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Influence of mechanical surface treatment on fatigue life of bonded joints

S. de Barros, P. P. Kenedi, S. M. Ferreira, S. Budhe, A. J. Bernardino, and L. F. G. Souza

Federal Center of Technological Education in Rio de Janeiro- CEFET/RJ, Rio de Janeiro/RJ, Brazil

ABSTRACT

Adhesively bonded joints can support a longer fatigue life if compared to conventional joining techniques, provided that a set of requirements is fulfilled. One of the most important requirements is the mechanical preparation of the bonded joint surface, which improves the joint interface adhesion. The aim of this work is to investigate the influence of surface roughness of mild steel substrates on fatigue behavior in adhesive bonded plates. To accomplish this objective, three different surface treatments were used on A36 steel substrate specimens, namely sand blasting, grit blasting, and bristle blasting. Bonded plate specimens, using end-notched flexure format, with a thin adhesive epoxy layer were manufactured and tested, under mode II loading condition, in both static and dynamic tests. The results confirm the importance of surface treatment of the substrate on the fatigue life, confirming that adhesively bonded joints have significant performance differences when subjected to static and dynamic loadings.

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Durability; fatigue; metal; surface treatments

1. Introduction

The increasing use of adhesively bonded joints in structural applications of high technological industries motivates the growing interest of the scientific community in the fatigue performance of adhesively bonded joints. This is particularly true for industrial application, where the adhesive bonding must be highly reliable, for instance in aircraft industry, leading to the evolution of adhesive bonding technologies.The majority of adhesively bonded joints used in structural components are subjected to variable loading. In a fatigue loading regime, a structure may fail even if the load remains within the elastic range; hence it is important to estimate the fatigue strength of bonded joints using a standard method that has been specially developed for this purpose. Nevertheless, a reasonable estimation of fatigue life is still quite a complex issue due to the multivariable nature of fatigue crack initiation.

CONTACT S. de Barros silvio.debarros@gmail.com Federal Center of Technological Education in Rio de Janeiro- CEFET/RJ, Av. Maracanã, 229, 20271-110, Rio de Janeiro/RJ, Brazil.
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Indeed, research on fatigue behavior of bonded joints has already been done. Crocombe and Richardson [1] investigated the influence of mean load and load frequency on fatigue behavior. It was found that the mean load has a significant effect on the fatigue response, while the load frequency showed to be relatively unimportant. Additionally, it was found that increasing the mean load has a deleterious effect on fatigue life. The effect of frequency on fatigue damage was also investigated by Underhill and DuQuesnay [2], which observed the independence between the frequency of load application and fatigue behavior in 10–60 Hz range. Fatigue tests were conducted on thick composite adhesively bonded joints in order to define a fatigue strength criterion to be used. The result of the study suggested the use of the peak elastic stress as an engineering tool for the fatigue assessment of joints in actual structures [3]. Quaresimin and Ricotta [4] presented a model for the prediction of the fatigue life of composite bonded joints. The model was based on fracture mechanics and divided the joint lifetime into crack initiation and crack propagation phases. It was concluded that a significant fraction of the fatigue life was spent at crack initiation phase. Work studied by Thevenet et al. [5] concerns about the influence of mean load and loading type on the mechanical behavior of a ductile adhesive under monotonic and low-cycle fatigue loading. They concluded that the amplitude is more significant to fatigue life than mean load and the shear behavior mainly controls the mix mode tensile-shear behavior of the bonded joint. Another extensive study by Meniconi et al. [6] describes the fatigue analysis of composite repair applied on the metallic hull of floating, storage, and offloading (FSO) platform. It was confirmed experimentally that the repair would not fail due to fatigue propagation of eventual defects at the adhesive interface. Furthermore, environmental aging gives beneficial effect as it caused an increase in the critical shear stress of the bonded interface.

Many studies have showed that the adequate surface preparation of bonded parts results in an increase of the strength [7]. Therefore, to obtain a tenacious joint, the surface treatment has to be carefully chosen. Hence, it is one of the most important operations in the adhesive bonding process. If the selection of surface treatment method is not according to the standard, then bonded joint can fail unpredictably and most probably there is failure between the adhesive and substrate, causing an ultimate adhesive failure. On the other hand, if the surface preparation is adequately done, the failure will always be cohesive. In fact, the surface preparation has the main objective of reaching the maximum surface wettability of the chosen adhesive, which ultimately depends on both surface energy and surface integrity. In addition, the increase in the surface area can lead to a relative increase of adhesion, as long as the surface roughness does not reduce the contact area between surfaces. For good bonding, the adhesive should be completely wet the substrate and not form any drops. To obtain this, the surface energy of the adhesive must be less than the surface energy of the material to be bonded (substrate). The degree of the adherend surface coverage by the adhesive depends on its viscosity, on the surface cleanliness, on the surface roughness, and on the adhesive curing time.

To obtain a specific surface roughness, a mechanical surface preparation such as abrasive or erosive wears can be used [8]. In both cases, the knurling and cutting of material occurs. The abrasive wear is a typical type of the mechanical preparation using grinding methods, which uses a big number of grains of irregular geometry and can be obtained by using hard particles. Muller [8] investigated the possibility of a surface roughness change influenced by load and path length using manual grinding. However, it was found that the roughness parameters of specimens prepared by different persons were statistically equivalent. The erosive wear is obtained by blasting. Note that the impact particle energy must be sufficient and the impact angle must be appropriately chosen for the material replacement and detachment from the surface to be obtained. The surface that has erosive wear presents a rippled and corrugated appearance.

Blasting is one of the good methods of treatment for large surfaces. Some authors [9] emphasize that the fine differences in the blasted grain types and size result in a measurable change on the surface characteristics. The coarser grit produces the rougher surface, which in general shows the lower surface energy, which agrees with the conclusions obtained by Chander et al. [10]. Spaggiari and Dragoni [11] investigated the effect of mechanical surface treatment of aluminum and steel joints. Two different adhesives (epoxy resin, acrylic adhesive), two-joint geometry (single lap, double lap), and three surface treatments (sand papering, sand blasting, and knurling) were employed in the experiments. The results obtained from the study confirmed that the surface treatment is the only variable which affects the joint performance. Sand papering and sand blasting surface treatment showed a better performance and also promote a cohesive failure in many cases, especially in the case of steel adherents. Extensive study was carried out by Silva et al. [12] in order to investigate the effect of material, geometry, surface treatment, and environment on the shear strength of single lap steel joints under quasi-static loading. It was concluded that the parameters such as overlap size, adhesive thickness, and adherend thickness have a significant effect on joints. Xu and Wei [13] numerically investigated the influence of different types of defects in the adhesive layer on metallic bonded joints and confirmed that the strength of the joints diminishes as the defect size is increased.

Surface preparation plays an important role in the interface quality between adhesive and substrate, affecting directly the fatigue performance of a joint. Bermejo et al. [14] pointed out the considerable influence of adherend surface treatment for fatigue life of adhesive steel joints. They tested the joints made with and without superficial treatment on adherend. A simple pre-painting with adhesive (epoxy) was used as a superficial treatment. The experimental results showed an increase of fatigue life resistance for the pre-painting joints by a 1.7 factor. Moreover, the qualities of failure locus of pre-painting joints were better than non-treated joints. The study of Bland et al. [15] is concerned about the influence of surface pretreatment on fatigue life of aluminum structural joints in liquid water and water vapor environments. They tested the joints with three surface pretreatments: grit-blast and degreasing (GBD), phosphoric-acid anodizing (PAA), and PAA followed by the application of an anti-corrosion primer (PAAP). The results revealed that GBD joints have less resistance in water vapor and even less resistance in liquid water comparing with PAA and PAAP joints. The failure locus of GBD joints is predominantly adhesive. The joints with PAA substrates have relatively good durability in both environments.

The study showed a significant effect of surface roughness of aluminum substrates on fatigue threshold strain energy release rate under mixed-mode fatigue loading. The smaller fatigue threshold strain energy release rates were obtained for the lowest and highest surface roughnesses used in this work [16]. Besides, for fatigue and quasi-static loading under mode I, the fatigue threshold strain energy release rate showed no dependency on surface roughness. In an experimental study, Hadavinia et al. [17] investigated the crack growth in epoxy bonded aluminum single lap joint under fatigue loading in different environments. They concluded that the lifetime of the joints was controlled by crack propagation and the surface treatment has a distinct effect in wet environment. Another work that concerns about crack propagation of grit-blasted aluminum joints belongs to Budzik et al. [18]. Double cantilever beam specimens were tested under monotonic and cyclic loadings. Dynamic test was performed under the load corresponding to 50% and 60% of critical fracture energy determined from monotonic test. They observed that the crack started to propagate right from the start and rapid propagation began after 4000 cycles. Gomatam and Sancaktar [19] investigated the effect of various substrate surface treatments on the fatigue and failure behaviors of single lap joints. They employed various chemical and mechanical modification techniques, under a variety of fatigue and environmental conditions; as a result significant effects of surface treatment were obtained on fatigue behavior of joints.

Although the study of the fatigue strength and the lifetime analysis of the bonded joints have been started some decades ago and a large number of works have been concentrated on this issue, the lifetime prediction of bonded joints remains a relatively unexplored issue. As stated by Wahab [20], the research about fatigue in adhesively bonded joints is not well developed and can be considered as in its early stage. Therefore, the present work was conducted to give a contribution to enhance the knowledge of fatigue theory of joints.

2. Experimental procedure

The objective of this experimental study is to investigate the effects of different mechanical surface treatments on bonded joints. Epoxy bonded joints with low carbon steels substrates were loaded under mode II condition in static and dynamic. Three different mechanical surface treatments were used: bristle blasting, grit blasting, and sand blasting. Although some studies related to static strength resistance of steel joints have already been carried out and it was found that surface treatment was not so important, the influence of roughness on fatigue life can be still treated as an open issue.

2.1. *Materials and methods*

The adhesive joints were made using plates of low carbon steel A36 and the structural epoxy adhesive NVT (Novatec S.A., Rio de Janeiro, Brazil). The distinct surface treatments were implemented on the steel plate surfaces, before they were cut in specimen size. The joints were manufactured in a mold and the adhesive thickness was controlled by a device specially designed in the laboratory. This dispositive guarantees the specimen's dimensions repeatability. The joints were cured in the conditions recommended from manufacturer: at 25°C, 35 min of application time, 120 min of initial cure time, and 24 hr of functional cure time. The mechanical properties of the adhesive, obtained from manufacturer according to ASTM D638 [21] and ASTM D2240 [22], are shown in Table 1.

The bonded joints were tested in static and at high-cycle fatigue loading conditions in a 100 kN Instron servo-hydraulic machine (Norwood, USA). The specimen installation in servo-hydraulic machine is presented in Fig. 1.

The mechanical properties of the substrate material are σ_{ys} = 250 MPa and σ_u = 400 MPa, according to ASTM A36/A36M-14 [23]. Two blasting machines were used to obtain necessary mechanical roughness in bonding surface: a manual blasting machine IBIX 25 (IBIX SRL, Lugo, Italy), which uses different types of blast material, and a bristle blasting machine MBX (Monti Tools Inc., Houston, USA),which uses high-carbon steel wire bristles. Two blast materials wereused to roughen the surface: garnet sand 20/40 mesh and grit steel G-25 (Jatofer, Campinas, Brazil). Initially, the area was degreased with acetone and then blasted in the way mentioned above and cleaned again with acetone before the application of the adhesive.

Table 1. Adhesive Mechanical Properties.

Mechanical properties	Value
Yield strength, σ_{ys} (MPa)	27
Hardness, *H*, (Shor)	60

Figure 1. Illustration of specimen installation in servo-hydraulic machine.

The blasted surfaces were analyzed in a Taylor Hobson roughness Talyscan 150 (Leicester, UK) equipped with a 2 mm diameter style probe, in accordance to ISO 4288-1996 [24]. The scan speed was 1000 μm/s under temperature and humidity control at 23°C and 60% relative humidity, respectively.

2.2. *Thick adherend shear test (TAST)*

The test method using thick adherend was performed in order to compare the failure load obtained with each surface treatment. Three specimens of each mechanical surface treatment were tested according to ISO 11003:2 2001 [25]. The specimen dimensions and configuration are presented in Fig. 2.

The specimen dimensions were: length, l = 110 mm; width, b = 25 mm; and thickness, h = 6 mm; overlap, c = 5 mm; and gap, f = 1.5 mm.

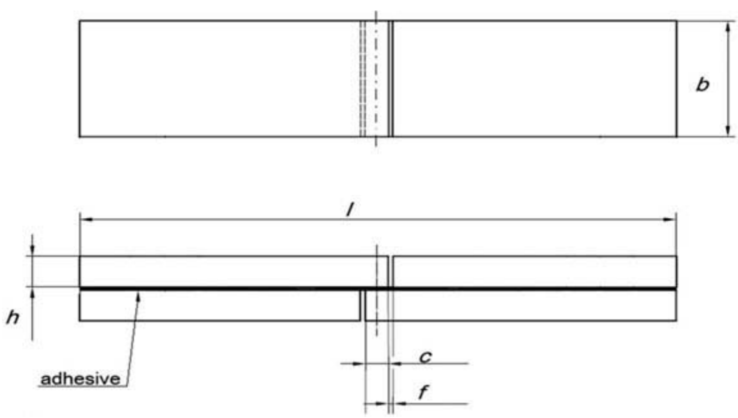

Figure 2. Specimen dimension and configuration.

Figure 3. Thick adherend shear test setup in the testing machine.

The adhesive thickness was set in 0.5 mm. Figure 3 shows the thick adherend shear test (TAST) setup in the testing machine.

2.3. *End-notched flexure test (ENF)*

Three-point bending tests were performed in both quasi-static and dynamic tests with end-notched flexure (ENF) configuration.

2.3.1. *Quasi-static test*

Quasi-static ENF tests were performed in order to determine the maximum load to be used as reference for the dynamic test program. The distance between the specimen´s supports was stated as $2L = 160$ mm. The pre-crack length was established as $a_0 = 25$ mm. The substrate dimensions can be resumed as length, $l = 190$ mm; width, $b = 25$ mm; and thickness, $h = 6$ mm. The adhesive thickness was set to 0.5 mm; the total length of the bonded area was 150 mm. The illustration of the specimen's geometry is shown in Fig. 4.

ENF configuration was selected as the most appropriate test for mode II fracture characterization of bonded joints. Under this type of loading, the

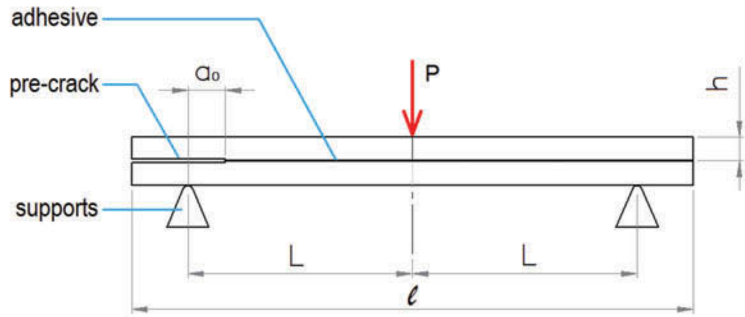

Figure 4. End-notched flexure joint dimension and configuration.

substrates are exposed to bending moment while the adhesive is subjected to pure shear loading. Quasi-static tests were executed at a crosshead speed of 3 mm/min. The load–displacement curve was recorded during the tests.

2.3.2. *Dynamic test*

Fatigue tests were performed at 50%, 60%, 70%, and 80% of the maximum reference load obtained from quasi-static test. Sinusoidal loading waveform with a frequency of 20 Hz and loading ratio $R = P_{min}/P_{max} = 0.1$ was used for the fatigue tests.Thus, the maximum fatigue load, P_{max}, for each level was proportional to this maximum static load. The load amplitude, P_{amp}, and average load, P_{avr}, were calculated using classic fatigue expressions. The specimens were tested until failure or up to the number of load cycles have reached 1×10^6, which was considered as infinite life for the work purposes. The load–displacement and load–time curves have been recorded during the test in order to control the test proceeding. Thirty-six specimens were used in the experiments. All of them were tested in the same environment conditions: room temperature of 25°C and relative humidity of 55%.

3. Results and discussion

The quasi-static and dynamic tests results are presented in this section and discussed hereafter.

3.1. *Roughness*

The values of substrate roughness parameters obtained through the mechanical surface treatment are presented in Table 2.

Analyzing the roughness parameters of three mechanical surface treatments performed on the substrates, it can be concluded that the bristle blasting mechanical treatment provides relatively low roughness and unevenness surface, compared to the grit blasting and sand blasting. Bristle blasting makes a surface as rough as sand blasting, *i.e.*, Ra(BB) ≈ Ra(SB), but with higher level of

Table 2. The Surface Roughness Parameters.

Treatment/Superficial parameter	Symbol identification	Ra (μm)	Rt (μm)	Sa (μm)
Grit blasting (G25)	R_{GB}	12.20	112.50	32.50
Sand blasting	R_{GB}	4.90	30.00	5.90
Bristle blasting	R_{GB}	4.66	45.15	16.49

unevenness surface in terms of picks and vales, *i.e.*, Rt(BB) > Rt(SB). Grit blasting provides approximately three times rougher and uneven surface than sand blasting or bristle blasting. Figure 5 presented the images of surface profiles obtained with 3D surface roughness tester, mentioned above.

3.2. *Thick adherend shear test (TAST)*

The average results obtained at the TAST executed at normalized specimens are shown in Fig. 6.

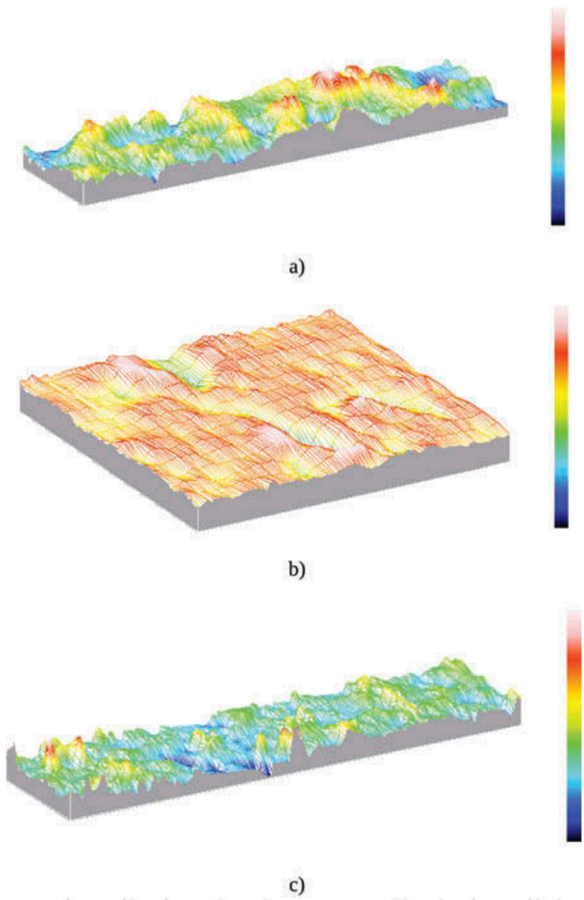

Figure 5. 3D surface profiles after mechanical treatment: (a) grit-blasted surface profile; (b) sand-blasted surface profile and (c) bristle-blasted surface profile.

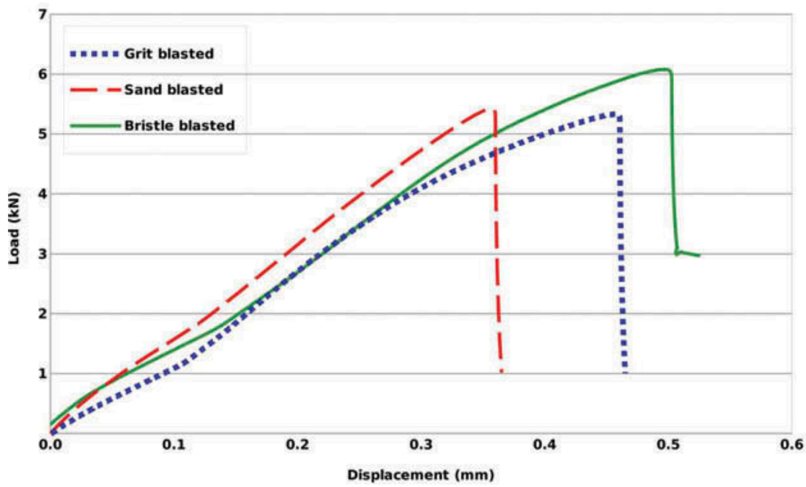

Figure 6. Thick adherend shear test results.

Three types of mechanical surface treatment on substrate joints reached the maximum load in the range of 5.3–6 kN. In particular, the bristle blasting showed the best result, even if there is no significant statistical difference among the results. Additionally, shear strength was determined, τ = 48 MPa, based on the bristle blasting result.

3.3. *End-notched flexure test (ENF)*

Both quasi-static and dynamic tests results with ENF specimens are presented in this section.

3.3.1. *Quasi-static tests*

Initially, the tests were performed with grit-blasted specimens. Three tested specimens presented similar behavior during the tests. One of the load–displacement curves obtained from static ENF tests is shown in Fig. 7.

Analyzing the load–displacement curve, it is possible to see that the failure occurs after significant plastic deformation of the specimen. There was no adhesive failure during all these tests since no crack propagation could be observed. Therefore, the reference load for fatigue tests was calculated using the quasi-static test data of grit blasting specimens. The average yield point load was calculated as $P(y)a$ = 6293 N, and this value was used as the maximum reference load to the dynamic test program.

3.3.2. *Dynamic tests*

According to the average yield load of material substrate obtained from the static test, the fatigue test program was defined and presented in Table 3. Three specimens were tested for each load level.

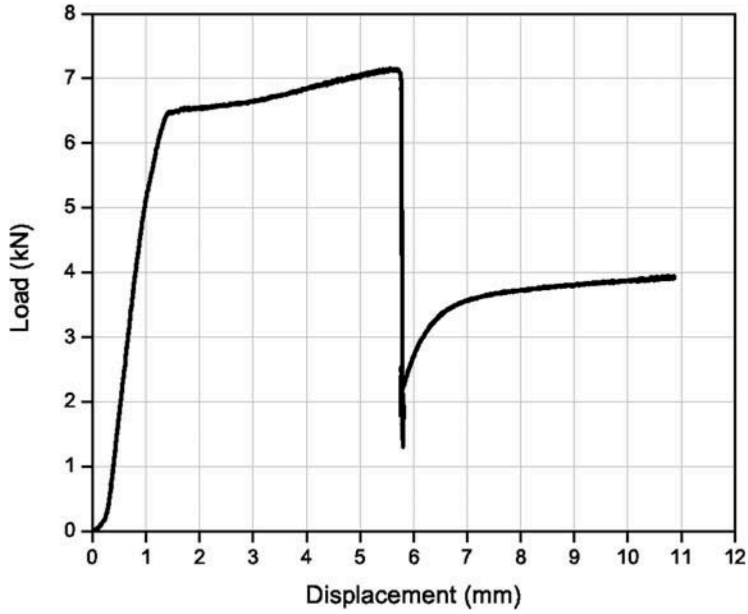

Figure 7. Load–displacement curve for quasi-static test of grit blasting specimen.

The dynamic tests performed at four different loading levels (50%, 60%, 70%, and 80%) and showed a significant influence of mechanical surface treatment on fatigue life. At the lower load level (50%), few specimens did not fail until the number of load cycles has reached 1×10^6; in these cases, the tests were stopped and they were considered as infinite life. Table 4 presents the most conservative lower cycle numbers that can be withstand by the joints for the particular surface treatments at different load level.

Table 3. Fatigue Test Program.

Level	Load level *P* (%)	P_{max} (kN)	P_{min} (kN)	P_{amp} (kN)	P_{avr} (kN)	*R*
1	50	3.15	0.315	1.416	1.731	0.1
2	60	3.78	0.378	1.699	2.077	0.1
3	70	4.41	0.441	1.982	2.423	0.1
4	80	5.03	0.503	2.265	2.769	0.1

Table 4. Numerical Results of Fatigue Test for the Specimens with Different Mechanical Treatment.

				Mechanical treatment/number of cycles, *N*		
Level	Load level *P* (%)	*P*max (kN)	*P*min (kN)	Grit blasting	Sand blasting	Bristle blasting
1	50	3.15	0.315	1×10^6	1×10^6	4×10^4
2	60	3.78	0.378	3×10^5	6×10^5	3×10^4
3	70	4.41	0.441	2×10^4	5×10^4	5×10^3
4	80	5.03	0.503	3×10^3	2×10^4	4×10^3

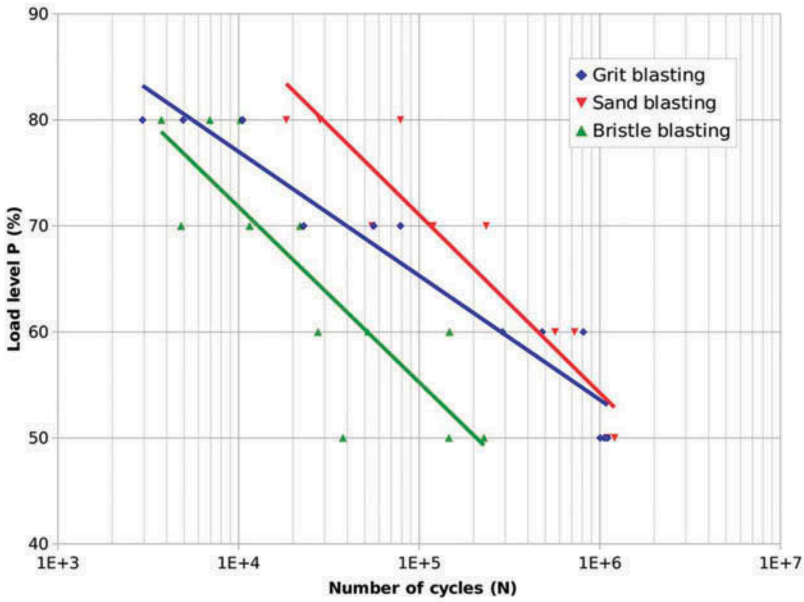

Figure 8. Fatigue results for three types of mechanical surface treatment.

All the results obtained from the fatigue tests are shown in Fig. 8. It can be seen that the fatigue tests results revealed a clear difference in the fatigue life of the specimens with different mechanical surface treatment. The best performance in fatigue tests was obtained by the specimens that have sand blasting mechanical treatment. The specimens with bristle blasting-treated substrates showed the poor results at all levels if compared with the results obtained for sand- and grit-blasted specimens. This result is particularly interesting considering that the bristle-blasted joints showed the good result in thick adherend shear static test. In fact, the joints (grit and sand blasting) that presented the same behavior in quasi-static tests reached the improved results in fatigue tests compared to bristle blasting. The experimental results evidenced the direct influence of mechanical substrate surface treatment on the fatigue behavior of bonded joints.

4. Conclusions

In this work, the influence of different surface treatment on the fatigue life of bonded joints was investigated. High-cycle fatigue tests of adhesively bonded joints prepared using three different mechanical surface treatments were performed under mode II loading. TASTs were performed in order to compare the failure load obtained with each surface treatment.

Failure load obtained through TAST in bristle blasting surface treatment joints was higher than the remaining two surface treatments.

It was verified that all the specimens presented similar behavior in quasi-static tests, independent of the surface treatment applied on the substrates. On the other hand, it was observed that mechanical surface treatment on substrate plays a significant role in fatigue behavior of adhesive joints. The effect of the surface treatment was clearly observed in ENF fatigue tests. Grit blasting mechanical treatment showed a better resistance together with sand blasting in dynamic loading condition compared to the bristle blasting. Furthermore, grit-blasted and sand-blasted joints have a fatigue life, overcoming 1×10^6 cycles for the 50% load level, but bristle-blasted joints demonstrated a very low fatigue performance even though the same quasi-static behavior was observed for all the three surface treatment joints. It can be concluded that substrate roughness proved much more relevant for fatigue testing than quasi-static testing.

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ORCID

Silvio de Barros http://0000-0002-2520-569X
Paulo Kenedi http://0000-0001-5563-843X
Svetlana Ferreira http://0000-0003-2478-2505
Alencar Bernardino http://0000-0003-0868-3662

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