EVALUATION OF THE FATIGUE RESISTANCE OF ALUMINUM ALLOY COMPONENTS USED IN THE AUTOMOTIVE FIELD
-SUMMARY-

Thesis for the scientific degree of Doctor of Engineering at the Politehnica University of Timişoara in the field of Mechanical Engineering by

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The **first chapter** presents the justification for the choice of the topic, taking into account the fact that aluminum alloys have an increasingly wide applicability in many areas of industrial activity.

One of the components used in the construction of motor vehicles is the pipe; it is used in the construction of support frames as well as for the transport of gases or fluids between various subassemblies. The connection between the vehicle's fuel tank and the elements of the fuel system located in the engine compartment is made with pipes. The cooling system of the internal combustion engine circulates the coolant between the engine block - cylinder head assembly and the cooling radiator through pipes. In the air conditioning system, the transport of the coolant between the compressor and the heat exchanger is done through pipes. The cooling radiators as well as the compressed air dryers in the truck braking system are made of pipes.

In most of the situations presented above, in addition to the fact that the inside of the pipes can be subjected to the corrosive action of the transported fluid, the material from which the pipe is made being chosen so as to have an optimal behavior in this situation, due to the vibrations transmitted to the vehicle body during operation, the pipes are subjected to an additional mechanical stress that leads to their cracking or breaking in the area of the fixing elements on the body, in the area of the clamping flanges or in various other areas depending on their geometry.

The research carried out worldwide on the behavior of pipes made of aluminum alloys presented in the **second chapter** shows the importance given to this research topic.

During their lifetime, products made of aluminum alloys face difficult cyclic loading conditions as a result of the influence of factors such as high temperature, friction or vibration under the action of disruptive forces, fatigue failure being predominant in approximately 80% of their failure cases.

Therefore, investigating the fatigue resistance of these products by various experimental methods has become increasingly important, as evidenced by numerous researches in the field.

This chapter presents:

- Fatigue testing of 7050 aluminum alloy pipes
- Fatigue testing of D16T aluminum alloy pipes
- Fatigue testing of welded pipes made of extruded aluminum alloy 6082-T6
- Fatigue testing of 6063-T5 aluminum alloy pipes
- Fatigue testing of 6063 aluminum alloy pipes with initial crack
- Quasi-static compression of 6063-T5 aluminum alloy pipes

The **third chapter** presents the International Standards of Aluminum Alloys that highlight the minimum characteristics that these materials must meet in order to be used at optimal parameters.

ISO standards are standards developed and published by the International Organization for Standardization, a world federation of national standardization bodies and are widely used in industry and research laboratories, being recognized worldwide. In contrast, ASTM (American Society for Testing and Materials) is a non-profit organization that develops and publishes technical standards for a wide range of materials, products, systems and services, being used mainly in the United States of America, but are also recognized globally.

There are also other standards such as ANSI – American National Standards Institute, DIN – Deutsches Institut für Normung, GOST – used by the Euro-Asian Council for Standardization, etc., but they have a lesser use.

A given material with distinct properties may be characterized in any of these standards but under different names, with a correspondence between them. Table 3.1 shows the correspondence for aluminum alloys in the case of ISO and ASTM standards.

The development of international standards is carried out through ISO technical committees, in which international, governmental and non-governmental organizations participate in their drafting in collaboration with ISO. The procedures used for the development of documents as well as those intended for their subsequent maintenance are described in the ISO/IEC Directives, Part 1, noting the different approval criteria required for the different types of ISO documents. Table 3.2 shows the mechanical properties of aluminum alloys according to ISO 6362-2.

The ISO 3522 standard specifies the permissible limits for the chemical composition of aluminum alloys obtained by the casting process, for its application making reference to the following ISO standards. Table 3.3 presents the chemical composition of aluminum alloys obtained by the casting process.

According to ANSI H35.1, EN 515 and ISO 2107 standards, after the basic name of the alloy, several characters can be assigned that define in detail the states of the aluminum alloy, these being presented in Table 3.4.

A first method of investigation prior to fatigue testing is the static characterization presented in **chapter four**. By accurately determining the characteristic curves of a sample taken from a product, the mechanical characteristics of the material used are highlighted.

In order to define the behavior of a material when it is stressed, it is first necessary to draw the characteristic curve that defines the relationship between the stress δ and the specific deformation ε.

The pipes in the car air conditioning system that we chose for the study are made of 3103 aluminum alloy, the first batch having an outer diameter of 12 mm and the second batch with an outer diameter of 18 mm. The pipes with a diameter of 18 mm were divided into three groups depending on the shape and dimensions of the mounting flange on the air conditioning compressor as well as the manufacturing technology of the respective part.

Group A was formed by air conditioning pipes whose material came from aluminum alloy pipes delivered in coil form and whose mounting flange was attached to the end of the pipe by a stamping process.

Group B consisted of air conditioning pipes whose material came from aluminum alloy pipes delivered in the form of a 6 m long bar cut to the appropriate size and whose clamping flange was attached to the end of the pipe by a welding process with filler metal.

Group C contains air conditioning pipes whose material came from aluminum alloy pipes delivered in the form of a 6 m long bar cut to the appropriate size and whose clamping flange was attached to the end of the pipe by the brazing process.

To draw the characteristic curve, we performed tests on a LBG TC100 tensile testing machine, with a maximum force of 100kN.

Before a sample was mounted on the testing machine, it was prepared by cutting it to a length of 220 mm and steel plugs were inserted at the ends of the pipe to prevent it from deforming when clamped between the machine jaws. The sample was clamped between the jaws of the tensile testing machine and the speeds at which the tensile stress was applied were set to the values of:

- slow travel speed = 10 mm/min
- fast travel speed = 50 mm/min

In the first part of the test, an extensometer was mounted on the tested sample. The characteristic curves drawn on the testing machine can be seen in the figures presented for each type of sample tested and the corresponding tables summarize the test results.

In the second part of the work carried out for the static characterization of the pipes in the air conditioning system, static mechanical tests were performed, the resulting values being mentioned in the tables:

- tensile test to highlight the thermally influenced zone
- bending test of pipes with a diameter of 18 mm
- bending test of pipes with a diameter of 12 mm
- torsion test of pipes with a diameter of 18 mm

Chapter five presents the fatigue tests performed under several loading conditions.

5.1. Bending fatigue test. We used 3103 aluminum alloy pipes with an outer diameter of 18 mm, from groups A and B described in chapter 4.1.2. A number of 24 samples distributed in four stress intensity groups were tested, until pronounced cracks appeared in the material.

In Fig.5.2. the S-N diagram is presented with the results obtained from the bending fatigue test of the pipes from group A. Analyzing the image, it can be seen that in the first two sets of tests, when the tension applied to the material is higher, the life of the tested specimens is represented grouped for each case, but has a very small value. If the sample material was stressed at a stress of 47.22 MPa, the maximum life was 23215 cycles, this decreased to a maximum of 9031 cycles for the stress of 58.70 MPa.

In the second stage of the bending fatigue tests, the 3103 aluminum alloy pipes from group B were tested. In Fig.5.3, the S-N diagram is presented with the results obtained from the bending fatigue test, and it can be seen that in the case of the 3103 aluminum alloy pipes from group B, the values are generally grouped, with extreme values further away from the average. The pipes in group A broke in the immediate vicinity of the stamped end portion (Fig.5.5) and the pipes in group B whose flange was welded to the pipe broke right next to the weld bead (Fig.5.6), which was expected, in those areas the bending moment had the maximum value.

5.2 Torsional fatigue test. We used the 3103 aluminum alloy pipes with an outer diameter of 18 mm, from group C, described in chapter 4.1.2. testing a number of 24 pipes distributed in four stress intensity groups, until pronounced cracks appeared in the material or the sample broke. The results after the first set of tests are presented in Table 5.9.

The first set of samples were loaded with a higher tension, but which is located on the linear portion of the characteristic curve in Fig.4.35. The rupture generally occurred at the side where the flange is mounted (Fig.5.8), but the S15C sample showed a rupture halfway between the ends (Fig.5.9).

The second set of tests was made with a tangential tension 9% lower than the first loading, the results after the second set of tests are presented in Table 5.10 and Fig.5.10 shows a ruptured pipe from this batch.

For the third batch of pipes, we set the stroke of the connecting rod of the clamping device described in the work to a value of 6 mm, corresponding to the rotation of the driven end of the pipe with an angle of 1.440°.

The stress applied to the samples in this case was 38 MPa representing 84% of the first load, Table 5.11 shows the results of these tests.

The last set of tests was done with a load of 33 MPa, Fig. 5.12 shows a broken pipe from group C4 and Table 5.12 shows the number of cycles performed.

For example, in group C1 where the samples were stressed the least and theoretically there should have been a much higher number of cycles performed than in any of the other situations, one of the pipes failed at 88456 cycles, breaking in the area between the ring of the joint made by the brazing process and the flange (Fig. 5.14). It is also noted that a sample from the first group tested broke at the highest load value, where the crack that appeared in the pipe also propagated to the flange (Fig.5.15).

By researching the static characteristics that we presented in the fourth chapter, we showed that although all the analyzed car air conditioning pipes had the 3103 aluminum alloy pipe as raw material, there are significant differences between the batches and types of pipes. These are due to the fact that the test samples were taken from components manufactured with different technologies through which the initial material was structurally affected.

If in the case of samples from group A the pipes were plastically deformed by rolling into coils by the manufacturer and the manufacturer of the air conditioning equipment unwound the pipe by subsequently processing it through a series of plastic deformations, and the samples from group C were thermally affected by the brazing process, it is justified that the static tests highlighted the differences between the characteristics of the two sets of samples taken from different components. The testing we performed (Fig.4.22 and 4.23) validated the fact that due to production processes and the use of different technologies, different behaviors can occur even on a relatively short piece of sample taken from a product.

5.3. Fatigue test at resonant frequency. We used the frame shown in Fig.4.33.a made of 12 mm diameter pipe made of 3103 aluminum alloy. To determine the resonant frequency, we clamped the pipe frame in a support device using two pairs of jaws, this whole assembly being subsequently attached to the exciter head of an electrodynamic exciter (Fig.5.16). Three accelerometers were fixed on the support device using magnetic supports (Fig.5.17.a and Fig.5.17.b), these being connected to a Brüel&Kjær PULSE 9727 data acquisition system. The sinusoidal signal for testing was provided by a generator connected to the input of a power amplifier whose output signal was applied to the electrodynamic exciter. By varying the generator frequency and adjusting the amplifier output amplitude, the first resonance frequency was determined at a frequency of 36 Hz and the second at a frequency of 105 Hz (Fig.5.17).

During the tests, the free end of the frame in the pipe moved between the test tips (Fig.5.19) without touching them. When a crack appeared in the pipe, the amplitude of the movement increased so that the free end of the frame came into contact with the test tips, and the electronic control device (Fig.6.12) commanded the interruption of the electrodynamic exciter, the number of cycles performed until the crack appeared being displayed on the device screen. The cracks appeared in the area with the highest bending moment [137], at the edge of the clamping jaws (Fig.5.22).

In **chapter six**, a presentation is made of the devices and devices designed and manufactured for performing static tests and fatigue tests. To achieve the objectives of the doctoral thesis, we used equipment appropriate to the proposed purpose: clamping devices on static test stands and fatigue testing machines, measuring and control devices as well as the necessary equipment for them, most of them being customized for each type of pipe taking into account the size, geometric shape and type of stress at which they had to be tested. Since fatigue tests are carried out over long periods of time, it is necessary that the devices and devices used in these tests be able to operate without interruption for a long time. Under these conditions, some devices must be able to release high powers and have efficient cooling.

- To power the exciter body coil from the electrodynamic exciter used, which has a consumption of 55 A at a voltage of 28 V, we built a power supply block (Fig.6.1).

- In the exciter body coil assembly, we mounted a temperature transducer and a Reed magnetic field sensor for monitoring the operating parameters.

- To ensure long-term operation without the risk of overheating the Brüel&Kjær 2707 power amplifier, its cooling was improved by adding an additional fan equipped with an electronic drive module (Fig.6.5), controlled by a thermistor temperature transducer that is fixed to the radiator of the power transistors in the amplifier.

- For tensile testing in the case of static tests, we designed and built an electric winch with a stepper motor (Fig.6.6) that can provide a tensile force of up to 450N and that is applied to the load by means of a synthetic wire wound on the motor cable drum.

- To control the winch, we designed and built an electronic assembly that is based on an Arduino Uno development board and that controls an H-bridge with which the stepper motor is driven (Fig.6.7).

- Since for determining the natural frequencies we needed a sinusoidal signal generator with high precision in terms of regulating the generated frequency as well as with good stability over time, we designed and built a Signal Generator (Fig.6.9).

- We performed the fatigue tests on components with a larger mass or requiring higher actuation forces using a testing machine driven by a three-phase asynchronous motor (Fig.6.11). The eccentric flywheel has an adjustment screw that allows the distance between the eccentric axis and the motor axis to be changed, thus adjusting the useful stroke of the connecting rod.

- Taking into account the fact that fatigue tests are performed until cracks appear or even component breakage, the test duration can reach several tens of hours of uninterrupted operation. During this time, the drive motor, which has a power of 3KW at a speed of 1450 rpm, can heat up to quite high temperatures, which can destroy it. To prevent this, we designed and built a device (Fig.6.12) that has the role of automating the fatigue testing process, having several functions: it can automatically control the stopping of the testing machine when the tested part breaks, stops the testing machine if the motor temperature exceeds a preset value, counts and memorizes the number of cycles performed by the machine until the tested part breaks.

- On the machine frame, we designed and mounted a device with an infrared barrier that detects the moment of the tested part breaking (Fig.6.15.a).

- To monitor the breakage of the pipe tested in the torsion fatigue test, we built a device that has an electrically insulated plate, fixed to the machine support (Fig.6.16).

- To perform the fatigue tests, we made two connecting pieces that are mounted by tightening on the tested pipe, the other end being provided with a fork that is mounted on the inner ring of the bearing at the end of the machine's connecting rod. In Fig. 6.17 the connecting piece for the bending fatigue test is shown. In Fig.6.18 the connecting piece between the tested pipe and the machine's connecting rod in the case of torsional fatigue tests can be seen.

- To determine the maximum amplitude of the displacement of a part whose natural resonance frequency is determined, we made the device in Fig.6.19 for which we designed and built both the mechanical part and the electronic device attached to the device.

- For fixing the pipes on the head plate of the electrodynamic exciter we made two devices. Figure 6.20.a shows the fixing device for pipes that are tested in a vertical position, and Figure 6.20.b shows the fixing device for pipes that are tested in a 45° inclined position.

- The pipes are attached to these devices by means of aluminum jaws (Fig.6.20.b) or hardwood (Fig.6.21.a) tightened with screws and nuts on the device by means of steel sheet plates (Fig.6.21.b).

- For static testing of pipes we made the device in Fig.6.22.a. It is mounted on the testing frame and the jaws in which the pipes are clamped are fixed on the movable crossbar. The movable crosshead has the possibility of rotating around its horizontal axis with angles between 0° and 45°.

- In the case of torsional fatigue tests, the pipe end driven by the machine connecting rod can also perform movements in the vertical or horizontal plane that can additionally load the tested specimen with stresses due to the bending moment. To eliminate this inconvenience, we made the device in Fig.6.23.

- Preventing the movement in the horizontal or vertical plane of the driven end of the statically tested pipe is done using the device in Fig.6.24.

- We made various clamping systems and assembly elements shown in Fig.6.26, Fig.6.27, Fig.6.28.

Conclusions

The initial study of the current state of research worldwide on fatigue testing of aluminum alloys in various industrial products and subassemblies highlighted the current research trends in the field, taking into account the fact that they are increasingly used in many fields of activity, automotive components being some of the products for the manufacture of which this type of alloy is used on an increasingly wide scale.

Fatigue testing in materials research laboratories and various manufactured components can highlight the problems to which they will be subjected during operation, anticipating the appearance of defects.

The doctoral thesis entitled “ASSESSMENT OF THE FATIGUE RESISTANCE OF ALUMINUM ALLOY COMPONENTS USED IN THE AUTOMOTIVE FIELD” deals with the research of the behavior of aluminum alloys as well as products manufactured from this material when subjected to prolonged stress.

Following the research activity related to the topic of the thesis for the doctoral degree, it can be concluded that through close collaboration between the manufacturer, design institutes and research laboratories, manufacturing processes can be optimized, new innovative advanced technologies can be discovered and new products with superior characteristics can be created that have a longer use.