Mechanical behavior of 2024 Al alloy specimen subjected to paint stripping by laser radiation and plasma etching

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Abstract

Paint removal is required in a series of aeronautical procedures such as maintenance and repair. Today’s paint stripping processes which are based on application of chemicals and abrasion are inadequate for modern aircraft structures in addition to environmental contamination. Several alternative techniques are in progress. However, the aspect of material property degradation when developing novel, alternative paint stripping techniques has not been properly faced up to present. The influence of two novel paint stripping processes on the mechanical properties of the substrate 2024 T351 aluminium alloy has been investigated. The paint stripping processes included laser radiation with excimer, CO₂, TEA-CO₂ and YAG laser sources as well as plasma etching. These processes have been applied for the removal of polyurethane coating which is a typical aeronautical paint system. The results indicated no significant degradation in yield strength and ultimate tensile strength. However a significant degradation in tensile ductility and toughness is observed with the application of all paint stripping processes, the highest degradation being associated with the ultraviolet excimer laser and plasma etching. On the other hand there is a considerable extension in fatigue life, which depends on the paint stripping process and the applied stress amplitude. At high stress there is no appreciable effect while at low stress there is an order of magnitude life extension associated with CO₂ laser paint stripping. At moderate stresses, there is an up to sixfold life extension associated with the excimer laser processing.

1. Introduction

Regular inspection, maintenance and repair techniques involved in aerospace industry require the application of paint stripping processes. Conventionally, paint stripping involves chemical strippers or mechanical (abrasive) paint removal from the component’s surface. The processes include serious technical and environmental drawbacks which have been extensively discussed in [1]. From the technical viewpoint, the mentioned techniques do not apply to fiber reinforced composite structures, as well as applications where thin aluminium alloy sheet structures are used beside fiber reinforced plastics or when thin coats are involved. In addition the techniques are associated to low yield and severe environmental problems; chemicals strippers involve materials which contain toxic components and create hazardous working conditions. Furthermore, large amounts of hazardous waste from the chemicals used are generated.

As a consequence of toxicity awareness, environmental regulations and the use of new structural materials, a number of novel paint stripping processes is now being investigated. These processes
include plastic media blasting, wheat starch dry media blasting, carbon dioxide pellet blasting, sodium bicarbonate blasting, as well as a series of thermal and photochemical methods which include the use of several types of lasers and flash lamps/carbon dioxide. Current advances in the mentioned alternative paint removal methods have been recently reviewed in [2]. Amongst these processes the use of laser beam scanning and plasma etching has drawn considerable attention. The processes provide significant potential advantages over the conventional techniques in terms of cost savings and environmental compatibility. In [3] paint removal rates of the order of 1 m²/h could be achieved by the use of laser scanning for both aluminium alloy and composite substrate, for a paint layer of about 100 μm thickness.

Evaluation of the paint removal processes which are currently under investigation occurs with regard to their effectiveness in stripping the paint, costs, as well as environmental effects and related health hazards. This viewpoint of evaluating is consistent with aircraft quality assurance specifications; the latter do not delve into a possible substrate material degradation resulting from the involved paint stripping process. This might be justified for chemical stripping of aluminium alloys but not in situations where the paint removal technique is associated to considerable mechanical or thermal loads. Nevertheless, a possible effect of these loads on the material properties which have been used for structural analyses has not been evaluated up to date with the exception of a small number of works (e.g. [3,4]). Usually, investigations include extensive studies of the ablative action of the laser on polymeric or metallic materials (e.g. in [5]) and have been limited on processing/structure relations. In [4] the influence of the laser paint stripping process on the flexural properties of some aircraft structure composite materials has been investigated. Generally, no appreciable substrate material degradation has been reported. However, in certain cases, a decrease on (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 to the stripping process has not been addressed in the open literature. The aim of the present work is to assess the effect of laser radiation and plasma etching paint removal methods on the mechanical behavior of the widely used structural aluminium alloy 2024-T351. The mechanical properties considered included tensile properties, fracture toughness and fatigue properties.

2. Experimental procedure

2.1. Material and preparation of specimens

The material used in the present investigation was aluminium alloy 2024. Refer to Table 1 for its chemical composition. The alloy was received in the T351 temper condition, in sheet form of 1.6 mm thickness.

Mechanical testing specimens have been machined from material samples which have been painted first with a white polyurethane paint, 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. After machining, the specimens have been stripped from paint using the processes described below.

2.2. Specimen paint stripping processes

Specimen paint stripping has been carried out with the following techniques:
1. laser radiation with an excimer laser source [6];
2. laser radiation with a CO₂ laser source [7];
3. laser radiation with an Nd-YAG laser source [8];
4. laser radiation with a TEA-CO₂ laser source [6];
5. plasma etching [9].

<table>
<thead>
<tr>
<th>Table 1</th>
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<tbody>
<tr>
<td><strong>Chemical composition (in wt%) of 2024 aluminium alloy</strong></td>
</tr>
<tr>
<td>Si</td>
</tr>
<tr>
<td>---</td>
</tr>
<tr>
<td>0.10</td>
</tr>
</tbody>
</table>
The applied processes as well as the experimental set-ups used for stripping the specimens are described extensively in [6-10]. The set-ups used for laser paint stripping involve a laser source capable of traveling in 2 dimensions over the sample surface as well as a micropositioner guided by a micropositioning controller. The latter is linked to the laser source via a personal computer. The set-up described in [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 strip up to the desired material surface layer, i.e. up to the primer or up to the blank material surface.

Plasma etching specimen paint stripping has been performed using the experimental set-up described in [9]. Stripping occurs in a plasma chamber. Adjustable parameters are the gas composition, the process pressure, the power as well as 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 made for all processes referred to above. To evaluate paint stripping quality the valid aircraft quality assurance specifications have been considered. Notice that the referred specifications take no account of a possible substrate material degradation. To strip the specimens optimized process parameters have been applied.

2.3. Mechanical testing

Following the stripping process the specimens have been subjected to mechanical testing. To obtain reference mechanical behavior all types of mechanical tests considered in the present investigation have also been performed using specimens from as-received 2024 T351 material. All tests have been performed under controlled laboratory conditions on an MTS 810 testing servohydraulic machine. Tensile tests were carried out according to the ASTM E8M specification, using a constant deformation rate of 10 mm/min. To obtain fracture toughness the procedure suggested in [11] have been followed.

According to the procedure referred to the CT specimen was placed in an anti-buckling device because of the 1.6 mm thickness of the specimen. The specimen has been subjected to tension with a constant load rate of 4.32 kN/min and the energy release rate $G$ can be calculated from the following simple formula:

$$G = \frac{AF(a_0/W)}{bbB},$$

in which $A$ is the area under the applied load versus load line displacement, $F(a_0/W)$ is a correction factor, $b$ is the initial uncracked ligament and $B$ is the specimen's thickness.

The value of $G$ can also be related to an equivalent fracture toughness $K_R$ as

$$G = aK_R^2/E.$$ (2)

In Eq. (2) $a$ is a constraint factor varying between 1 for plane stress conditions and 0.9 for plane strain conditions and $E$ is the effective elastic modulus calculated using the initial linear region of the load versus load-line displacement record.

Fatigue testing has been performed according to the specification ASTM E-466. Each specimen was subjected to axial fatigue loading with a frequency of 25 Hz and stress ratio $R = 0.1$.

3. Discussion of results

3.1. Tensile and toughness test results

Referring to the derived nominal stress–strain curves, the properties yield stress $S_{y0.2}$, ultimate tensile stress $S_u$, elongation to failure $A_{50}$ and energy density $U$ have been evaluated. Here, with $U$ is defined the quantity

$$U = \int_{0}^{A_{50}} S \, d\varepsilon.$$ (3)

Obtained tensile test results for stripped and reference specimens are summarized in Table 2. In the table, each value is the average derived of 3 to 7 tensile tests. Fig. 1 displays the variation of the tensile properties for the various paint stripping processes as a percentage to the tensile properties of the reference condition.
Table 2
Tensile properties of paint-stripped specimens

<table>
<thead>
<tr>
<th>Stripping process</th>
<th>Yield stress (S_{\sigma,2}) (MPa)</th>
<th>Ultimate tensile stress (S_u) (MPa)</th>
<th>Elongation to fracture (A_{50}) (%)</th>
<th>Energy density (U) (10^{-3}) J/mm(^3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference</td>
<td>330</td>
<td>483</td>
<td>17.68</td>
<td>78.75</td>
</tr>
<tr>
<td>TEA-CO(_2) laser</td>
<td>314</td>
<td>475</td>
<td>16.40</td>
<td>73.37</td>
</tr>
<tr>
<td>CO(_2) laser</td>
<td>314</td>
<td>474</td>
<td>13.1</td>
<td>59</td>
</tr>
<tr>
<td>YAG laser</td>
<td>323</td>
<td>475.5</td>
<td>12.85</td>
<td>56.31</td>
</tr>
<tr>
<td>Excimer laser</td>
<td>320.5</td>
<td>473</td>
<td>11.6</td>
<td>52</td>
</tr>
<tr>
<td>Plasma etching</td>
<td>330.9</td>
<td>463</td>
<td>3.08</td>
<td>14.33</td>
</tr>
</tbody>
</table>

From the data of Fig. 1 it is evident 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 down to 66% of the reference value with the use of the excimer laser, to 72–75% with the use of CO\(_2\) and YAG lasers and to the very low value of 22–24% for the plasma etching. In contrast with the other processes the TEA-CO\(_2\) did not affect the ductility properties appreciably.

The toughness properties in terms of \(G\) and \(K_R\) values are given as a function of the paint stripping process in Table 3. In Table 3 all values are mean values corresponding to 3 fracture toughness tests. Fig. 2 shows the variation of the toughness properties for the various paint stripping processes as a percentage to the toughness properties of the reference condition. \(G\) values are reduced down to 67–70% of the initial values for YAG laser, plasma etching and excimer laser while there is a lower reduction down to 77% of the initial value associated with the use of the CO\(_2\) laser. The results for the fracture toughness value show the same trend as the \(G\) values.

Summarizing the above results, yield stress and ultimate tensile strength have not been appreciably affected by none of the considered paint stripping processes; tensile ductility and toughness have been more or less severely degraded. According to the data shown in Figs. 1 and 2 the quantity of energy density has been proved as most capable to reflect the material response to the loads associated to the applied processes.

The obtained material embrittlement is not intuitively understandable. However, a similar behavior has been recently reported in [12] for the case of
Table 3
Toughness properties of paint-stripped specimens

<table>
<thead>
<tr>
<th>Stripping process</th>
<th>$G$ (kJ/m²)</th>
<th>Equivalent $K_R$ (MPa√m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference</td>
<td>127.83</td>
<td>96.50</td>
</tr>
<tr>
<td>TEA-CO₂ laser</td>
<td>162.76</td>
<td>111.05</td>
</tr>
<tr>
<td>CO₂ laser</td>
<td>97.92</td>
<td>83.69</td>
</tr>
<tr>
<td>YAG laser</td>
<td>88.89</td>
<td>81.55</td>
</tr>
<tr>
<td>Excimer laser</td>
<td>85.06</td>
<td>81.69</td>
</tr>
<tr>
<td>Plasma etching</td>
<td>89.40</td>
<td>80.34</td>
</tr>
</tbody>
</table>

2024-T3 and two advanced Al–Li alloys subjected to several corrosive environments. In [12] the obtained embrittlement was attributed to hydrogen produced during the corrosion process. It is likely that the paint stripping processes under consideration result in hydrogen production due to bond dissociation in the hydrocarbon paint layer. However the latter statement should be further investigated and experimentally confirmed. As far as the lasers are concerned, the infrared lasers (TEA-CO₂, CO₂ and YAG) result in lower degradation in tensile ductility than the ultraviolet excimer laser. With regard to the mentioned hydrogen embrittlement hypothesis this difference could be attributed to the thermal/pyrolytic action of the infrared lasers relative to the chemical/photolytic action of the ultraviolet excimer laser. Plasma etching is associated with higher chemical action than the excimer laser and results in higher degradation in tensile ductility.

From the viewpoint of the obtained degradation in tensile ductility and toughness the paint stripping processes may be ranked according to the percentage decrease from the reference value. This ranking generally gives the sequence TEA-CO₂ laser, CO₂ laser, YAG laser, excimer laser and plasma etching, with the TEA-CO₂ giving the lowest and plasma etching the highest property degradation for the processes investigated.

3.2. Fatigue test results

The cycles to failure at the specified maximum stress levels for all the paint stripping processes examined as well as for the reference material appear in Fig. 3 in the form of the $S-N$ diagram. The solid line in Fig. 3 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 paint stripping process and stress amplitude level.

At high stress levels (300 MPa) there is no appreciable effect of paint stripping processing beyond the
expected experimental error, regardless of the processing method used (laser or plasma), with the exception of TEA-CO\(_2\) which improves significantly the fatigue life.

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

At intermediate stress levels (250 MPa) there is also a significant extension of fatigue life associated with paint stripping processes, with the YAG and TEA-CO\(_2\) laser providing the best fatigue performance in this case.

It should be mentioned that TEA-CO\(_2\) results in a consistent fatigue life improvement at all stress levels employed.

An initial effort to rationalize the observed behavior should include (a) the effect of applied stress amplitude and (b) the effect of paint stripping process.

### 3.2.1. Effect of stress amplitude

In high cycle fatigue (HCF) total fatigue life is controlled by fatigue crack initiation rather than by crack propagation. Crack initiation results from failure on the alloy surface. The conditions for fatigue failure initiation have been discussed in [13,14]. With regard to [13–15], it is evident that crack initiation depends severely 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. Previous work on excimer laser surface treatments of aluminium alloys [16] has shown a polishing effect associated with the photo-etching action of the excimer laser. In [17] excimer laser surface treatment has introduced compressive residual stresses at the surface of laser treated aluminium alloys. Both effects are beneficial towards increasing fatigue life. It is expected that these effects also operate in the case of laser or plasma paint stripping under investigation. At high stress amplitudes, the fatigue crack initiation process zone exceeds the area modified by the paint stripping processes. Therefore the paint stripping processes have no appreciable effect on fatigue life. However, 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.

### 3.2.2. Effect of paint stripping process

The experimental results suggest that at low stress amplitudes a longer fatigue life extension is associated with CO\(_2\) laser processing, while at intermediate stress amplitudes it is the treatment with the excimer laser that results in longer fatigue life. It is believed that this difference in behavior is associated with the fact that the CO\(_2\) laser emits in the infrared (IR) while the excimer laser emits in the ultraviolet (UV). 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. The excimer laser has better absorptivity and coupling with the metal surface but the effects are limited to a very thin surface layer. Therefore, the effect of the excimer laser is prominent at intermediate stress amplitudes, where the fatigue crack initiation process zone is comparable to the excimer laser modified surface zone.

To clarify the above considerations, more experimental work is needed in the areas of residual stress measurements, roughness and microhardness evaluations. This work will be presented in a future paper.
Notice that the beneficial effect of the paint stripping processes on fatigue life should always be considered in conjunction with the obtained embrittlement of the material. The expected fatigue benefit might turn into a disadvantage when considered for structural analysis in situations where crack initiation is not essential. In addition, this benefit can not be made manageable when concluding for the fatigue life of structures on the basis of fatigue models which do not delve into damage initiation and focus attention on the growth of a dominant crack at the critical locations.

4. Conclusions

The mechanical behavior of aluminium alloy 2024 T351 was assessed after paint stripping with CO$_2$ laser, Nd-YAG laser, TEA-CO$_2$ laser, excimer laser and plasma etching techniques. The experimental results showed the following:

- There is no significant effect of the paint stripping processes on the yield stress and the ultimate tensile strength of the 2024 aluminium alloy.
- There is a significant degradation in tensile ductility. The highest degradation results from the use of the plasma etching technique and excimer laser. The lowest degradation results from the use of the infrared YAG and CO$_2$ lasers. In addition, there is a significant reduction in toughness which is consistent with the reduction in tensile ductility.
- There is no degradation in fatigue properties by the application of the investigated paint stripping techniques. There is a considerable extension in fatigue life, which depends on the stress amplitude in conjunction with the stripping process applied. At high stress there is no appreciable effect with the exception of TEA-CO$_2$ which improves fatigue life considerably. At low stress there is an order of magnitude extension associated with CO$_2$ laser paint stripping. At moderate stresses, there is an up to sixfold life extension associated with the excimer laser processing. It is believed that the beneficial effect of paint stripping processing is associated with surface modification, most important factors being the surface roughness, the surface layer plastic flow behavior and residual stresses.

- The obtained fatigue life benefits should be evaluated in conjunction with the embrittlement (fracture toughness decrease) associated to the stripping processes when exploited for fatigue analyses.
- Application of paint removal techniques associated to mechanical or thermal loads of the structure under stripping might yield to degradation of the properties which have been used for structural design. It calls for a reconsideration of aircraft quality assurance specifications when using the mentioned techniques in aeronautical procedures such as maintenance and repair.

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References


