FATIGUE CHARACTERIZATION OF ALUMINIUM WELDED JOINTS

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ABSTRACT
This contribution deals with the fatigue characterization of aluminium welded joints for automotive applications. The base material is a vacuum casting alloy, whereas the joints have been hand welded by means of the TIG process. The joint category is a butt-welded type, one side only, full penetration without backing. The samples have been tested both in tension-tension and in bending. Tests results have been processed according to the ISO 12107 standard: SN curves have been retrieved as well as the endurance limit of the joints at \(5 \times 10^6\) cycles.

Keywords: fatigue, aluminium, weld, vacuum casting alloy.

INTRODUCTION
Aluminium vacuum die-casting alloys find typical applications in the automotive field, to be used in manufacturing space frame nodes, automotive front cross members, suspension arm axles, connecting rod and rocker arms. The wall thickness for many of these components, ranges from 2 to 5 mm.

The vacuum die-casting process, (e.g. commercially known as Vacural\(^\text{TM}\)) consists of the following steps: (i) degassed metal is drawn into the shot chamber through a suction tube under vacuum; (ii) vacuum is applied to the die: this allows achieving a minimal gas entrapment in the casting, so that the castings can be heat treated for enhanced strength and ductility; (iii) die faces are sealed in order not to allow air entering the cavity [1]. Nonetheless, these alloys are still seldom used when welding operations need to be performed to obtain the finished component.

The present paper aims at investigating the fatigue performances of welded joints realized on vacuum die-casting aluminium base metal since the industrial interest towards the use of such alloys in components comprising welded joints is steadily increasing.

The specimens used for the experimentation are made of two halves of a dogbone shaped plate, joined along a transverse section placed at half span of the gage length. The two halves are butt-welded on one side only with full penetration without backing, as shown in Fig. 1. Fatigue tests have been carried out both in tension-tension (R=0.1) and in bending (R=-1) condition. Both the SN curves and the endurance limit of the specimens for the two load cases have been retrieved. The test results have been compared with the fatigue data provided by UNI EN 1999-1-3:2007 standard [2] for the same detail category: it is important to remark that such a standard is only relevant to welded components manufactured with wrought aluminium alloys.
MATERIALS AND METHODS

According to Standard [2], in the case of a constant amplitude load cycle, the endurance limit for aluminium welded joints is set at $5 \times 10^6$ cycles. According to Standard [3], the statistical estimation of fatigue strength at a given fatigue life must be carried out by means of a “staircase method”, which requires at least 15 specimens for exploratory tests and at least 30 specimens for reliability data. Moreover, the determination of the SN curve requires a minimum of 8 specimens for exploratory testing. In fact, it is recommended that two specimens be tested at each of four equally spaced stress levels. In order to comply with the aforementioned suggestions, even if limited to the case of exploratory data, testing must be performed as quickly as possible. The Rumul Mikrotron 654 produced by Russenberger Prüfmaschinen AG (Fig. 2) is a resonant testing machine suitable for loads up to 20kN, capable of testing frequencies of about $f=115\text{Hz}$ for a test piece with a mass like that of the specimens under investigation. Such a testing frequency allows reaching the runout limit ($5 \times 10^6$) in about 12 hours, without significantly affecting the results in terms of fatigue strength at a given life [4 - 6].

Fig. 2 - Rumul Mikrotron 654 at the testing facility (University of Bologna)
Fatigue tests have been carried out both in tension (R=0.1) and in bending (R=-1), the total number of samples at R=0.1 is \(n_{0.1}=36\) while that at R=-1 is \(n_{-1}=30\). Each load configuration required 15 specimens for the determination of the fatigue limit; the remaining specimens have been used for drawing the SN curve. All the specimen blanks (halves) have been extracted by milling finished motorcycle cast components, as shown in Fig. 3. It is worth noting that the need to extract the specimens from finished components poses a constraint to their maximum thickness, which is limited to \(t_{\text{max}}=5\text{mm}\).

![Fig. 3 - Extraction of the specimen blanks from a finished component](image)

Then, the halves have been joined by a TIG manual welding process and then reworked in order to obtain the gage section: no subsequent grinding operation has been done. For specimens to be tested in bending, the planarity of the side surfaces at the grip area is of paramount importance in order to avoid any undesired prestressing of the specimen (Fig. 4): for this reason, all the bending specimens have been reworked after welding, only at the grip side surfaces.

![Fig. 4 - Misalignment of a welded bending specimen](image)

The specimens dimensions are reported in Tab. 1. All the specimens have been inspected for non-conformities upon arrival at the testing facility: all the relevant data have been stored in a datasheet. For instance, the actual thickness value has been recorded for each specimen, in order to allow an individual adjustment of the load imposed by the testing device for each specimen, so as to achieve the exact remote stress value. The values reported in Tab. 1 for the thicknesses are intended as an average calculated over the batch.
Tab. 1 - Specimens characteristic dimensions

<table>
<thead>
<tr>
<th></th>
<th>Bending</th>
<th>Tension</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness (mean)</td>
<td>4,50 mm</td>
<td>4,90 mm</td>
</tr>
<tr>
<td>Width at grip</td>
<td>24 mm</td>
<td>30 mm</td>
</tr>
<tr>
<td>Grip length</td>
<td>50 mm</td>
<td>45 mm</td>
</tr>
<tr>
<td>Radius</td>
<td>10 mm</td>
<td>15 mm</td>
</tr>
<tr>
<td>Width at gage</td>
<td>20 mm</td>
<td>15 mm</td>
</tr>
</tbody>
</table>

The testing procedure for the tension specimens is quite straightforward [7-8] and will not be described further. As for the bending tests, these had to be performed by means of a special four point bending fixture, provided by the same manufacturer of the test stand. Such fixture is represented in Fig. 5: a pilot specimen (without weld) is visible inside the fixture.

The specimen is clamped at four points placed along the grip length. The two elements indicated by the arrows in Fig. 5 are leaf springs which allow the clamps behaving like simple supports: in other words, thanks to their flexibility, they allow for rotations of the specimen sections along the axis normal to the view plane. It is worth noting that, due to the combination of material strength and load cell range, the specimens have to be loaded in such a manner that the bending moment acts along the first principal inertia axis of the section. The clamping force is provided by two M10 8.8 hexagon socket head screws for each point: normally, these screws are tightened under torque control. The actual preload of a screw is related to the tightening torque through the coefficients of friction of the joint [9-11]. Since the coefficients of friction are, in this case, unknown, the final preload force acting on the specimen cannot be determined. In the case of an excessive clamp preload, the specimen may undergo significant deformation right after tightening, especially in the vicinity of the radius. An FEA better clarifies such occurrence: the analysis has been run by means of the Ansys code V.17. Fig. 6 shows the boundary conditions of the problem. It consists of a plane stress model, having a double symmetry at edges B and C and a total node count of n=1500 nodes. The elements are 8 node quadratic, called PLANE183 in the Ansys nomenclature. By applying a downwards directed vertical load F_y=10kN at the contact surface between the specimen and the inner clamp, which roughly corresponds to a tightening torque of T=20Nm (assuming μ_m=0.15), a peak normal stress σ_x≈31MPa arises at the radius, as shown in Fig. 7. Such a stress level is not negligible with respect to the fatigue loads to be imposed during testing, therefore a method to control the actual preload force must be implemented. It must
be noted, however, that just the preload force generated by the two inner clamps has an effect on the stresses at the radius. In fact, the stresses induced by the preload of the external clamps is extinguished at an abscissa far enough from the radius. Based on the results shown in [10, 12] a set of four instrumented sleeves has been introduced under the head of the inner clamps screws. Such a device allows to control the actual preload during tightening: the knowledge of the friction coefficient is no longer needed.

Fig. 6 - FEA for the evaluation of the clamp load effect on $\sigma_x$ stresses: boundary conditions

Fig. 7 - FEA for the evaluation of the clamp load effect on $\sigma_x$ stresses: stress plot at $F_v=10kN$

Fig. 8 - (a) Instrumented specimen and (b) instrumented sleeve for screw preload control: constant stress area
In order to double check the outcomes of the numerical analysis, and to establish a preload threshold under which no significant effect on the stresses of the test piece is expected, an experimentation has been run on a instrumented specimen, in combination with the aforementioned instrumented sleeves. The specimen has been instrumented by means of two strain gauges, (Vishay LY13, 6mm grid, 120Ω) placed at the radiused surface, as shown in fig. 8 (a). Fig. 8 (b) represents the stress plot on the instrumented sleeve when a preload $F_y=10\text{kN}$ is applied to the M10 screw. It can be seen that, at an axial distance of about 5mm from the underhead contact surface, the axial stress distribution is nearly constant: according to this observation, the strain gauge (Vishay LY13, 6mm grid, 120Ω) has been mounted at half the length of the sleeve. The experimentation proceeds as follows: (i) the specimen is placed inside the fixture, (ii) zero calibration is performed on the specimen and sleeves strain gauges, (iii) the internal screws are tightened, controlling the actual preload by means of the sleeve reading, (iv) the external screws are tightened by means of a torque wrench, (v) the strain along the longitudinal axis of the specimen is read. It can be concluded that, in the presence of a screw preload of about $F_y=1.5\text{kN}$ ($\approx 65\mu\varepsilon$ compressive strain at the sleeves) the stresses at the specimen remain below $\sigma_x\approx 2\text{MPa}$, which can be considered negligible. Therefore, for the whole experimentation, the specimens have been mounted on the bending fixture by controlling the actual preload force, setting a target sleeve reading of $65\mu\varepsilon$.

**RESULTS AND CONCLUSIONS**

The results from the tensile and bending fatigue test are shown in Fig. 9. The SN curves have been plotted in the interval $10^4$ - $5\cdot10^6$ cycles. The inverse slope of the experimental $\Delta\sigma$-$N$ curve is $m_1=4.5$ for the tension load case. As for the bending load case, the inverse slope of the experimental $\Delta\sigma$-$N$ curve is $m_1=3.55$.

![SN curves for tension (thick lines) and bending (thin lines) load cases.](image)
The SN data provided by Standard [2] for the same detail category are in good agreement with the data reported in Fig. 9 for the tension load case, whereas the curves relevant to bending suggest noticeably higher strength values for given life. Fig. 10 reports two fracture surfaces: (a) relevant to a tension specimen, failed at $n=224,700$ cycles, and (b) relevant to a tension specimen failed at $n=137,500$ cycles. Both sections show a considerable number of cavities on the reinforcement of the weld bead, while an attentive examination of the surfaces reveals how the initiation site is often placed at the weld root.

As mentioned in the introduction, the constant amplitude fatigue limit $\Delta \sigma_D$ is set at $5 \cdot 10^6$ cycles, according to Standard [2]. The results of the present experimentation show that the fatigue limit of the bending specimen is notably higher than that of the tension specimen ($\Delta \sigma_D_{\text{bending}} \approx 2.5 \Delta \sigma_D_{\text{tension}}$). Such occurrence may in part be ascribed to the favourable stress gradient which characterizes the former load case. Nonetheless, as the intensity of the gradient effect usually falls inside the range 10% to 30% [13], it cannot explain the whole difference if considered alone.

Hence, future developments of this work will deal with:

(i) a FEA assessment of the theoretical stress concentration factors $K_t$ at the weld root and toe: the results for the cases of tension-tension and bending will be compared;

(ii) a thorough analysis of the stresses induced on the specimen during bending tests, by means of a dynamic sampling apparatus.

Such investigations should help defining the factors responsible for the great difference in terms of stress-life relationship for the two load cases.

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