FAILURE ANALYSIS OF THE TITANIUM ALLOY HORN USED IN ULTRASONIC PROCESSING OF POLYMERIC MATERIALS IN THE AUTOMOTIVE INDUSTRY

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Abstract
This paper analyzes a particular case of micro-cracking and breaking of a titanium alloy (titanium grade 2) horn used for ultrasonic processing of polymeric materials in the automotive industry. The specialized ultrasonic equipment, working at 20 kHz frequency (20,000 oscillations per second) and with an output power of 2500 Watt was used for joining car armrests.

The mechanical stresses to which the titanium alloy horn has been submitted, the usage time and/or its improper exploitation lead, after 6 months, to the emergence of micro-cracks. Their propagation in the maximum amplitude plane of the horn has caused its disuse.

The paper presents macro-structural characterization of the material fracture area, design and manufacturing process of the ultrasonic assembly components by using specialized software (C.A.R.D.), material choosing criteria, frequency and amplitude required in order to obtain strong joints and recommendations for increasing lifetime and safe use of the ultrasonic components.

Keywords:
Ultrasounds, titanium horn, joining process, micro-cracking

1. INTRODUCTION
Titanium and its alloys possess many beneficial characteristics including excellent mechanical properties, unrivalled corrosion resistance and outstanding biocompatibility. This is why their usage is found in many different fields varying from industrial and automotive to medical and consumer applications [1].

Crack initiation is a term used differently by scientists studying fatigue in the laboratory and engineers designing and maintaining structures. To the scientist, initiation is the number of cycles required to generate, nucleate, or form the smallest crack that they can detect by any means [2].

The materials failure including wear, corrosion and fatigue is well known to be dependent on the material surface state [3].

To gain insight into the interaction between foreign object damage and fatigue behaviour, a number of experimental and computational studies have been carried out in the last decade. The analysis of fatigue behaviour due to foreign object damage is a complex topic, which brings together impact mechanics, fracture mechanics and fatigue analysis [4].

2. EXPERIMENTAL
In order to analyze the micro cracking of the horn used for polymer ultrasonic joining, it is important to know the characteristics of the material employed for manufacturing the horn, its design, execution and characterization in terms of shape, dimensions and loadings arising in the material submitted to ultrasonic
micro vibrations and also to present some data about the equipment used during polymer ultrasonic bonding in the automotive industry.

2.1 Material – Titanium grade 2

Materials used for manufacturing the ultrasonic assembly parts must hold a number of qualities, taking into account the environment and the loadings at which they are subjected.

The material used for manufacturing the horn represents a compromise between ultrasonic and application needs. Materials employed are characterized by low internal friction, so that they oppose low inertia to vibration transmission, causing at the same time minimum amortization of these vibrations. So far, high strength and low internal friction titanium is considered the best material in horn manufacturing. Besides titanium, other materials employed are: titanium alloys (TiAlV64), steel, stainless steel, strong ceramics, aluminum and its alloys (AlCuMg2, AlCuMgPb, and so on). Many other materials can be used but with high risk of power loss. It is also noted that the application can dictate the type of material employed for manufacturing the ultrasonic assembly parts.

The material used in the project is titanium grade 2 alloy in cylindrical form. Physical, mechanical and chemical properties of the titanium grade 2 alloy at room temperature are presented in table 1 [5].

Table 1. Physical, mechanical and chemical properties of the TiGr2 alloy

<table>
<thead>
<tr>
<th>Physical properties</th>
<th>Mechanical properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>4.51 g/cc</td>
</tr>
<tr>
<td>Hardness, Rockwell B / Vickers</td>
<td>80 / 145</td>
</tr>
<tr>
<td>Tensile Strength, Ultimate</td>
<td>344 MPa</td>
</tr>
<tr>
<td>Tensile Strength, Yield</td>
<td>276 – 448 MPa</td>
</tr>
<tr>
<td>Elongation at Break</td>
<td>20 %</td>
</tr>
<tr>
<td>Reduction of Area</td>
<td>30%</td>
</tr>
<tr>
<td>Modulus of Elasticity</td>
<td>103 GPa</td>
</tr>
<tr>
<td>Compressive Modulus</td>
<td>110 GPa</td>
</tr>
<tr>
<td>Poissons Ratio</td>
<td>0.37</td>
</tr>
<tr>
<td>Fatigue Strength</td>
<td>300 – 425 MPa</td>
</tr>
<tr>
<td>Fracture Toughness</td>
<td>66 MPa-m½</td>
</tr>
<tr>
<td>Shear Modulus</td>
<td>45 GPa</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Chemical properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Titanium, Ti</td>
</tr>
</tbody>
</table>

2.2 Ultrasonic horn

Horn design as well as the whole ultrasonic joining equipment must take into account the industrial application for which it is built, i.e. optimal choice of mechanical and electrical characteristics, shape and size of the entire ultrasonic joining equipment.

The specialized horn design was fulfilled by means of dedicated software (CARD). Given the horn material and generator features, application and all ultrasonic assembly components particularities, the horn form and dimensions were delivered by CARD together with its overall characterization (variation chart of mechanical oscillation amplitude along the horn and internal stress variation...
graphic along the TiGr2 horn). Special attention was paid to the horn micro cracking initiation area and later to its failure and decommissioning.

Figure 1 shows the horn shape and dimensions, main stresses graphics and values (vibrations amplitude and internal stress) in the horn failure plane - red dotted area at 112 mm from the horn bottom.

![Horn Shape and Dimensions](image)

**Fig. 1** Horn characterization by simulation using the CARD program:

- a – Variation of the relative amplitude along the horn length
- b - curve of variation of internal stress along the horn length
- c – Design and shape of the horn

The theoretical characterizations of horn obtained by simulation and used in the experimental program are presented in Table 2 and in figure 2 is presented de ultrasonic assembly after designing in specialized software.

**Tab. 2** Horn characterization

<table>
<thead>
<tr>
<th>Component</th>
<th>Specialized Horn</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material type</td>
<td>Aliaj TiGr.2</td>
</tr>
<tr>
<td>Sounds velocity [m/s]</td>
<td>4618</td>
</tr>
<tr>
<td>Horn length [mm]</td>
<td>142</td>
</tr>
<tr>
<td>Resonance frequency [kHz]</td>
<td>20</td>
</tr>
<tr>
<td>Horn gain / Quality factor $Q$</td>
<td>3,05/26000</td>
</tr>
<tr>
<td>Coordinate of oscillation node [mm]</td>
<td>54,8</td>
</tr>
<tr>
<td>Maximum stress [MPa/mm] At 78/122</td>
<td>78/122</td>
</tr>
<tr>
<td>Total strain energy [Joules] At 1.73x10^-4</td>
<td>1.73x10^-4</td>
</tr>
<tr>
<td>Dissipated power [Watt] output</td>
<td>8,4x10^-4</td>
</tr>
</tbody>
</table>

2.3 Equipment for ultrasonic joining

Previous cooperation approached a wide range of ultrasonic joining applications for different types of materials such textile reinforced plastics bonded to a polymeric support.
The plastic support - polypropylene (PP), polycarbonate (PC) or acrylonitrile-butadiene-styrene (ABS) – represents the base material of the assembly over which the cover material - artificial leather (polymer with textile fiber) - is inserted by means of special adhesive and ultrasonic edge bonding. This ultrasonic strengthening operation is specific to the armrest manufacturing in automotive industry. Figure 3 shows a car armrest covered with ecological leather which was ultrasonic edge bonded, while Figure 4 presents the specialized ultrasonic equipment for polymeric materials joining which has performed these bonds.

3. RESULTS AND DISCUSSION

3.1 Effect of frequency

Working frequency is dictated by the application to be performed and by the frequency of the ultrasonic generator available. Lowest frequency used is usually 20 kHz. At this frequency, energy transfer and activation efficiency are optimal. Effect of the mechanical micro-vibrations, in time, can
lead to damage by fatigue of the horn (sonotrode). The material and design of the horn were chosen in order to resist at least 2 years in normal work conditions.

3.2 Effect of the damage on the horn surface
Macroscopic analysis of the horn failure surface attests the fatigue failure characterized by parallel propagation steps (Figure 5.a), while the detail view from Figure 5.b highlights a fragile area which basically represents the horn final failure.

![Image]

**Fig. 5** Macroscopic analysis of the horn failure:
- a - breaking area at the horn surface of titanium alloy (TiGr2.)
- b - detail breaking area the horn surface of titanium alloy (TiGr2.)

An imperfection – pinch - (red dotted area in Figure 1), occurred due to improper handling of horn, was detected on its surface at 112 mm distance from the bottom. This pinch, while subjected to micro vibrations of ultrasonic frequency (20kHz - 20,000 oscillations per second), amplitude in failure plane of 69µm and internal tensions of 68N/mm² determined the crack initiation and lead to the failure of the horn (Figure 6) as initial failure.

![Image]

**Fig. 6** Imperfection at the horn lavel

Samples surfaces from Figure 7 highlight that 70% of the total failure area is characterized by fatigue failure, while 30% by brittle fracture.

![Image]

**Fig. 7** Macroscopic analysis of the horn surfaces in the failure area:
- a – corresponding macroscopic view from the top sonotrode area;
- b - corresponding macroscopic view from the base horn area.

Under these conditions, it can be said that the ratio of 0.73 between brittle fracture and fatigue failure is high, fatigue failure being the main cause of horn degradation.
4. DISCUSSION
Material from which the horn has been manufactured as well as its shape and dimensions, were correctly chosen, taking into account the loadings to which it has been subjected. TiGr2 tensile strength (344MPa) was higher than the maximum one obtained by simulation load (78MPa), while the vibration amplitude was high enough (90µm / 2500W) to achieve resistant bonds.

Horn failure occurred after 6 months of operation during normal working hours (8 hours/day) with a productivity of 50 armrests made in an hour. The failure was not obtained as a result of normal use of the sonotrode (optimum welding parameters and appropriate handling of all equipment), but because of its misuse. A defect (pinch), as a result of an accidental collision with an extremely hard object, was detected on the outer surface of the sonotrode, at a distance of 112mm from the its bottom and caused the failure of the sonotrode and its decommissioning. This pinch, initially manifested on a 1.48mm area of and then on the whole section of the TiGr2, represented the concentrator needed by the sonotrode so that the micro cracking and then the material failure could occur for the ultrasonic joining application characterized by a frequency of 20,000Hz (equivalent to 20,000 oscillations per second) and an equivalent amplitude of 69µm in the pinch plane. In normal work conditions, for ultrasonic applications, breaking fatigue is possible to manifests in the top area of sonotrode, in the tread pattern area there where the vibration amplitude is maximum.

5. CONCLUSION
Not only appropriate choice of the ultrasonic generator materials and components is of great importance for ultrasonic active applications, but also their machining (all exterior surfaces of ultrasonic assembly parts mustn’t have right angles, while their roughness - Ra - must be at least 1.6 µm), operation and maintenance.

In the present application, micro cracking and later cracking and sonotrode decommissioning didn’t occur due to inappropriate choice of material or ultrasonic generator characteristics, resonant frequency amplitude or sonotrode usage time, but as a result of sonotrode misuse in operation, which calls for better training of technical personnel.

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LITERATURE