter circuit depicted in Figure 4 was assembled by the use of relatively uncomplicated elements. The tested samples were electrolyzed and their potential was measured systematically. Obtained results from the experiment are shown in Figure 5 as the potential value in time function. In the described experiment two grades of steel in a defined coating combination were investigated.

Figure 5 illustrates the potential curves for E235A steel samples coated with chlorite and boron polyethylene, whereas Figure 6 demonstrates the electrolytes potential made of steel 20 coated with Epidian 5 and PVC [4, 9]/

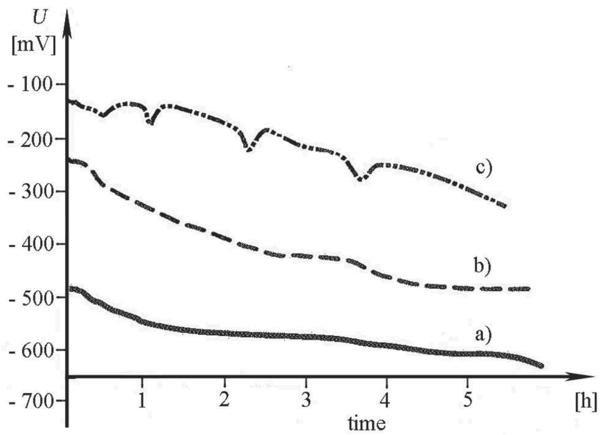

Fig. 6. Electric potential graphs for the electrode made of steel 20: a) no plastic-coated, b) PVC coated, c) Epidian 5 coated

2.2. Layer to metal adhesion

Adhesion, as a physical or chemical superficial interaction, occurs between condensed phases while being in molecular contact. Adhesive connections are formed due to attractive forces linking two in-contact mediums. The nature of the forces is various e.g.: van der Waals, dipolar, ion, metallic forces. Moreover, some chemical bonds in the adhesive layer are possible. Some of the adhesions forces are caused by the existence of EDL on the metal-plastic boundary since the attraction of surface opposite charges strengthen the adhesive connection because of intermolecular forces [6].

The adhesion measure is the force or work required to separate adherent solid bodies and it is measured experimentally. Table 2 presents average values obtained by the authors, in order to specify the influence of adhesion in the analyzed samples.

On the basis of average adhesion ratio of the PVC and Epidian 5 coated on steel 20 and steel 45 samples, the influence of the layer can be easily noticed. Evidently, the Epidian 5 layers have greater positive electric potential shift, which is depicted in Figure 4. The results from the experiment included in Table 2 also prove the layer influence on the samples subjected to a shearing (R_t) and tearing test (R_m) [4].

Additionally, some experiments regarding the adhesion force for a chlorite and boron polyethylene layer were conducted. The experiments followed the Worjucki and Szapaołow method, where the separation velocity was 6 cm/min. In the test 10 mm wide copper samples (strips of copper foil [13]) coated with a 100-120 µm thick plastic. The obtained data were correlated in Table 3.

Table 2.
Average values of the layer adhesion ratio

Type of plastic	Steel 20		Steel 45	
	R_t [MN/m^2]	R_m [MN/m^2]	R_t [MN/m^2]	R_m [MN/m^2]
PVC	0.139	0,021	0.107	0.033
Epidian 5	12.662	0,204	16.078	0.259

Table 3.
Adhesion force values of the copper layers

Shear force	Percentage of chlorine or boron					
	45% Br	18% Cl	35% Cl	44% Cl	50% Cl	*50% Cl +chlor.
[N/m]	18.835	18.413	3.561	0.412	3.384	2.893

* chlorination with a softening agent

Table 4.
The results of measurements of mechanical properties and chemical constitution of the samples

Material	Mechanical properties				Chemical constitution				
	R_m	R_e	A_{10}	Z	C	Mn	Si	P	S
	MPa	MPa	%	%	%				
Steel 20	493.0	309.1	27.2	65.6	0.19	0.54	0.26	0.02	0.02
Steel 45	640.8	386.6	20.5	25.5	0.43	0.65	0.32	0.034	0.029

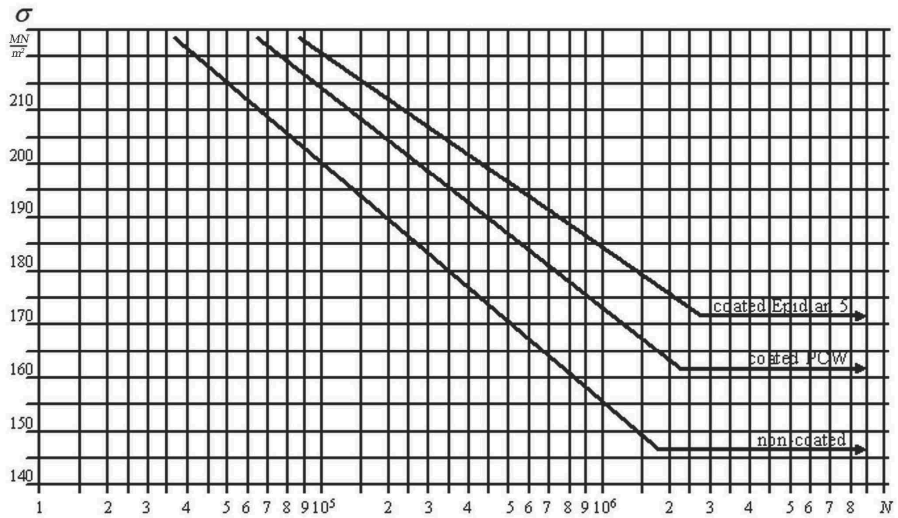

Fig. 7. The graphical interpretation of the fatigue strength for bended samples made of steel 20

Consequently, polyethylene consisting of 45% Br and 18% Cl, while having the greatest positive electric potential shift (Fig. 5), appears to have the finest adhesive force value.

In summary, the layer-metal adhesion force value is characterized by various forces such as dipolar, ionic and EDL. Once the research has been completed it may be assumed that EDL, which is a part of the adhesive force, positively effects on the fatigue strength of the plastic-coated metals.

2.3. Fatigue strength of metals

The scope of the current step is to analyze the samples in a fatigue test. In order to verify the influence of the plastic-coated metals on their fatigue strength more experiments were conducted. Previous research (see p. 2.2.) proved the theoretical assumption about the positive effect of the plastic coatings on the adhesive force.

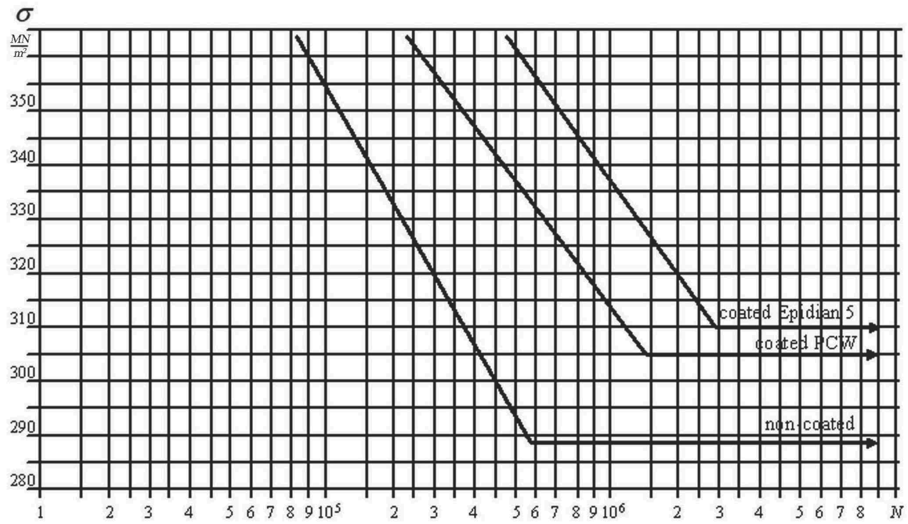

Fig. 8. The graphical interpretation of the fatigue strength for bended samples made of steel 45

The samples preparation, before they were coated, required some additional operations. The initial material i.e. steel 20 and steel 45 were annealed in a steel mill following the specified norms (Table 4). Afterwards the heat treatment the samples were coated with Epidian 5 and PVC. The coating was held in the laboratory conditions where the cold fluid coating was applied onto the samples and then hardened at room temperature. A 0.1 mm thick layer was obtained. The coated samples underwent both torsional and bending fatigue tests. In Figure 7-8 the results from this test are depicted.

As it can be noticed, in the whole fatigue range, greater fatigue strength increments are observed in the samples coated with Epidian 5 comparing to the PVC-coated samples.

The Epidian 5 layers have also a greater positive electrode potential shift and show greater adhesive force to the metal then the PVC coating.

The electrode potential shift is the measure of layer porosity. Hence, the differences in the results are caused by the Epidian 5 and PVC porosity (as the PVC layer is more porous).

3. Conclusions

The plastic layers coated on the metal samples create the Electric Double Layer (EDL) on the metal-plastic boundary. The layers increase the fatigue strength of the samples regardless of the polarization the layer.

The fatigue strength tends to increase when:

- the porosity of a sample is minimal;
- the electrode potential is shifted towards positive;
- the value of the adhesion force between a layer and metal is relatively high.

Furthermore, on the metal-plastic boundary a thin layer is created- its properties are unlike metal or plastic. The layer consists of metal, plastic and air atoms. The atoms from a plastic penetrate surface flaws and diffuse into an oxide layer on the metallic surface [4]. Between the atoms of the intermediate layer some various bonds and interactions can be noticed. In addition, in the intermediate layer there is the EDL, which contributes to the total value of the adhesion force between the layer and metal.

In summary, basing on the results put forward in this paper, the conclusions are as following:

- for the plastic-coated metals there is a correlation between: the adhesion force of the plastic layer and metal surface, the electrode potential shift and finally the fatigue strength increase;
- the electrode potential shift is a result of plastic layer porosity;
- the changes in the plastic-coated metals fatigue strength is caused by the ultra thin intermediate layer on the plastic-metal boundary; the layer consists of metal, plastic and air atoms which are mutually contacted by various forces- its properties are different from metal and plastic properties;
- the opposite charges attraction in the Electric Double Layer contributes to the total value of the adhesion force between the layer and metal.

In the further studies the authors will make an effort to find a solution regarding the correlation between the EDL and the adhesion force increase. The results will be presented in forthcoming papers.

References

[1] W. Jargulinski, J. Szelka, Formation of a double electric layer on the metal-plastic boundary, Journal of Materials Science 40/5 (2004) 702-705.

[2] W. Jargulinski, The electrostatic field and metals’ durability, Monograph, The General Tadeusz Kosciuszko Land Forces Military Academy, Wroclaw 2006 (in Polish).

[3] A. Waynman, Moder state of the problem of hydrogen embrittlement of metal of TPP thermo-mechanical equipment of pre-and overcritical parameters, Proceedings of the 3rd International Conference, Fracture Mechanics of Materials and Structural Integrity, Lviv, 2000.

[4] W. Jargulinski and others, The electric field influence on metals fatigue durability, Unpublished Science Reports of The General Tadeusz Kosciuszko Land Forces Military Academy, Wroclaw 2000 (in Polish).

[5] W. Jargulinski, J. Szelka, The electric double layer and metals fatigue durability, Proceedings of the 20th Mechanical Symposium, Fatigue and The Mechanics of Fracture, Bydgoszcz-Pieczyska, Special Journal, 2002, 121-127 (in Polish).

[6] H.R. Kemp, L.H. Keys, Characteristics of stress corrosion cracking in austenitic stainless steels, Metallurgy and Metal Forming 7 (1977) 259-300.

[7] P. Praveen, K. P. Yarlagadda, A. Turong, Study of droplet behavior in active control of metal transfer, In Brito, Caludio D. and Ciampi, Melany, Eds. Proceedings of the Global Congress on Manufacturing and Management, Santos, Brazil, 2006, 12-16.

[8] L.A. Dobrzanski, R. Honysz, S.D. Fassois, On the identification of composite beam dynamics based upon experimental data, Journal of Achievements in Materials and Manufacturing Engineering 16 (2006) 114-123.

[9] K. Jamroziak, W. Jargulinski, Fatigue life forecasting of modern constructional materials with the use of electric double layer, Proceedings of the 9th International Conference Computer Aided Engineering, 2008, Opencast Mining, Issue 4-5 (2008) 148-151 (in Polish).

[10] K. Jamroziak, W. Jargulinski, J Szelka, The electric double layer in hydriding metals, GCMM Publication Synopsis, Queensland University of Technology, 2008, 133-138.

[11] M. Szata, Description of development of fatigue cracking in energetic approach, Monograph, University of Technology, Wroclaw 2000 (in Polish).

[12] L.A. Dobrzański, A. Grajcar W. Borek, Hot-working behaviour of high-manganese austenitic steels, Journal of Achievements in Materials and Manufacturing Engineering, 31/1 (2008) 7-14.

[13] M. Staszewski, Z.M. Rdzawski, A. Wrona, Residual stresses in the strips from copper-based alloys, Journal of Achievements in Materials and Manufacturing Engineering 25/2 (2007) 35-38.

[14] J. Mikula, L.A. Dobrzański, PVD and CND coating systems on oxide tool ceramics, Journal of Achievements in Materials and Manufacturing Engineering 24/2 (2007) 75-78.

[15] W. Jarguliński, J. Szelka, Athesion force in durability of fatigue coated plastic materials, Journal of Science, The General Tadeusz Kosciuszko Land Forces Military Academy, Wroclaw, 4 (2005) 5-11 (in Polish).