Manufacture of an abrasive jet machining (AJM) equipment adapted for the treatment of rotary flexion fatigue specimens

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Abstract: The influence of micro-geometric irregularities on fatigue strength and, in particular, surface topography is widely accepted. Different machining processes generate surface roughness on machined parts that may significantly modify their fatigue behaviour and compromise their use in components where structural stability is required. Therefore, the study of these materials behaviour under cyclic loading stresses becomes highly relevant. The aim of this work is to design and manufacture an abrasive jet machining machine, in order to improve the surface roughness in the dry turning of aluminium alloys for a study of the influence on fatigue life after modification of its surface topography, using similar parameters to any equivalent industrial equipment. For this purpose, several components from obsolete machines belonging to the Manufacturing Engineering Department of the University of Malaga have been reused, to reduce the final cost. Several tests have been carried out with the aim of testing the manufactured equipment. The experimental data have shown results in line with those offered by others in industrial use for similar abrasives and processing material. The equipment has been built in accordance with the ISO 12100:2010 Safety of machinery - General principles for design - Risk assessment and risk reduction.

Keywords: Surface texture, Aluminium alloys, Superficial treatments, Abrasive jet machining.

1. Introduction

Abrasive Jet Machining (AJM) is a manufacturing technology based on erosion localization and intensification with a growing role for the toughest industrial demands. In this process, microscopic abrasive particles are accelerated in a compressed carrier gas and fed through a nozzle to produce a jet of high velocity particles. In most AJM applications, the depth and shape of the machined surface are relevant. Highly accurate AJM processes can be achieved by controlling various parameters such as the stand-off distance between the nozzle tip and surface, particle size, particle speed, nozzle diameter, etc. [1]. Reduction of the area affected by machining, precise erosion predictability and process controlling are current challenges in AJM.

In addition, the different machining processes by chip removal generate micro-geometrical surface irregularities alterations, in relatively wide intervals, directly influenced by: the machining parameters, cutting tools properties, workpiece properties and cutting phenomena [2]. The influence of the micro-geometrical irregularities on fatigue strength and, in particular, the surface topography, is widely accepted, even though their basic principles are unknown [3]. In some industrial sectors, such as those dedicated to the manufacture of aircraft structural parts, mechanical properties, such us compressive strength, tension load or fatigue behaviour, are critical requirements [4].
Currently, the “Manufacturing Engineering” research group of the University of Málaga is working in the analysis of the surface integrity in dry machined parts of light alloys for aeronautical applications. Within this context, an AJM equipment adapted for rotary flexion fatigue specimens has been built, to be used for the initial study of the influence of the surface topography on the fatigue life of these alloys. The study analyzes whether there is a modification of the fatigue life before and after an AJM treatment of the specimens. The values of the arithmetic mean roughness ($R_a$) and the maximum height of the profile ($R_z$) have been selected to evaluate the surface profile quality. It is intended to carry out some initial studies for the comparison of the rotary bending fatigue life of aluminium specimens with the topography determined by dry turning and those subsequently subjected to a surface AJM abrasion process. For this reason, the manufacture of an AJM, with reuse components of disused equipment, has been considered satisfying the requirements for these initial studies and according to the standard ISO 12100:2010 [5].

2. Experimental methodology

2.1. AJM design requirements

In order to fulfill the industrial requirements of an AJM machine, the following elements are needed: a conduction of abrasives in gaseous or liquid medium; a magnetorheological jet machining for superfinishing of precision optics; an abrasive jet that can be assisted by cryogenic or high temperatures; an air cavitation system. Specifically, for the surface treatment of fatigue specimens, a blasting equipment is needed with the capability of providing three alternative processes: Abrasive Air Jet Machining (AAJM), micro AAJM and the Abrasive Air Jet Polishing (AAJP). AAJM is aimed at material removal, while conventional shot blasting is applied mainly to surface cold-hardening. Glass beads as abrasive material are mainly used for producing matt surfaces for reducing transparency. When the nozzle exit diameter and machining feature is less than 1 mm, the process can be called micro-AAJM, micro-blasting or powder blasting [6].

A variant of the AAJM process is the AAJP, having the same basic principles as the traditional sandblasting process. The material removal from the workpiece is generated when the abrasive particles are driven by the high-speed airflow to impact the workpiece surface. The abrasive particles impact the material surface and generate many small fragments. Each impact can only remove minimum material quantity. The airflow takes both the abrasive particles and broken fragments of workpiece material away. A typical AAJP system is shown in figure 1 [7].

![Figure 1. AAJP operating principle.](image-url)
AAJP systems basically require a gas supply, which must be pressurized, and which can be supplied by an air compressor; as well as compressed air, which is cleaned through the system filter and dried using a coalescing filter, designed to remove liquid aerosols, water, oil, and submicron particles from its pneumatic system (figure 2 (a)). These filters provide oil free air for several application; a pressure control system for the air outlet flow, controlled by the valve and the pressure regulator; a deposit for feeding abrasive particles that will be displaced by a flow of compressed air; a chamber for mixing particles, with a powder feeder that conveys dosed powder to the spray gun by means of a mass flow-controlled carrier gas (figure 2 (b)); an abrasive particle outlet nozzle (figure 2 (c)); a workpiece rotational positioning table due to the cylindrical geometry of the specimen; a work cabin, with air extraction; and a deposit for collecting particles and material removed from the part surface.

![Figure 2. (a) Dried Air filter and pressure regulator. (b) Powder feeder and mixer. (c) Abrasive bead glass.](image)

The compressed air moves through the pressure adjusting valve to the nozzle where it is mixed with abrasive particles and blasted at the workpiece with controlled pressure. The used particles and the material removed from the part are eliminated from the machining area by the dust catcher. By impacting the substrate, the particles produce small fractures or plastic extrusion, depending on the part material properties and process parameters. After the impact, gas flow carries away both the abrasives and material removal [8]. Figure 3 shows an operating diagram of this equipment.

![Figure 3. AAJP operating diagram.](image)
2.2. **AJM parameters**

Surface roughness and material removal rate are included by several parameters in the AAJP, as shown in table 1. For the purpose for which this equipment is intended, the reduction of surface roughness of rotational bending fatigue test samples, optimize the parameters of jet machining is very important. Previous studies reveal that the abrasive mesh, jet pressure and jet angle are the main factors to obtain a lower surface roughness. It has been stated that the influence of the displacement speed is small [9].

| Table 1. Influenced parameters in AAJP. |
|----------------------------------------|
| **Polishing parameters** | **Abrasive parameters** | **Pneumatic parameters** |
| Material properties | Particle size | Nozzle diameter |
| Impact angle | Flow rate | Jet pressure |
| Standoff distance | Abrasive material | Jet velocity |
| Traverse speed |

To verify the results, a series of abrasion tests were carried out at the AAJP on aluminum alloy UNS A97075-T6 specimens, whose mechanical and physical properties are defined in table 2.

| Table 2. Mechanical and physical properties of alloy UNS A97075-T6 at 20 °C. |
|---------------------------------------|
| **Mechanical properties** | **Physical properties** |
| Ultimate tensile strength (Rm) | 530 N/mm² | Modulus of elasticity | 72 000 N/mm² |
| Yield strength (Rp) | 0.2 N/mm² | Density | 2.81 g/cm³ |
| Elongation | 5-8% | Melting range | 475-635 °C |
| Brinell hardness | 140 HB | Thermal conductivity | 134 W/m·K |
| Fatigue limit | 300 N/mm² | Electrical resistivity | 5.2 μΩ·cm |
| Shear strength | 350 N/mm² |

These specimens have been machined in a dry turning operation using an uncoated ISO DCMT 11T308 - 14 IC20 type tool inserted in a SDNCN 1616H1 neutral type tool holder. The main cutting angle ($K_r$) during the machining operation was 62.5°. The cutting conditions implemented for machining were: $v_c = 150$ mm/min (cutting speed), $a_p = 2$ mm (cutting depth) and $f = 0.20$ mm/rev (feed). After the machining test, the surface profile was evaluated by using a Mitutoyo SJ210 surface roughness tester. Glass microspheres of size 100/200 μm have been used as abrasive; whose characteristics are described in table 3:

| Table 3. Abrasive material characteristics. |
|-------------------------------------------|
| **Physical properties** | **Chemical composition** |
| Melting point | >1350° C | SiO2 | 70-73% |
| Shape | Spherical | Na2O | 13-15% |
| Density | 2.5 g/cm³ | K2O | 0.2-0.6% |
| Hardness | 6 Mohs | CaO | 7-11% |
| Granulometry (cumulative through mass %) | | MgO | 3-5% |
| Sieve - μm. | 250 | Al2O3 | 0.5-2% |
| Minimum | 99 | | |
| Maximum | 100 | |

The geometry of the nozzle was a truncated cone with an outlet diameter $D = 5.74$ mm. The tests were performed with the following parameters: The jet pressure, nozzle/probe spacing (2 and 4 times
the nozzle outlet diameter), and the relative nozzle/probe positioning angle, are shown in Table 4. In all tests, the displacement speed was kept constant and the tests were carried out without additives.

| Test | Impact angle (°) | Jet pressure (10^5 Pa) | Standoff distance (mm) | Ra (µm) | Rz (µm) | initial Ra (µm) | initial Rz (µm) |
|------|------------------|------------------------|------------------------|---------|---------|----------------|----------------|
| 1    | 90               | 4                      | 24                     | 1.147   | 7.067   |                 |                 |
| 2    |                  | 4                      | 24                     | 1.251   | 7.886   |                 |                 |
| 3    |                  | 6                      | 24                     | 1.303   | 8.215   |                 |                 |
| 4    |                  | 8                      | 24                     | 1.327   | 7.375   |                 |                 |
| 5    |                  | 4                      | 24                     | 1.394   | 8.831   |                 |                 |
| 6    |                  | 6                      | 24                     | 1.404   | 8.183   |                 |                 |
| 7    |                  | 8                      | 24                     | 1.411   | 8.476   |                 |                 |
| 8    |                  | 4                      | 12                     | 1.451   | 7.705   |                 |                 |
| 9    |                  | 6                      | 12                     | 1.475   | 7.58    | 1,597           | 7,077          |
| 10   |                  | 6                      | 24                     | 1.488   | 9.445   |                 |                 |
| 11   |                  | 8                      | 12                     | 1.611   | 12.734  |                 |                 |
| 12   |                  | 8                      | 24                     | 1.674   | 8.638   |                 |                 |
| 13   |                  | 4                      | 12                     | 3.083   | 14.588  |                 |                 |
| 14   |                  | 6                      | 24                     | 3.096   | 15.494  |                 |                 |
| 15   |                  | 4                      | 24                     | 3.768   | 17.274  |                 |                 |
| 16   |                  | 6                      | 12                     | 3.955   | 18.338  |                 |                 |
| 17   |                  | 8                      | 12                     | 3.964   | 17.129  |                 |                 |
| 18   |                  | 24                     |                         | 4.23    | 18.327  |                 |                 |

3. Results and discussion

The mean values of the arithmetic mean deviation (Ra) and the maximum height of profile (Rz) obtained after the machining tests were 1.597 µm and 7.077 µm, respectively. Table 5 shows the experimental data for the surface profile variables analyzed (Ra and Rz) after de AJM treatment. It is important to evaluate the effects of the polishing process on the specimen surface to determine which of the parameters used are suitable for the purpose of the equipment. The modification of the jet pressure leads to a variation on the higher kinetic energy of the particle. As shown in figure 4, the surface roughness after polishing increases with an increase of the fluid pressure for equal values of pressure. The position angle of the nozzle with respect to the samples (impact angle) is a determining factor. As this angle decreases, the surface roughness increases, with the highest value at an angle of 30 degrees and a pressure of 8 bars. The distance between the nozzle and the specimen is not decisive for values between two and four times the nozzle diameter. It is observed that for angles of position of 90 degrees, the arithmetic mean deviation (Ra) decreases with respect to the initial one, remaining approximately the same in the case of 60 degrees and being largely affected in the case of projection at 30 degrees. The effect of the maximum height of profile (Rz) profile shows the same type of effect as the position angle decreases. The results obtained with this equipment can be contrasted with other industrial equipment, such as Melentiev et al [10], states that increasing pressure leads to growth in surface roughness, with working pressures typically between 0.2 to 1 MPa for AAJM. Zhu et al [11] shows in the tests that the evolution of the surface roughness profile increases with decreasing angle of incidence for the same pressure and SOD; an increase of the SOD above the initial jet region leads to a reduction of the particle
velocity, reducing the surface roughness, remaining between the tested values of 2 and 4 times the nozzle diameter. The results obtained correspond to those described by other authors cited.

![Graph of Jet Pressure vs. Jet Angle and Arithmetic Mean Roughness](image)

**Figure 4.** Arithmetic mean roughness evolution.

The final cost of the abrasive jet machining was 548 € (labor 180 € and materials 368 €) distributed as shown in figure 5(a). It should be noted that most of the components have been reused from other out-of-service equipment belonging to the University of Malaga, such as: air control valves, dust mixer, hoppers and extraction systems, pressure switches, etc.

![Pie Chart and Image of AJM - University of Malaga](image)

**Figure 5.** (a) Manufacturing cost distribution. (b) AJM - University of Malaga.

Ordering a system with similar characteristics and requirements, costs around 5000 € to which should be added the fixation mechanism for the test specimens. Therefore, more than a 85% savings have been achieved by reusing the powder supply and others control units. The manufactured equipment is shown in figure 5(b), showing the mixing and dosing unit for the abrasive powder.
4. Conclusions
The initial proposal to manufacture a low-cost abrasion process equipment for the study of the fatigue behavior of UNS A97075 aluminum alloy specimens, obtained by dry turning and subsequently modified in surface roughness by glass bead blasting treatment has been achieved. It has been shown that the use of standard AAJP process parameters achieves results equivalent to those obtained with other industrial equipment on aluminum alloys for aeronautical use. A versatile working area has been created, where the nozzle and the specimen clamping devices can be implemented, allowing a stable abrasion process throughout the procedure. The equipment has been designed, tested and manufactured according to the ISO 12100:2010 standard, allowing the use of other abrasive particles and different configurations, in order to process other geometries, metallic, polymeric, natural etc. materials. Many of the manufacturing components have been reused, thus reducing design time and manufacturing cost, achieving savings up to the 85% of the cost of a commercial machine. With the tests carried out and described on the aluminium alloy specimens, it can be considered that the use of this low-cost equipment satisfies the needs for its use in the modification of surface roughness prior to the rotary bending fatigue tests, obtaining results equivalent to those that could be generated by the use of industrial equipment.

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