Effect of novel paint removal processes on the fatigue behavior of aluminum alloy 2024

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Received 13 February 1998; accepted 12 May 1998

Abstract

Conventional paint removal processes, based on application of chemicals and abrasion, are becoming inadequate for modern aircraft structures. In addition they are associated with severe environmental problems, mainly due to the production of hazardous waste. Several alternative novel techniques are being developed. However, the aspect of material property degradation due to the application of these new paint removal techniques has not been addressed adequately. The application of laser radiation (carbon dioxide and excimer), as well as plasma etching, has recently been associated with significant ductility deterioration and fatigue life extension. Residual stress measurements, roughness measurements and fractographic analysis were employed in order to rationalize the effect of these novel paint removal processes on the fatigue behavior of aluminum alloy 2024. The observed enhancement of fatigue life is attributed to the development of compressive residual stresses during paint removal processing. At low fatigue stresses, the magnitude of the residual stress correlates with the relative enhancement in fatigue life for the three processes investigated. The effect of surface roughening towards decreasing fatigue life is surpassed by the effect of residual stresses in extending fatigue life. Finally, the decrease of toughness and associated damage tolerance ability which follows the application of paint removal processes has been confirmed by fractographic measurements. © 1998 Elsevier Science S.A.

Keywords: Laser paint stripping; Plasma etching; Residual stress; Fractographic analysis

1. Introduction

Paint stripping in the aerospace industry conventionally involves chemical or mechanical (abrasive) paint removal from the component’s surface. The conventional processes include significant technical and environmental drawbacks which have been extensively discussed in Ref. [1]. From the technical viewpoint, most of these techniques do not apply to fiber-reinforced composite structures, nor in applications where thin aluminum alloy sheet structures are used in conjunction with fiber-reinforced plastics or when thin coats are involved. In addition, the techniques are associated with low yield and severe environmental problems. Chemical paint removal involves toxic components, hazardous working conditions and generation of large amounts of hazardous waste. As a consequence of toxicity awareness, environmental regulations and the use of new structural materials, a number of novel paint stripping processes are now being investigated. These processes include: plastic media blasting, wheat starch dry media blasting, carbon dioxide pellet blasting, sodium bicarbonated as well as a series of thermal and photochemical methods which include use of several types of laser and flash lamps. Current advances on the above-mentioned alternative paint removal methods have been recently reviewed in Ref. [2]. Amongst the above processes, the use of laser beam scanning and plasma etching have found considerable attention. These processes provide significant potential advantages over the conventional techniques in terms of cost savings and environmental compatibility. Paint removal rates of the order of 1 m² h⁻¹ have been achieved by the use of laser scanning for both aluminum alloy and composite substrate for a paint layer of about 100 μm thickness [3].

The study of the possible effects of these novel paint removal processes on the mechanical behavior of the substrate materials has been limited. Usually, investigations include extensive studies of the ablative action of the laser on polymeric or metallic materials [4] and have been limited on processing-structure relations. The influence of the laser paint stripping process on the flexural properties of some aircraft structure composite...
materials has been investigated [5]. Generally, no appreciable substrate material degradation has been reported. However, in certain cases, a decrease of flexural properties reaching values up to 15% has been obtained; the degree of degradation depends on the laser type, the composite substrate material and the stripping process parameters.

For the case of metallic substrates the issue of mechanical property degradation due to mechanical or thermal loads associated with the stripping process has only recently been addressed. Pantelakis et al. [6] conducted a detailed study of the effect of paint stripping processes, including laser radiation and plasma etching, on the mechanical behavior of the widely used structural aluminum alloy 2024-T351. The mechanical properties studied were tensile properties, fracture toughness and fatigue life. It was found that although there appears to be no significant effect on yield strength and ultimate tensile strength, the tensile ductility and fracture toughness degrade considerably. On the other hand, fatigue life was extended, but no experimental rationalization was offered for the observed behavior. The aim of the present work is to study in more detail the effect of laser radiation and plasma etching on the fatigue life of aluminum alloy 2024-T351 and to rationalize the observed behavior in conjunction with the mechanical testing reported in Ref. [6].

2. Experimental procedures

The material used in the present investigation was aluminum alloy 2024. The chemical composition appears in Table 1. The alloy was received in the T351 temper condition, in sheet form of 1.6 mm thickness. Prior to preparing test specimens, the sheets were coated using an epoxy as primer, a white polyurethane paint as top coat and acrylic finishing, similar to the paint used in the aircraft industry. Tensile, fracture toughness and fatigue specimens have been machined according to the specifications ASTM E8M-94a for the tensile specimens, ASTM E813-89 for the fracture toughness specimens and ASTM E466-82 for the fatigue specimens. All specimens were cut in the long transverse (LT) direction. Specific details concerning the preparation of the above specimens are given in Ref. [6]. Specimen paint stripping has been carried out with the following techniques: laser radiation with excimer laser source [7], laser radiation with CO₂ laser source [8], and plasma etching [9]. The applied processes, as well as the experimental set-ups, used for stripping the specimens are described extensively in Refs. [7–10]. The set-up used for laser paint stripping involves a laser source capable of scanning the sample surface as well as a micropositioner guided by a suitable micropositioning controller, linked to the laser source via a computer. The set-up described in Ref. [10] also involves an emission spectroscopy unit. Spectral analysis of the emission during the ablation process occurs between two successive laser pulses. The emission spectrum provides a tool for surface state analysis as well as process monitoring and control, thus making it manageable to remove up to the desired material surface layer, i.e. up to the primer or up to the blank material surface. In the present work the stripping was made up to the blank material surface.

Specimen paint stripping with plasma etching has been performed using the experimental set-up described in Ref. [9]. Stripping occurs in a plasma chamber. Adjustable parameters are the gas composition, the process pressure, the power and the substrate position, which has a strong influence on the etch rate. Parametric stripping optimization with regard to stripping quality and paint removal rate has been conducted for all processes referred to above. To evaluate paint stripping quality, aircraft companies apply internal procedures involving visual inspection; they have been considered for the present investigation. It should be noted that referred procedures take no account of a possible substrate material degradation. Paint stripping of test specimens has been performed with optimized process parameters.

Following the paint removal process, the specimens were subjected to mechanical testing. Tensile tests were carried out according to ASTM E8M specification. For fracture toughness testing, the procedure suggested in Ref. [11] was followed, and fatigue testing was performed according to the specification ASTM E-466. The details of the above mechanical testing procedures have been described in Ref. [6].

Macroscopic residual stresses were measured with the X-ray diffraction sin²θ method [12] using Cr Kα radiation. The reflection of the (311) lattice plane was used for the measurements with a 2θ angle of 139.3°. The measurements were performed in the grip section of the fatigue specimens. Three sets of fatigue specimens were used, corresponding to maximum stresses of 200, 250 and 300 MPa. The irradiated area was 0.5 mm x 4 mm with the long axis aligned parallel to the long dimension of the fatigue specimen.

Surface roughness was determined with a stylus profilometer. Line scans were taken in the grip section of the tensile specimens in the longitudinal as well as transverse directions.

Fractographic analysis was performed on the fracture surface of the fatigue specimens. The aim of the analysis was to determine the ratio of the fast fracture surface

| Table 1
| Chemical composition (wt%) of 2024 aluminum alloy |
|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Sn | Fe | Cu | Mn | Mg | Cr | Zn | Ti | Zr |
| 0.10 | 0.18 | 4.15 | 0.87 | 1.36 | 0.01 | 0.07 | 0.03 | 0.01 |

to the total fracture surface $S_f$. The measurements were performed using a stereo-optical microscope under magnification of 30-60×. Prior to the measurements, an effort was undertaken to identify the areas of fast and fatigue fracture with scanning electron microscopy. However, this proved to be a very difficult task owing to the absence of the characteristic fatigue striations in the fatigue zone. Fatigue striations were observed locally, but they did not span the complete fatigue propagation area. However, the absence of continuous fatigue striations is characteristic of 2000 series aluminum alloys. The measurements were then based on the different intensity of light reflected from the fracture surface under the stereo-optical microscope.

3. Results and discussion

With regard to the tensile properties, the data in [6] show that there is a relatively small effect of the paint stripping process on the ultimate tensile stress and on the yield stress. However, there is a significant effect on the elongation to fracture and on the energy density values, i.e. the tensile ductility properties. Tensile ductility is decreased to 66% of the reference value with the use of the excimer laser, to 72–75% with the use of CO$_2$ and to the very low value of 22–24% for the plasma etching. Fracture toughness, in terms of energy release rate $G$ and $K_f$ values, is reduced to 67–70% of the initial values for plasma etching and excimer laser, whereas there is a lower reduction to 77% of the initial value associated with the use of the CO$_2$ laser.

With regard to fatigue behavior, the cycles to failure at the specified maximum stress levels for the paint stripping processes examined in this work, as well as for the reference material, appear in Fig. 1 reproduced from Ref. [6] in the form of the $S$–$N$ diagram. The solid line in Fig. 1 fits the $S$–$N$ curve of the reference material. Examination of this diagram reveals that there is no degradation in fatigue properties resulting from the application of laser or plasma paint stripping at all stress levels investigated. On the contrary, there is an improvement in fatigue life which depends on the paint stripping process and stress amplitude level.

At high stress levels (300 MPa) the effect of paint stripping processing, beyond the expected experimental error, is low, regardless of the processing method used (laser or plasma).

At low stress levels (200 MPa), however, there is a significant improvement in fatigue life associated with the application of the paint stripping processes. There is a two- to four-fold life extension associated with excimer laser processing, a four- to six-fold extension associated with plasma etching and more than an order of magnitude life extension associated with CO$_2$ laser processing.

3.1. Experimental results

To rationalize the observed behavior, residual stress measurements, surface roughness measurements and fractographic analysis were performed. Macroscopic residual stresses were determined for the three sets of fatigue specimens (corresponding to maximum stress of 200, 250 and 300 MPa) and for the three paint stripping methods. In all cases the residual stresses were compressive. The values of the residual stresses appear in Table 2.

The highest compressive residual stress is associated with CO$_2$ laser radiation, followed by plasma etching and excimer laser radiation. It should be noted that in Ref. [13] excimer laser surface treatment was also found to introduce compressive residual stresses at the surface of laser-treated aluminum alloys; the roughness resulting from paint stripping was determined by profilometry. The $K_f$ values for both the longitudinal and transverse directions of the fatigue specimens are given in Table 3, for the three paint stripping techniques examined. All paint removal processes resulted in surface roughening relative to the reference untreated surface. These results show a quite different behavior than earlier experiments on excimer laser surface treatments of aluminum alloys [14], where a polishing effect associated with the photoetching action of the excimer laser was reported. However, this disagreement can be attributed to the different processing parameters (laser power, pulse rate, pulse duration and overlap) employed in the two cases. For the longitudinal direction, the CO$_2$ laser radiation resulted in the lowest relative roughening, followed by plasma etching and excimer laser radiation. For the transverse direction the lowest roughening is associated with plasma etching, followed by CO$_2$ and excimer laser radiation.

The ratio $S_f$ of the fast fracture surface to the total
Table 2
Compressive residual stresses for various paint removal methods examined in this work

<table>
<thead>
<tr>
<th>Paint removal method</th>
<th>Compressive residual stress (MPa)</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>At max fatigue stress of:</td>
</tr>
<tr>
<td></td>
<td>200 MPa 250 MPa 300 MPa</td>
</tr>
<tr>
<td>CO₂ laser</td>
<td>45 ± 2 44 ± 4 46 ± 4 45</td>
</tr>
<tr>
<td>Plasma etching</td>
<td>31 ± 3 30 ± 3 30 ± 6 30</td>
</tr>
<tr>
<td>Excimer laser</td>
<td>19 ± 5 20 ± 5 20 ± 5 20</td>
</tr>
</tbody>
</table>

Table 3
Roughness measurements \( R_a \) in the longitudinal and transverse directions (average values in parentheses)

<table>
<thead>
<tr>
<th></th>
<th>( R_a ) ( \mu \text{m} )</th>
<th>longitudinal</th>
<th>transverse</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference</td>
<td>0.18, 0.19, 0.17, 0.18</td>
<td>0.08, 0.09, 0.10, 0.11, 0.09, 0.08 (0.081)</td>
<td></td>
</tr>
<tr>
<td>Excimer laser</td>
<td>0.37, 0.39, 0.36, 0.35, 0.32, 0.38 (0.361)</td>
<td>0.33, 0.35, 0.38, 0.37, 0.35 (0.356)</td>
<td></td>
</tr>
<tr>
<td>CO₂ laser</td>
<td>0.21, 0.24, 0.25, 0.22, 0.23, 0.24 (0.231)</td>
<td>0.24, 0.25, 0.23, 0.25, 0.24, 0.23 (0.240)</td>
<td></td>
</tr>
<tr>
<td>Plasma etching</td>
<td>0.24, 0.26, 0.17, 0.27, 0.28, 0.28 (0.250)</td>
<td>0.16, 0.17, 0.18, 0.17, 0.18, 0.18 (0.175)</td>
<td></td>
</tr>
</tbody>
</table>

fracture surface was determined from fractographic analysis. Characteristic fractographs from the areas of fatigue fracture and fast fracture are shown in Fig. 2 and Fig. 3 respectively for the case of CO₂ laser-treated specimens. In Fig. 2 characteristic fatigue striations are evident, although, as discussed earlier, fatigue striations do not appear continuously over the fatigue fracture area. Fig. 3 is characteristic of the fast fracture appearance, and it can be classified as a mixture of ductile and quasi-cleavage modes owing to the simultaneous presence of dimples and ridges. The ratio \( S_f \) was determined to be 0.80–0.85 for plasma etching, 0.60–0.65 for excimer laser and 0.50–0.55 for CO₂ laser radiation. The highest \( S_f \) ratio for the plasma etching technique correlates with the most severe deterioration of fracture toughness. On the other hand, the CO₂ laser treatment is associated with a lower \( S_f \) ratio and a less severe deterioration of fracture toughness. Obviously, \( S_f \) also depends on the applied stress amplitude. For the range...
of stress amplitudes investigated the effect on $S_f$ is included in the determined deviations of $S_f$ given above; compared with the effect of the paint removal process itself, it is a secondary-order effect. With regard also to uncertainties discussed for determining $S_f$, the magnitude of the latter quantity may be given as an average value for each paint removal process, independent of the applied stress. The above results appear, for comparison purposes, in Table 4.

3.2 Discussion of the fatigue behaviour

The experimental results presented in Section 3.1 provide a useful means to rationalize the observed fatigue behavior. The structural changes caused by the stripping processes, as reflected in the quantities measured above, affect the material fatigue behavior in opposing ways; increase in surface roughness as well as increase of the $S_f$ ratio are expected to reduce fatigue life, whereas increase of the residual compressive stresses should extend fatigue life. Generally, in high cycle fatigue (HCF), total fatigue life is controlled by fatigue crack initiation rather than by crack propagation. The crack initiation phase, as a percentage of the total fatigue life, depends on the stress amplitude and increases with decreasing stress level; the contribution of the fatigue crack growth phase to the total fatigue life becomes appreciable when stress amplitude levels become medium or high.

Crack initiation results from failure on the alloy surface. The conditions for fatigue failure initiation have been discussed in Refs. [15,16]. According to this work, crack initiation depends greatly on the surface condition of the material, the major parameters being the roughness, residual stresses and the plastic flow behavior of the surface (2–4 μm) layer. All these factors are affected by the laser or plasma stripping processes.

Regarding the effect of surface roughening, a decrease of fatigue life is expected relative to the untreated material for all paint removal processes examined. This decrement should be greater for the excimer laser followed by the plasma etching technique, whereas treatment with the CO$_2$ laser results in the lowest relative roughening and, therefore, the lowest fatigue life decrement. On the other hand, it is evident that the predominant factor affecting fatigue behavior is the development of compressive residual stresses. The larger the magnitude of these stresses, the larger is the effect in extending fatigue life. Referring to Fig. 1 and Table 2, the observed fatigue life enhancement is fully compatible with the magnitude of the residual stresses: it is highest in CO$_2$ laser treatment, followed by plasma etching and excimer laser treatment. At low stress levels, the depth of material modified by the laser or plasma paint stripping processes is greater than the fatigue crack initiation process zone, thus affecting fatigue life beneficially. The experimental results suggest that, at low stress amplitudes, a longer fatigue life extension is associated with CO$_2$ laser processing. It is believed that this difference in behavior is associated with the fact that the CO$_2$ laser emits in the infrared, whereas the excimer laser emits in the ultraviolet. This suggests that the CO$_2$ laser has a more pronounced thermal effect than the excimer laser; it results in a deeper thermally affected and modified zone, thus affecting fatigue behavior significantly with the development of compressive residual stresses. The excimer laser has better absorptivity and coupling with the metal surface, but the effects are limited to a very thin surface layer. At high stress amplitudes, the fatigue crack initiation process zone exceeds the area modified by the paint stripping processes; thus the impact of near-surface residual stresses on fatigue life becomes smaller.

In addition, one should also note the deterioration of ductility reported in Ref. [6]; this has been confirmed in the present work by the measurement of the $S_f$ ratio. The increase of the $S_f$ ratio might be interpreted as a drop of the material fracture toughness and reflects the damage tolerance ability of the alloy; for a certain stress amplitude the critical crack length and, consequently, the duration of the fatigue crack growth phase become shorter. One should recall that the effects of the development of compressive residual stresses and the increase of $S_f$ ratio are opposite with regard to the expected fatigue life. Macroscopically, at high stress amplitude levels, the paint stripping processes have no appreciable effect on fatigue life. The cycles of fatigue failure for all stripped specimens examined in this work are summarized again in Fig. 4; they are displayed at the specified maximum stresses reduced by the residual compressive stresses measured for the respective paint removal.
(1) The observed enhancement of fatigue life is attributed to the development of compressive residual stresses during paint removal processing. At low stresses, the magnitude of the residual stress correlates with the relative enhancement in fatigue life for the three processes investigated.

(2) The effect of surface roughening towards decreasing fatigue life is surpassed by the effect of residual stresses in extending fatigue life.

(3) The decrease of toughness and associated damage tolerance ability which follows application of the paint removal processes has been confirmed by fractographic measurements.

References