Fatigue behaviour analysis of AISI 316-L parts obtained by machining process and additive manufacturing

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Abstract: Due to the great technological growth, 3D printing is becoming of great relevance within the automotive, aerospace and even medicine sectors. With this manufacturing method, parts with a complex geometry can be manufacture with considerable time and material savings compared to traditional processes such as machining. However, additive manufacturing processes still have a series of unresolved problems. Present work makes a comparison between AISI 316-L samples obtained by Selective Laser Melting technique and Dry Machining. The comparison is focus in properties mainly relevant in the industrial sectors highlighted. Macro and microgeometrical deviations, such as roughness, roundness and straightness are obtained in each case study and compared. Results show that, although for the printed samples the material deposition direction plays a fundamental role, being the horizontal samples the ones with better results due to the direction of the layers, the machining process is the one with significant better results compared to the 3D printing process. After the macro and microgeometrical deviations measurements, all samples were subjected to a rotational bending fatigue test for a mechanical behaviour study. As expected, the mechanized specimens have a better fatigue behaviour due to the better surface finish, among other aspects. Between the additive manufactured specimens, the vertical is the one that presents a better behaviour due to the transverse orientation of the deposited layers.

Keywords: Additive Manufacturing, Machining Processes, Roughness, Geometrical Deviations, Fatigue Behaviour.

1. Introduction

Additive manufacturing, also known as 3D printing, was born at the end of the 70s. Due to the great technological growth of recent years and the release of the patents established at the time, this manufacturing method has suffered a great boom, reaching high precision and detail in the parts generated and being implemented in different industrial sectors (engineering, construction, etc) [1-3]. Initially it was a technology designed for the manufacture of polymeric components. However, today the incorporation of materials of different nature is feasible thanks to the enormous development of the technique, being possible to manufacture with composite and metallic materials [4-6] and select the printing process throughout all the technologies available (Selective Laser Sintering, Stereolithography, Direct Metal Laser Sintering, Selective Heat Sintering, Electron Beam Additive Manufacturing, among others). Table 1 shows the advantages and disadvantages of some of the technologies available.
3D printing offers the possibility to manufacture complex geometry parts or even parts impossible to elaborate by any other manufacturing process, with a considerable saving of time and material compared to traditional processes such as machining. However, the mechanical properties of the 3D printed parts are limited, which presents clear disadvantages compared to those obtained through the traditional manufacturing processes mentioned [7–9].

On the one hand, the manufactured parts size is still very limited. It depends on the additive manufacturing equipment size. On the other hand, production costs are quite profitable and economically striking when it comes to polymeric materials. However, for metallic materials, the manufacturing cost is still high since the process is complicated both to obtain the material for its transformation and the transformation itself, without taking into account that the price of the metallic material is higher compared to the basic polymers.

### Table 1. Advantages and disadvantages of different additive manufacturing Technologies [4,6].

| Technology               | Advantages                                                                 | Disadvantages                                                                 |
|--------------------------|-----------------------------------------------------------------------------|------------------------------------------------------------------------------|
| Material Extrusion       | Widespread, inexpensive                                                     | Nozzle radius limited                                                        |
|                          | ABS plastic can be used (good structural properties and easily accessible)  | Low accuracy and speed                                                        |
|                          | Relatively inexpensive                                                     | Required constant pressure of material                                        |
|                          | Suitable for visual models and prototypes                                   | Relatively slow speed                                                         |
|                          |                                                                             | Lack of structural properties in materials                                    |
| Powder Bed Fusion        | Ability to integrate technology into small scale                            | Size limitations                                                              |
|                          | Office sized machine                                                        | High power usage                                                              |
|                          | Powder support structure                                                    | Finish dependent on powder grain size                                         |
|                          | Large material options                                                     |                                                                             |
| Binder Jetting           | Different colours                                                           |                                                                              |
|                          | High range of materials                                                     | Not always suitable for structural parts, due to the use of binder material   |
|                          | Fast process                                                                | High time post processing                                                     |
|                          | Allows two materials                                                        |                                                                              |
| Material Jetting         | High accuracy, low waste                                                     |                                                                              |
|                          | Multiple material parts and colours under one process                       | Support often required                                                        |
|                          |                                                                             | Limited materials                                                             |
| Directed Energy Deposition | High quality, functional parts  | May require post processing for desired effect                               |
|                          | Speed often sacrificed for high accuracy                                    | Limited material                                                              |
|                          |                                                                             | Fusion processes require more research                                         |
| Sheet Lamination         | High speed                                                                  |                                                                             |
|                          | Low cost                                                                    | Relatively expensive                                                          |
|                          | Ease of material handling                                                   | High post processing time                                                      |
| Vat Photopolymerisation  | High level of accuracy and good finish                                      | Limited material                                                              |
|                          | Relatively quick process                                                    | Requires support structures                                                    |
|                          | Typically, large build areas                                                |                                                                              |

Another additional problem presented by metal parts manufactured by additive manufacturing is the dimensional accuracy, as well as the mechanical and physical-chemical properties. This fact, in the
case of structural parts for automotive or aeronautical components, becomes a very relevant inconvenience to take the definitive step to implement this type of manufacturing process.

Within this framework is the present work established. The main objective is to compare the dimensional accuracy at a micro and macro-geometric level (surface roughness and geometric deviations), as well as comparing the mechanical behaviour (fatigue by rotating bending) obtained in parts manufactured by machining and additive manufacturing processes.

2. Methodology

Focusing on the requirements of the Metallic materials-Rotating bar bending fatigue testing standard ISO 1143:2010 [10], the samples geometry is shown in figure 1(a). The material used for the experimentation is AISI 316-L steel, due to its corrosion resistance, suitability for welding and that provides greater resistance to high temperatures [11]. The material provided is certified according to EN 10204:2006 [12] and the composition is presented in table 2.

Two different manufacturing methods have been used, additive manufacturing and dry turning. The Selective Laser Melting technique (SLM) is the one selected among the different additive manufacturing methods. It works extending a layer of metal particles to be subsequently sintered by laser, which shapes the geometry to be formed. The process is repeated, layer by layer, until the part is complete. The part is manufactured inside a cabin under controlled atmosphere (Solution GMBH 250 equipment) [13]. The metal particles are exposed to an inert gas, achieving high temperatures. This process allows using of a wider range of materials, including titanium and aluminum. Currently, this technology is being developed and used in the aeronautical industry [14-16].

| Table 2. AISI 316-L samples composition (Weight %) obtained by arc atomic emission spectroscopy. |
|---------------------------------------------------------------|
|                | C  | Mn | Si | S  | P  | Cr | Ni | Mo |
| Min            | -  | -  | -  | -  | -  | 16.50 | - | 2.05 |
| Max            | 0.035 | 2.00 | 0.75 | 0.030 | 0.045 | 18.00 | 14.00 | 2.50 |
| Sample         | 0.024 | 1.60 | 0.39 | 0.020 | 0.035 | 16.95 | 10.05 | 2.05 |

For the additive manufacturing specimens, two types of specimens have been considered depending on their manufacturing direction, vertical or horizontal. Knowing that the visual difference between one method and another is undetectable, they have been identified in a simple way, being VAMX and HAMX, Vertical and Horizontal Additive Manufacturing specimens respectively, with X as the sample number (figure 1 and figure 2(c)).

For the samples obtained by dry turning, an AISI 306-L steel bar was cut into 205 mm individual bars. Subsequently, they have been machined to the geometry shown in figure 1, using a CNC lathe. The cutting tool (DCMT11T308-F2 TP2500), shown in figure 1(b), has not been renewed between passes, being the same for roughing as for finishing process. However, a new tool was used for every test, in order to ensure the same starting conditions. The feed (f) and the cutting speed (v_c) used for the finishing process were f = 0.05 mm/r v_c = 40 m/min. These cutting parameters have been selected in order to minimize surface roughness and avoid vibrations that can be transmitted to the part during the machining process [17, 18]. Each sample has been identified with a simple code: MACX. In total, 4 specimens have been manufactured for each method.

Once the specimens have been produced, the different geometrical deviations and roughness analyses are implemented.

For the roughness profile analysis, the arithmetical mean height (Ra) is obtained as a control parameter. The machine used was Mitutoyo SJ210, with integrated software (ISO1997 standard). The measurements are taken as shown in figure 2(c).
For the specimens obtained by machining, a measurement has been made at four different points, separated each 90 degrees. $Ra$ is calculated using the average of these four points. For the additive manufacturing specimens, knowing the high roughness values and the high results dispersion, results of the manufacturing process itself, the $Ra$ measurements have been made at eight generatrix per section in each specimen, in order to be as accurate as possible.

For geometrical deviation measurements, a straightness and roundness analysis have been carried out. The diameters of all the specimens have been measured in order to obtain the average diameters throughout different points in each section. In total, twelve points where measured and, at each point, four different generatrix per section have been measured. To measure the different diameters, a digital gauge has been used.

The straightness can be defined as the variation of a certain surface with respect to a theoretical line. While the roundness can be defined as the tolerance, in which the variation of a circle with respect to an axis can be obtained. In this analysis, the straightness and roundness of the specimen are measured with a dial gauge, a flatness table, V wedges and a ruler (figure 2(a)).

In this case study, once the machining process is completed, the specimens are leaved to cool on the same lathe, since expansion could occur in certain parts of the specimen giving rise to part distortions. In total, twelve points have been measured and at each point, the generatrix are measured every thirty degrees (figure 3).
Figure 3. Tested sections for roundness and straightness measurements.

The measurements for the roundness analysis are taken with a dial gauge with the specimens’ assembly in the fatigue test bench. In each of the measurement zones (grip and load zones), generatrixes are measured every thirty degrees making a total of 12 measures, the assembly can be seen in figure 2(b).

The machine used for the fatigue tests has been designed and created by the Manufacturing Engineering research group TEP-933 (figure 4), from an old parallel lathe. The samples are clamped at one end and loaded at the opposite end. The load amplitude is regulated adding different weights, resulting in a cyclic bending load on the specimen. For this case study the selected load was 14.5 kg so, the expected stress at the fracture zone is around 343,1 MPa. After the specimen breaks due to the material fatigue, the machine automatically shuts down by a stop switch. The number of load cycles is counted by an electrical counter and digitally displayed [17].

Figure 4. Fatigue machine created by the area of Manufacturing Engineering.

3. Results

Regarding Ra (figure 5(a)), the 3D printed specimens that have been manufactured horizontally have a surface quality superior to those printed vertically. This is because in the vertical manufacturing specimens the deposition lines are perpendicular to the measurement direction, which worsens the average roughness. On the other hand, the specimens obtained by turning process present a lower Ra because the machining processes present good finished surfaces in general and the cutting parameters used were a low feed rate and a high cutting speed. In figure 5(b) is presented VAM and HAM as the mean values for the vertical and horizontal additive manufacturing specimens and MAC for the machined ones.

As for the average roughness depth (Rz), in additive manufacturing specimens a lower depth is obtained in horizontal manufactured specimens due to the emerging of fewer pores during the metal cooling. Rz is lower in the machining specimens, having certain values very similar to the additive manufacturing specimens that have been manufactured horizontally, being a workpiece more continuous and with fewer cracks. From the observation of the error bar shown in figure 6 it can be seen that the dispersion of the results obtained from Rz is very high in the machining specimens, probably due to vibrations caused during the cutting process.

As for the roundness values, the additive manufacturing specimens that where manufactured horizontally present higher values than the vertically manufactured, which are similar to the ones obtained from the machined parts (figure 5(c)). The difference between the values among the
horizontal and vertical 3D printed specimens is on the layers. The vertical ones have a greater number of layers, and so, have a higher resolution and greater precision, closer to the machining values.

![Graphs showing average results for (a) Arithmetical mean height, (b) Average roughness depth, (c) Roundness deviations, and (d) Straightness deviations from the specimens tested.]

Focusing on the straightness values, the machined specimens show similar values to the horizontal additive manufacturing specimen, while the values obtained in the vertical specimens are higher than the rest (figure 5(d)). The HAM specimens obtain good results compared to the machined specimens, although a great disparity between is observed due to imprecision in the manufacturing. In a similar way, it happens with the MAC specimens. Due to the wear of the cutting edge, the results obtained for the first sample are better than for the last one.

As for the fatigue behaviour (figure 6), the machined specimens have a better performance than the additive manufacturing specimens. In addition, considering only the 3D printed specimens, the vertical material deposition specimens have a better performance than the horizontal material deposition specimens.

An important fact when assessing fatigue behaviour is the analysis of the crack growth. After the analysis of the fractured section, it can be appreciated that the area is smoother due to the same orientation of the layers as the fracture section, while for the horizontal fabrication specimens, the material deposition layers have a transverse orientation to the fractured surface.

The best performance obtained in the mechanized specimens is mainly due to the better geometrical results and the fact that the crack growth is hindered by the orientation of the material grains, while in the 3D printed specimens, growth is favoured due to the material deposition by layers. Also, the better $Ra$ of the machined specimens compared to those of additive manufacturing delays the onset of microcracking on the surface, improving its fatigue behaviour [18]. Moreover, it can also be considered that the internal structure of the additive manufacturing specimens, in the period of solidification, trap
small air pockets, helping the crack growth. This variable combination is a disadvantage for the printed samples. Figure 7 shows the cracks on the specimens after the fatigue test.

![Figure 6. Fatigue life comparison for the different specimens tested (Average).](image)

![Figure 7. Cracks shown in (a) VAD, (b) HAM and (c) MAC specimens.](image)

4. Conclusions

Due to the manufacturing process, the machined specimens have a better finish surface \((Ra)\) than the ones obtained by SLM due to the material deposition layer by layer. Between the 3D printed specimens, the horizontal SLM samples have better \(Ra\) values than those manufactured vertically, due to printing direction itself. For the horizontal specimens the \(Ra\) measurement direction coincides with the orientation of the material deposition, while for the vertical samples the measurement direction is transverse.

Similarly, the macrogeometric deviations in the machined parts show lower values than in the additive manufacturing samples, taking into account that the feed that has been used for the machining process is a low value and so, the macrogeometric parameters can be better controlled than with high feed. However, the aim is the comparison of finished samples and so, the feed speed needs to be low. Among the additive manufactured specimens, the horizontal samples present lower macrogeometric deviations than the vertical ones, mainly due to the number of layers used in the manufacturing process, being higher the number of layers for the vertical samples.

As expected, the mechanized specimens have a better fatigue behaviour than the additive manufacturing specimens. This is, among other aspects, due to the better surface finish, making it difficult for surface microcracks to appear and nucleate, as well as hinder the growth of the crack during the fatigue test due to the internal structure of the specimens. Between both printed specimen types, the fatigue behaviour of vertical additive manufacturing samples is better than the horizontal ones. Although the surface finish is better in the horizontal orientation, the horizontal specimen layers are transverse to the application of the load, reducing their fatigue behaviour.

Also, the costs generated for the additive manufacturing specimens are higher than those obtained
by machining process. Although, for this study, the machining equipment was available, nowadays metal additive manufacturing is still a more expensive process.

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