Crack growth study of dissimilar steels (Stainless - Structural) butt-welded unions under cyclic loads

Andrés L García Fuentes a*, Rafael Salas a, Leiry Centeno b and Alberto Velásquez del Rosario c

a Department of Mechanical Engineering, IUT RC “Dr. Federico Rivero Palacio”, Caracas, 1090, Venezuela
b Department of Materials Technology Engineering, IUT RC “Dr. Federico Rivero Palacio”, Caracas, 1090, Venezuela
c School of Metallurgy and Electromechanical Engineering, ISMM “Dr. Antonio Núñez Jiménez”, Moa, Holguín, Cuba

Abstract

The research shows the study of the mechanisms of emergence and propagation of fatigue cracks caused by mechanical tension stress fluctuations in dissimilar steels butt-welded joints; structural steel ASTM A537 (I), austenitic stainless steel ASTM A240 (304L), through GMAW with argon as protecting gas and ASTM A240 (E308L) as supplier material, without pre and post welding thermal treatment. Samples were evaluated through optical and scanning electron microscopy and inspected by not destructive test with penetrating liquids and ultrasound, to discard surface and internal defects. The following mechanical tests were completed; Vickers microhardness profile, tension, impact Charpy, bending guided, axial fatigue, and speed of propagation of fatigue cracks. The phenomenon of initiation and crack growth was characterized from pre-cracked specimens, using the curve of the crack size vs. the number of fatigue cycles, and the curve of crack growth rate, vs. the variation of stress intensity factor. Results showed a proper mechanical steel behavior under cyclic loads, in spite of showed high values of microhardness, mainly in the fusion line between the welding and 304L stainless steel, as well inclusions between the structural and the stainless one. Pre-cracked test evidence a faster growth of crack in the fusion line between structural steel and stainless steel.

Keywords: Axial fatigue; Crack growth; Dissimilar welding; Stainless Steel.

1. Introduction

In the industrial sector of production, refining and transportation of petroleum and derivatives, it is usual to weld on site; new installations, repairs, annex and structural connections are developed with the use of welding. Techniques are often used for Shield Metal Arc Welding (SMAW) [1] using a similar composition between the base metal (BM) and the filler metal (FM). In the present research, Gas Metal Arc Welding (GMAW) technique [1] was used, a semi-automatic process with inert gas protection, with argon as a shielding, so special attention was given to the melt, where the parties to unite fuse together with heat application, using FM. In the welding of austenitic stainless steels (ASS) is common to keep the temperature as low as possible, this is achieved using low currents, adequate penetration and fusion, slow arc sequence, short cords, or simply waiting for the piece cool each passes [1].
To weld ASS with structural steel (SS) [2], known as a dissimilar welding, both in the weld and in the Heat Affected Zone (HAZ), depending on the chemical composition of the union, property develops brittle martensitic structure and cracking possibility, conditions that affect the mechanical properties of the union and in particular, significantly involved in the initiation of the crack to cyclic loading. Consequently, the fatigue strength of the weld metal (WM) is affected. In this way, and to avoid premature failure, it is usual to refer the WM to a thermal treatment (TT) before and after welding, to dissolve the martensitic structure. To perform these repair processes, requires plant stoppages, wishing that times are kept to a minimum possible because they generate significant economic impact, causes production losses and affect the performance of workers. In other way, some vessels, exchangers and piping sections are difficult to access, which is complicated by the TT [3, 4]. On track to avoid the TT, reduce plant downtime, contributing to the economic sustainability of the process and increase the life of the materials involved, and thus to promote environmental sustainability, this research focused its efforts on studying the mechanical behavior of dissimilar welded joints without pre and post TT, which represents an important contribution to the field of scientific knowledge, as it contributes to the establishment of mechanisms of emergence and propagation of fatigue cracks caused by fluctuations of thermal and mechanical loads, occurring during operations filling and emptying, or through natural expansion or contraction of the container due to significant changes in the temperature of the content [5]. The concept of dissimilar welding between BM & FM was employed, using an ASS (308L) as FM [2, 6], which chemical composition differs from the BM1 and BM2, also different from each other, using an ASS (304L) [2, 6] and an SS (A537) [2, 7] It aims to reduce the formation of martensite during solidification structure of WM and with this to avoid any possibility of cracking in the cord, its fusion lines and the HAZ. In this sense, the main objective of this research was: Obtain a theoretical – experimental model, based on values of mechanical strength that allows it to predict the durability of pressure vessels and pipes welded between the materials listed above. Specifically, the research focused on: to characterize mechanical properties of weld; to analyze influence of the factors that affect the quality of welding on mechanical behavior of the joint under alternative loads; and develop a model to determine the location of crack initiation and growth, and life cycles for welded joint. To achieve those objectives, the work focused on the factors that affect quality of welding, such as, surface and internal defects (cracks, slags and fouling undercuts), microstructure, extent of the HAZ and mechanical properties (microhardness profile, tension, impact, face and root bending guided, fracture toughness, axial fatigue, and speed of propagation of fatigue) [8].

2. Experimental procedure

Materials used for this study consisted of an ASS plate ASTM A240 (304L, BM1) and a SS plate ASTM A537 (BM2), both dimensions (1200x2400x4.76) mm. The weld was made at top, in pieces of 280 mm in length, with bevels of 60 degrees, flat according to ASME Section IX QW-463.1 [8], using GMAW with argon and a FM consumption of SS ASTM A240 (308L) of 1.6 mm, on a single pass, following the scheme illustrated in Fig. 1.

![Fig. 1. Setting the weld, bevel and location of the materials involved.](image1)

Welding parameters were: current, I = 250 A; voltage, E = 27 V; energy, Q0 = E.I = 6.75 kW; Heat Input, HI = 0.80 KJ/mm; wire speed = 4 m/min; and arc speed = 0.508 m/min; AWS specifications [1]. After welding, each sample was subjected to Not Destructive Test (NDT) [5], by penetrating liquids and ultrasound techniques, to rule out the presence of cracks or other defects and inner surface which could alter the results of mechanical tests. The chemical composition of BM was checked, using Atomic Absorption Spectrophotometry method (AAS) and Energy Dispersive X-ray Analysis (EDX). In view of difference between the code reference and laboratory composition, Chromium and Nickel equivalent were recalculated to characterize the weld with the data obtained. Samples were cut in axial and transverse directions of the plates of BM1 & BM2, in order to rule out microstructure differences in relation to the direction of forming the sheet. From each sample welded, cut WM representative samples containing the BM1, BM2 and the HAZ. Samples were metallographically prepared using conventional mechanical polishing.
method, according to ASTM standard E3 [9]. Final polishing was done with diamond paste of 1 μm. Samples were attacked with Vilella reagent (45 ml glycerol, 15 ml nitric acid, hydrochloric acid 30 ml) for BM1 and Nital 3% (100 ml Ethyl Alcohol 96% nitric acid +10 ml) for BM2, while the weld was attacked with 3% Nital to reveal the interface between the SS and ASS, and then with Vilella to form the profile of the weld microstructure. All samples were analyzed by using an Optical Microscope (OM), with inverted plate with attached image digitizer system; NIKON, and EPIPHOT 200 model; and a Scanning Electron Microscopy (SEM) PHILIPS, model XL 30 with EDX.

Microhardness tests, tensile, Charpy, guided bending, axial fatigue, and speed of propagation of fatigue cracks, were performed. Profiles Vickers hardness (HV) was measured, covering BM1 & BM2, HAZ and WM. A MITUTOYO microhardness was used, MVK-H1 model, calibrated applying a load of 100 g for 15 s correspondence to ASTM E-92 [10]. Samples were selected for tensile and bending as shown and detailed in Fig. 2. The excessive FM was eliminated to ensure a uniform thickness on the plate of 4.8 mm (3/16”). The ends of the welded plate were discarded (01 & 08), two specimens were tested for each BM and two more of WM, accordance to ASME Section IX [2, 8]. Specimens were machined in a conventional manner with the use of a universal milling machine ELGOBIAR, model F2UE, using coolant to prevent the heat generated during machining operations affect samples microstructure. Tensile tests were performed on a SERVOSIS Universal Tensile Machine; PBI-20 Model, 20 ton. For guided bend tests, four specimens were prepared for each section welded, two faces and two roots; according to ASME Section IX [4, 8]. To observe ductile material behavior without actually generate in the area of greatest distortion of the specimen failure greater than 3.2 mm (1/8”), the specimens were bent up to 180° until “U” form, placing welding in the area under greater strain. To do this, a 40 Ton hydraulic press was used, dimensions accordance to AWS [1] in terms of yield strength of the WM so previously the tensile tests at the joints were performed. For Charpy impact tests, five specimens were prepared for each BM and five for the WM, according to ASTM E-23 [12]. Tests were performed with a CHARPY/IZOD pendulum; HOYTOM, J300 model, at room temperature (23°C). For axial fatigue test, ten specimens were prepared for each BM, and ten for WM, corresponding to ASTM E-606 [13]. It was performed using the same universal tension machine, generating an implementation a cycle axial load frequency of one pulse per second (1 Hz), R=0, and twenty different loads, taking as initial value as calculated using the fatigue factor of 0.4 [5, 14] and the maximum stress to the tension (0.4 \( \sigma_{UTS} \)) determined by testing traction. For speed propagation fatigue cracks test, three specimens were prepared for each BM, and nine for WM, cracked by wire Electrical Discharge Machining (EDM); ONA PRIMA, E250 model, wire diameter 0,25 mm, according to ASTM E- E466 [15]. It was performed with the same axial fatigue conditions, on the stress value estimated in the models obtained for one million cycles. Referencing the yield strength of the WM and ASME specifications [8] a base type A (up to 360 MPa; 55,0 psi) was used.

3. Results and Discussion

Results of chemical analysis are shown in Table 1. Average difference was observed between the composition 16% referenced in ASME and that obtained in laboratory. The biggest difference was made in BM2, specifically Chromium (Cr), Nickel (Ni) and Molybdenum (Mo). In view of difference between the referenced in ASME composition and laboratory, the Cr and Ni equivalent were recalculated, depending on Schaeffler, Delong, WRC and Creq/Nieq [2, 16] to characterize the weld obtained with laboratory composition.

Table 1. Base materials composition (% mass), and difference between laboratory results.

<table>
<thead>
<tr>
<th>Element</th>
<th>ASME (AA)</th>
<th>EDX</th>
<th>Diff</th>
<th>ASME (AA)</th>
<th>EDX</th>
<th>Diff</th>
<th>ASME (AA)</th>
<th>EDX</th>
<th>Diff</th>
<th>304L – 308L</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>0.030</td>
<td>0.028</td>
<td>7%</td>
<td>0.240</td>
<td>0.230</td>
<td>4%</td>
<td>0.033</td>
<td>0.154</td>
<td>0.093</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cr</td>
<td>19.00</td>
<td>18.24</td>
<td>4%</td>
<td>17.74</td>
<td>7%</td>
<td>0.250</td>
<td>0.180</td>
<td>0.28%</td>
<td>18.731</td>
<td>7.943</td>
<td>13.337</td>
</tr>
<tr>
<td>Ni</td>
<td>10.00</td>
<td>8.880</td>
<td>11%</td>
<td>9.465</td>
<td>5%</td>
<td>0.250</td>
<td>0.200</td>
<td>0.20%</td>
<td>9.316</td>
<td>4.138</td>
<td>6.727</td>
</tr>
<tr>
<td>Mo</td>
<td>0.000</td>
<td>0.000</td>
<td>0%</td>
<td>0.080</td>
<td>25%</td>
<td>0.100</td>
<td>0.000</td>
<td>0.060</td>
<td>0.030</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mn</td>
<td>2.000</td>
<td>1.890</td>
<td>6%</td>
<td>1.735</td>
<td>13%</td>
<td>0.102</td>
<td>0.090</td>
<td>13%</td>
<td>1.145</td>
<td>2.128</td>
<td>1.537</td>
</tr>
<tr>
<td>Si</td>
<td>0.750</td>
<td>0.660</td>
<td>12%</td>
<td>0.425</td>
<td>43%</td>
<td>0.325</td>
<td>0.280</td>
<td>14%</td>
<td>0.435</td>
<td>0.753</td>
<td>0.529</td>
</tr>
<tr>
<td>N</td>
<td>0.100</td>
<td>0.100</td>
<td>0%</td>
<td>0.140</td>
<td>12%</td>
<td>0.100</td>
<td>0.116</td>
<td>0.128</td>
<td>0.122</td>
<td></td>
<td></td>
</tr>
<tr>
<td>P</td>
<td>0.045</td>
<td>0.035</td>
<td>22%</td>
<td>0.035</td>
<td>0.030</td>
<td>14%</td>
<td>0.037</td>
<td>0.034</td>
<td>0.035</td>
<td></td>
<td></td>
</tr>
<tr>
<td>S</td>
<td>0.030</td>
<td>0.028</td>
<td>7%</td>
<td>0.035</td>
<td>0.035</td>
<td>0%</td>
<td>0.029</td>
<td>0.033</td>
<td>0.031</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cu</td>
<td>0.000</td>
<td>0.006</td>
<td>0%</td>
<td>0.350</td>
<td>11%</td>
<td>0.310</td>
<td>0.004</td>
<td>0.185</td>
<td>0.095</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

17% | 17% | 14% | 18%
However, Cr and Ni equivalent, with the laboratory composition of materials, did not show significant variation regarding Schaeffler diagrams, Delong, WRC and Creq/Nieq. Fig. 3 shows the microstructures of BM2 consist of ferrite and perlite in proportions 20% and 80% respectively. The average ferrite grain size, determined by the intercept method of ASTM E-112 [23], it is $15 \pm 2$ μm. The microstructural features observed in the cross section are similar to the vertical alignment. It was observed that the SS has a high density of inclusions. Fig. 4 shows the microstructures of BM1. It corresponds to an ASS, deformation maclas were observed. The average austenite grain size, determined by the intercept method of ASTM E-112 [16], it is $26 \pm 2$ μm. The MO features observed in the cross section are similar to the vertical alignment. It was noted that ASS has a low level of inclusions [17].

![Fig. 3. Microstructure of BM2, 200x, Vilella](image1)

![Fig. 4. Microstructure of BM1, Nital 3%](image2)

![Fig. 5. Microstructure of WM, without chemical attacked, 100x](image3)

![Fig. 6. Microstructure of WM, 50x, fusion line, Nital 3%](image4)

![Fig. 7. SEM of BM2, 500x](image5)

![Fig. 8. SEM of BM2, 2000x](image6)

![Fig. 9. SEM of BM2, 5000x](image7)

![Fig. 10. SEM of WM, 500x](image8)

![Fig. 11. SEM of WM, 2000x](image9)

![Fig. 12. SEM of WM, 5000x](image10)

![Fig. 13. SEM of HAZ, near to FM, 500x](image11)

![Fig. 14. SEM of HAZ, near to FM, 5000x](image12)

![Fig. 15. SEM of HAZ, near to FM, 5000x](image13)

![Fig. 16. Fusion line between BM2 (A537) &FM (308L), 500x](image14)

![Fig. 17. Fusion line between BM2(A537) &FM (308L), 1000x](image15)

![Fig. 18. Fusion line between BM2(A537) &FM (308L), 2000x](image16)
Fig. 5 shows microstructure of WM without chemical attack, and illustrates dissimilar area. It demonstrates low level of inclusions to ASS and high level to SS. The contrasts permit to distinguish various sub-regions, defined by microstructure in each product of local thermal conditions during the process. Fig. 6 shows weld surface after chemical attack (Nital 3%); both materials are different, revealing the SS microstructure, consisting of grains of acicular ferrite, and perlite in grain boundaries. This corresponds to HAZ and growth is evident in grain size. Similarly, illustrates junction region consisting of SS which includes grains of perlite and acicular ferrite. Fig. 7 shows SEM of BM2, and observed a heterogeneous grain structure of ferrite and perlite. Figs. 8 & 9 detail fragmentation of perlite, noticing clearly iron carbide (cementite) globular and laminar. Fig. 10 shows SEM of WM, and observed the grain size decreased as a result of recrystallization occurred by the heat generated during welding. Figs. 11 & 12 detail the lamellar microstructure of fine perlite. Fig. 13 shows SEM of HAZ, zone adjacent to the WM, and observed increase of grain size because in this area provides more HI to metal (process of recrystallization / growth). It also shows the massive formation of ferrite Widmanstätten [18] as a result of rapid cooling to room temperature. Figs. 14 & 15 show details of the fragmentation of perlite and ferrite needles. Fig. 16 shows SEM of HAZ, and detail the fusion line between BM2 & FM and confirms the well joint between the steels. Figs. 17 & 18 show dendritic microstructure of FM. Fig. 19 shows microhardness profile of HAZ, measured in middle, upper third and lower third of weld, similar trend was observed in all three measurements. HAZ has a progressive HV increase, between BM1&BMB2 (150-383HV). It also shows that fusion line between WM & BM1 has the maximum (383HV), while fusion line between WM & BM2 has a maximum relative (200HV). Properties are reported in Table 2. Fig. 20 shows S-c curve, having higher strength and ductility in BM1, same strength in BM2 & WM, but lower ductility. It may be noted that results of welded specimen are similar to BM2 values. It experienced less elongation, corresponding to less ductility, by presence of martensite in cooling, but remains above 20% of what can be classified as ductile joint [19]. It is important to mention that tensile welded specimens, failed outside HAZ and weld, in BM2; results consistent with microstructure presented. The regions hardest phases ferrite modifies response of material when it is under load. These structures make material more resistant to being deformed; leading to an increased effort to produce plastic deformation and, at the same time, accept lower degree of lengthening [20]. The mechanical properties at impact (Charpy test) of BM1, BM2, & WM are also reported in Table 2. To determine the fatigue life for BM, & WM, was taken as reference the relationship of fatigue (0,4) with respect to maximum stress ($\sigma_{UTS}$) previously determined by tensile test [21, 22]. Diagram was constructed for each BM & WM, resulting in the curve for welded joint next above that of BM2. The values determined are reported in Table 3. It can be seen from the diagram S-N (Fig. 21) of WM is 8% higher than BM2, which reinforces the non-existence of internal cracking a decisive influence on the opening of crack and consequently in the resistance to fatigue of the welded joint.

Table 2. Mechanical properties of the samples under study (required by ASTM specifications and results obtained in the laboratory)

<table>
<thead>
<tr>
<th>Material</th>
<th>ASTM specifications</th>
<th>$\sigma_y$ (MPa)</th>
<th>ASTM specifications</th>
<th>$\sigma_{UTS}$ (MPa)</th>
<th>ASTM specifications</th>
<th>$\sigma_{UTS}$ (MPa)</th>
<th>Elongation (%)</th>
<th>ASTM specifications</th>
<th>Charpy (J)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BM1 A240 (304L)</td>
<td>270</td>
<td>388±2</td>
<td>515</td>
<td>648±2</td>
<td>35</td>
<td>34±2</td>
<td>86±2</td>
<td>80±2</td>
<td></td>
</tr>
<tr>
<td>BM2 A537 (L)</td>
<td>240</td>
<td>265±6</td>
<td>458</td>
<td>458±2</td>
<td>40</td>
<td>48±2</td>
<td>68</td>
<td>60±2</td>
<td></td>
</tr>
<tr>
<td>FM A240 (308L)</td>
<td>345</td>
<td>481±3</td>
<td>550</td>
<td>585±2</td>
<td>22</td>
<td>19±2</td>
<td>----</td>
<td>----</td>
<td></td>
</tr>
<tr>
<td>Weld Metal (WM)</td>
<td>----</td>
<td>283±3</td>
<td>----</td>
<td>456±2</td>
<td>----</td>
<td>25±2</td>
<td>----</td>
<td>55±2</td>
<td></td>
</tr>
</tbody>
</table>

It is noteworthy that in all welded specimens, tested in fatigue, the crack was initiated at the fusion line between WM & BM2, where the fault occurred subsequently. To determine the fatigue crack growth for BM, & WM, was taken the same axial fatigue conditions, on stress value estimated in the models obtained for one million cycles previously determined by axial fatigue test. Curve of the crack size, $a$ (mm) vs. the number of fatigue cycles, $N$
(cycles), and curve of crack growth rate, $da/dN$ (mm/cycles) vs. the variation of stress intensity factor, $\Delta K$ (MPa) were constructed for each BM (type 1 & 2) & WM, in three different positions for WM (each fusion line and weld metal) [23, 24]. Figs. 22, 23 & 24. Values determined (Paris coefficients of the samples) are reported in Table 4.

Table 3. Mechanical fatigue properties of the samples under study

<table>
<thead>
<tr>
<th>Material</th>
<th>$S_f = 0.4 \sigma_{UTS}$ (MPa)</th>
<th>$\sigma_{fatigue}$ (MPa)</th>
<th>$f$</th>
</tr>
</thead>
<tbody>
<tr>
<td>BM1 A240 (304L)</td>
<td>259±2</td>
<td>218±2</td>
<td>0,36</td>
</tr>
<tr>
<td>BM2 A537 (I)</td>
<td>183±2</td>
<td>122±2</td>
<td>0,27</td>
</tr>
<tr>
<td>Weld Metal (WM)</td>
<td>182±2</td>
<td>135±2</td>
<td>0,30</td>
</tr>
</tbody>
</table>

Table 4. Pre-cracked specimens (Paris coefficients; C, m) [5]

<table>
<thead>
<tr>
<th>Type</th>
<th>location of the crack</th>
<th>C (mm/cycle)</th>
<th>m</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>BM1 [24]</td>
<td>2,70E-10</td>
<td>2,287</td>
</tr>
<tr>
<td>2</td>
<td>BM2 [24]</td>
<td>1,13E-10</td>
<td>2,000</td>
</tr>
<tr>
<td>3</td>
<td>HAZ A537-308L</td>
<td>2,42E-10</td>
<td>2,690</td>
</tr>
<tr>
<td>4</td>
<td>WM 308L</td>
<td>9,67E-10</td>
<td>1,480</td>
</tr>
<tr>
<td>5</td>
<td>HAZ 308L-304L</td>
<td>3,00E-13</td>
<td>5,216</td>
</tr>
</tbody>
</table>

Fig. 22. Type 3. Pre-cracked on BM2

Fig. 23. Type 4. Pre-cracked on WM

Fig. 24. Type 5. Pre-cracked on BM1

4. Conclusions

In this paper, hardness profile, tension, impact, bending, axial fatigue, and speed of propagation of fatigue cracks experiments tests were conducted on a dissimilar steel welded unions. The results obtained were listed as follows: The union of steels ASTM A240-A537, ASTM A240 welded (308L) with GMAW process, using argon as a shielding gas, has mechanical and microstructure properties under cyclic loading, which can be considered adequate to withstand the mechanical requirements in service conditions, despite the relatively high values of microhardness in the HAZ, specifically in the fusion line between the weld and stainless steel. A statistically based model was obtained, that allows predicting the fatigue life Wöhler on joints of steel ASTM A240 (304L) - ASTM A537, welded with filler material ASTM A240 (308L) and GMAW process, applicable to recipients and pressure pipes with stories of efforts between 140-250 MPa. The fatigue resistance of 135 MPa for one million cycles, and fatigue ratio of 0.3 (limit of fatigue strength / tensile strength) results, which may be extensive to other alloys, processes and types of joints and sees potential for expanding the horizon of research. Pre-cracked test allowed to determine the coefficients of Paris for dissimilar joints and showed higher growth rate of crack in the fusion line between the structural steel (A537) and stainless one (308L) It proposed to complement the mechanical characterization by the research: Physical metallurgy and mechanical behavior of welded joints on T and overlap, of dissimilar steels (ASTM A240-A537) by GMAW process piping and vessels under pressure applications.

5. Environmental contribution

The results represent a contribution to ecological sustainability and conscious use of natural resources incorporated into productive activities, and increasing equipments lifetime will improve use rate of renewable and nonrenewable resources with this will increase time for depletion. At the same time, decrease negative environmental impacts on
account of damage and losses presented and decrease economic losses arising, and consequent mitigation of impacts generated by exhaust gases and pollution subsoil, favoring sustainable development [25, 26].

Acknowledgements

This research was made possible by joint effort between researchers at the Higher Institute of Mining and Metallurgical, ISMM “Dr. Antonio Núñez Jiménez”, Moa, Holguín, Cuba; Central University of Las Villas, UCLV, Santa Clara, Cuba; and University Institute of Technology, IUT “Dr. Federico Rivero Palacio”, Caracas, Venezuela; under the PhD in Electromechanical, within the cooperation agreement Cuba - Venezuela. The authors wish to record appreciation to individuals, managers and educational institutions for funding, facilities for conducting the tests, reviews, attending events, and suggested corrections to the papers.

References