A comparison on the Energy Release between traditional and Additive Manufactured AISI 316L steel during static tensile test

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Abstract. Additive Manufacturing (AM) allows the creation of mechanical components and biomechanical devices with low weight and reduced material consumption compared to traditional manufacturing techniques. Despite design opportunities increase, on the other hand, also the process parameters to consider when dealing with AM are relevant on the mechanical performance. It is of fundamental importance to assure the structural integrity and reliability of such components. Energy release could give relevant information on the mechanical performance of the material; hence the Static Thermographic Method (STM) has been proposed as a rapid test procedure to assess the initiation of damage within the material monitoring the temperature evolution during static tensile tests. The aim of the present work is to compare the energy release of a stainless steel during static tensile tests. Specimens made of AISI 316L were produced with the same geometry, both with traditional and AM techniques. A comparison on the microstructure has been also performed in order to assess the possible cause of failure under static loads.

1. Introduction
Additive manufacturing (AM) is a very promising rapid prototyping technique which is moving to the production of final mechanical components. Industrial applications in aerospace [1] or biomedical field [2,3] are still increasing. Primary developed for polymers, 3D printing also allow the realization of components made in steel [4], with the possibility of exploring new design thanks to topology optimization [5]. One of the most common 3d-printed metal is the stainless steel AISI 316L, a low carbon steel with excellent mechanical properties. However, the mechanical properties of 3D-printed materials are severally affected by process parameters [6], as well as their microstructure. In high energy deposition process, the laser beam power, scanning speed and beam size play an important role in the finished part [7,8].

As the mechanical characteristics change with the printing parameter, it is necessary to perform several tests to retrieve both static and fatigue properties. This would lead to performing a huge number of tests with a high material consumption. On the hand, for traditional engineering materials rapid test procedure based on the energy release of the material have been developed in the last thirty years. The first researcher who apply the infrared thermography to monitor the superficial temperature of a specimen subjected to fatigue load was Risitano [9]. The development of the Thermographic Method (TM or Risitano TM) [10] leads to a rapid assessment of the fatigue limit of the material and of the SN...
curve [11]. Other researchers adopted also thermography and other energy-based techniques to assess the fatigue properties of a wide class of materials. In 2013 Risitano and Risitano proposed a rapid test procedure to assess the beginning of damage within the material monitoring the superfluous temperature during a static tensile test [12], i.e. the Static Thermographic Method (STM). A limit stress could be identified when a deviation from the linear thermoelastic trend of the temperature signal is noticed. The Static Thermographic Method has been applied to several kinds of materials and compared both with traditional fatigue test and TM, showing good agreement [13–16]. Santonocito, for the first time applied the STM to 3D-printed PA12 [17] and monitored the temperature trend of AISI 316L specimens obtained by SLM [18].

In this work, a comparison between traditional AISI 316L specimens and AM specimens of the same material, but with two different printing configurations, has been carried out monitoring the energy release during static and fatigue tests.

2. Theoretical background

2.1. Thermographic Method

As observed by La Rosa and Risitano [10], during a fatigue test, performed at a stress level above the fatigue limit \(\sigma_0\) of the material and at a given stress ratio \(R\) and test frequency \(f\), the temperature evolution exhibits three phases (Figure 1a). In the first phase (Phase I), there is an increment until the temperature stabilize at a value equal to \(\Delta T_{st}\) (Phase II). As the material approaches to fail, temperature experiences a very rapid increment (Phase III), compared to the previous one. Fatigue limit can be identified in a rapid way as the first stress level at which the stabilization temperature is noticeably higher compared to the previous value. For each constant amplitude (CA) fatigue test, it is possible to evaluate the energy parameter \(\Phi\) as the subtended area of the temperature versus number of cycle curve (\(\Delta T\)-\(N\)). Generally, the higher the applied stress, the higher the stabilization temperature, but the energy parameter could be assumed as material property, at a given stress ratio and test frequency. It is also possible to perform a stepwise fatigue test (Figure 1b), increasing the applied stress level and registering the relative stabilization temperature. As the specimen fail, it is possible to evaluate the energy parameter \(\Phi\) and assess the number of cycles to failure for each stress level, as the specimen would be stressed at that stress level with CA tests, simply dividing the energy parameter for the different stabilization temperatures and neglecting Phase I and III, usually smaller compared to Phase II. In this way, knowing the \(N-\sigma\) values, it is possible to obtain the complete SN curve of the material with a very limited number of tests.

![Figure 1](image-url)
2.2. Static Thermographic Method
In 2013, Risitano and Risitano [12] proposed a very rapid procedure to assess the first damage within the material monitoring its temperature evolution during a uniaxial tensile test. During a static tensile test of common engineering materials, the temperature evolution, detected by means of an infrared camera, is characterized by three phases (Figure 2): an initial approximately linear decrease due to the thermoelastic effect (obeying to Lord Kelvin’s law, Phase I), then the temperature deviates from linearity until a minimum temperature value (Phase II), therefore it experiences a very high further increment until material failure (Phase III).

Under uniaxial stress state and in adiabatic test conditions, Equation 1 can be simplified as:

$$\Delta T = -K_\sigma T \sigma_t$$

(1)

Figure 2. Temperature trend during a static tensile test.

The use of high precision IR sensors allows to define experimental temperature vs. time diagram during static tensile test in order to define the stress at which the linearity is lost. In 2010, Clienti et al. [19] for the first time correlated the damage stress $\sigma_{lim}$ related to the first deviation from linearity of $\Delta T$ temperature increment during static test (end of phase I) to the fatigue limit of plastic materials. If it is possible during a static test to estimate the stress at which the temperature trend deviates from linearity, that stress could be related to a critical macro stress $\sigma_{lim}$ which is able to produce in the material irreversible micro-plasticity. This critical stress is the same stress that, if cyclically applied to the material, will increase the microplastic area up to produce microcracks, hence fatigue failure.

3. Materials and Method
Three set of three specimens each, made of low carbon stainless steel AISI 316L, were tested. The geometry of the specimens was of the type “Continuous radius between ends”, according to the ASTM E466 standard (Figure 3a). The first set of specimens was realized by traditional manufacturing, processing a bar of material by turning. The second and third set of specimens were produced by Selective Laser Melting (SLM) printing process, adopting AISI 316L powder. The specimens were built along Z direction, in nitrogen atmosphere, adopting a laser power of 230W and a laser scanning speed of 1400 mm/s for the second set; while 190W and 1200 mm/s for the third set and tested “as built”.

Static tensile tests were performed under stress control, adopting a stress rate equal to 3 MPa/s, with a servo-hydraulic loading machine MTS 810 with a maximum load capacity of 250 kN (Figure 3b). The stress rate must be adopted in order to assure adiabatic conditions during the tensile tests, i.e. the specimen must not have the time to exchange heat with the surrounding environment.
During the tests, the specimen surface temperature was monitored with an infrared camera FLIR A40, recording the temperature evolution with a frequency of 5 Hz. The maximum value of a rectangular area placed on the specimen was recorded and post processed with a low pass filter, with a data span of 5%, to exclude outliers and enhance the linear trend.

Stepwise fatigue tests were performed on four specimens with the same loading machine, adopting two stress ratio, R= -1 and R= 0.1, and a testing frequency of 20 Hz. During the fatigue test the temperature trend was monitored with the IR camera.

![Servo-hydraulic load machine MTS 810 250kN](image)

![IR camera FLIR A40 (f= 5Hz)](image)

Figure 3. a) AISI 316L specimens obtained by SLM; b) Experimental setup.

4. Results and discussion

4.1. Static tensile test on Traditional steel

Tensile tests were performed on three specimens made of AISI 316L and manufactured by turning. The tests were performed under stress control, adopting a stress rate of 3 MPa/s, able to assure a low heat exchange between the specimen and the surrounding environment. The rupture instant of the specimen has been chosen to sync the temperature and load data. The applied stress has been reported versus the filtered temperature signal in Figure 4.

It is possible to distinguish a first linear thermoelastic trend, then the temperature trend shows a deviation from the linearity till a minimum point. Suddenly, it experiences a high increment, due to prevalent plastic deformation, till specimen failure. To assess the limit stress, it is possible to perform two linear regressions and make their intersection. The first regression has been performed with the $\Delta T_1$ points, corresponding to the linear thermoelastic trend (Phase I); while the second regression has been performed with the $\Delta T_2$ temperature points of the plateau region (Phase II). Temperature points near the knee have been neglected.

The first two specimens (Figure 4a-b) show a clear temperature behaviour, with a value of limit stress $\sigma_{lim}$ equal to 233.7 and 265.7 MPa. Also the third specimen shows a deviation from the linearity, but for a stress level lower compared to the previous specimens, i.e. 207.3 MPa (Figure 4c).
4.2. Static tensile test on AM steel

Static tensile tests were performed on specimens, made of AISI 316L powder, produced by SLM printing process. Two laser powers were adopted: 230W and 190W. The tests were performed under stress control, with the same stress rate of the traditional material.

In Figure 5 are reported the temperature trend of the three specimens built along Z direction, with a laser power of 230W. As done for the traditional material, it is possible to perform two linear regressions with the temperature points of the linear and plateau regions. Compared to the traditional material, the deviation from the linearity is slightly evident. For the first two specimens, the limit stress is equal to 202.6 and 199.3 MPa, while for the third specimen it is equal to 171.1 MPa.
Figure 5. Temperature trend vs. applied stress of AM AISI 316L specimens (230W, 1400 mm/s).

As regard the specimens built with a laser power of 190W, the temperature signal it is not very clear. For the first test (Figure 6a) the deviation from the thermoelastic trend has been observed for a stress level equal to 174.7 MPa. For the second specimen (Figure 6b), a very noisy temperature signal has been obtained, hence it was not possible to assess a value for the limit stress.
Figure 6. Temperature trend vs. applied stress of AM AISI 316L specimens (190W, 1200 mm/s).

4.3. Comparison

In Table 1 are reported, for each tested specimen, the value of the ultimate strength $\sigma_U$ and the limit stress $\sigma_{\text{lim}}$ as assessed by STM, with their average estimation. While the traditional specimens show a little standard deviation, the AM specimens exhibits a high variability in terms of ultimate strength.

| Specimen type      | No. Specimen | $\sigma_U$ [MPa] | $\sigma_{\text{lim}}$ [MPa] | $\sigma_U$ ave[MPa] | $\sigma_{\text{lim}}$ ave[MPa] |
|--------------------|--------------|------------------|-----------------------------|---------------------|-----------------------------|
| AISI 316L Traditional | 1            | 707              | 234                         |                     |                             |
|                     | 2            | 709              | 266                         | 714 $\pm$ 11        | 236 $\pm$ 30               |
|                     | 3            | 727              | 207                         |                     |                             |
| AISI 316L AM (230W) | 1            | 370              | 203                         |                     |                             |
|                     | 2            | 373              | 199                         | 329 $\pm$ 74        | 191 $\pm$ 17               |
|                     | 3            | 244              | 171                         |                     |                             |
| AISI 316L AM (190W) | 1            | 614              | 175                         | 580 $\pm$ 48        | 175                         |
|                     | 2            | 546              | -                           |                     |                             |

4.4. Fatigue behaviour

In order to compare the value of the limit stress with the value of fatigue limit of the traditional material, four fatigue tests were performed with a test frequency of 20 Hz and two stress ratio $R$, 0.1 and -1.

In Figure 7a the temperature trend vs. the applied stress level, for a specimen tested at $R= -1$ with a stress increase of $\Delta \sigma= 10$ MPa and a number of cycles per block $\Delta N= 20,000$, is reported. For each stress level the corresponding value of the stabilization temperature has been estimated. As it is possible to observe, the temperature experiences a very high further increment when the stress level raise from 250 to 260 MPa. For the last stress level of 270 MPa, temperature does not stabilize, increasing up to
specimen failure. It is reasonable to consider the fatigue limit for a stress ratio of R= -1 in the range 250÷260 MPa, where the higher temperature increment is noticed. It is worth noting that the limit stress found with the STM is within the previous stress range assessed with fatigue test.

The stepwise fatigue test with stress ratio R= 0.1 was performed with Δσ= 20 MPa and ΔN= 10,000, ranging from 200 MPa to 560 MPa (Figure 7b) and recording the stabilization temperature.

![Figure 7. Stepwise fatigue test of Traditional AISI 316L specimens: a) R= -1; b) R=0.1.](image)

Reporting the stabilization temperature vs. the relative stress level (Figure 8), it is possible to observe a bilinear trend. For stress levels below the fatigue limit of the material, with a stress ratio R= 0.1, a slight temperature increment is noticeable. On the other hand, temperature increments are clearly higher for stress levels above the fatigue limit. By performing the linear regression of the lowest set of points and of the highest, then making their intersection, it is possible to assess the fatigue limit at R= 0.1 with the TM, which is equal to σ₀R₀.₁ = 388 MPa. Considering the same applied maximum stress, it is evident how the fatigue limit for stress ratio of 0.1 is higher compared to the one for R= -1. In facts, this stress condition, in the tension-compression domain, is the more damaging for the materials, leading also to higher temperature increment.

![Figure 8. Fatigue limit of traditional AISI 316L at R= 0.1 by Thermographic Method.](image)
Fatigue tests on AM AISI 316L specimens, printed by SLM with a laser power of 230W and laser scanning speed of 1400 mm/s, were performed by Santonocito et al. [18] on the same specimen geometry of the present work (Figure 9). In that work, the authors shown how the fatigue life, for a stress ratio $R=0.1$, of such AM material is shorten compared to other literature data [20]. From the TM, the fatigue limit at $R=0.1$ for traditional AISI 316L is equal to 388 MPa, a value considerably higher compared to the value of circa 80 MPa at $10^6$ cycles, as reported by Solberg et al. (green triangles of Figure 9). In addition, under stepwise fatigue tests (red and black circles in Figure 9), specimens fail for stress levels below the value of the limit stress (191 ± 17 MPa and 175 MPa) in an unpredictable way and fatigue life seems depending also on the test frequency.

![Figure 9](image_url)

**Figure 9.** S-N curve for AM AISI 316L, from [18].

4.5. Microstructure

To confirm the mechanical behaviour of AISI316L steel obtained through AM and by traditional method, microscopies were carried out on the fracture surface suitably treated with a lapping machine.

As is clearly shown in Figure 10a and Figure 10b, the surfaces have a different structure which justifies the different behaviour of the samples when subjected to static and fatigue tests. In fact, the specimen obtained by traditional method has a uniform surface and does not show any macroscopic defects. On the other hand, the sample made by AM technique has a surface characterized by numerous defects, such as inclusions and incomplete fusions. In particular, as shown in Figure 10c, the microstructure defects take on considerable dimensions even in the order of hundreds of microns, becoming the cause of possible crack initiation.

As anticipated in the materials and methods section, the sample production methodology is shown in Figure 10d, in which characteristic streaks are highlighted indicating the laser melting direction.

Andreau et al. [21] performed a fatigue test campaign on SLM specimen, made of 316L stainless steel, fabricated using three different hatching strategies, varying the scanning speeds in the internal portions of the parts, in order to assess the impact of the inner porosity rate on the fatigue behaviour. Samples with lack of fusion near the surface showed reduced fatigue properties with increasing pore size distribution. A high amount of internal porosity was found to not impact the fatigue properties below 10% of the areal layer porosity, while they exhibit premature cracking for values above. Fatigue life is mostly affected by small porosities at the specimen surface.

Shrestha et al. [22] found that lack of fusion in subsequent layers is responsible for fatigue crack initiation. The presence of large internal defect due to lack of fusion has a preponderant effect on fatigue cracks compared to surface roughness. Internal defects can severally affect the ultimate strength when the pore diameter is about 2400 μm and elongation when they are about 1800 μm [23].
5. Conclusion
In this work, the energy release of traditional and AM stainless steel AISI 316L has been monitored during static tensile and stepwise fatigue test. The mechanical properties of the different set of specimens have been assessed and compared in terms of ultimate strength and limit stress. AM specimens have shown a higher dispersion compared to the traditional material. In addition, by applying the Static Thermographic Method, the limit stress of traditional material is considerably higher than the AM one. To verify the limit stress, conceivable as the first damage initiation within the material, stepwise fatigue tests have been performed on traditional specimens with two stress ratios. The limit stress is in good agreement with the range of fatigue limit assessed by Thermographic Method for a stress ratio of $R=-1$. For a stress ratio of $R=0.1$, traditional AISI 316L exhibit better fatigue life performances compared to the AM counterpart.

Energy methods, such as Static Thermographic Method and Thermographic Method, can be a useful aid to assess in a rapid way the fatigue properties of AM materials, where the process parameters strictly affect the mechanical properties of the produced mechanical components.

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