Numerical and experimental evaluation of the energetic release during static tensile tests on short fiber reinforced composite material

D Santonocito

University of Messina, Department of Engineering, Contrada di Dio, 98166 Messina, Italy

email: dsantonocito@unime.it

Abstract. In this work, a simple numerical model is presented in order to evaluate the energetic release of short fiber composite PA66GF35 under static tensile tests. The micro-mechanical behavior of the fiber-matrix system was taken into account, as well as the fiber distribution and orientation. Numerical simulation at macro scale level were carried out to predict the temperature evolution of the material under monotonic load. Experimental validation was performed on dog-bone specimens monitoring the surface temperature with an infrared camera. A deviation from the linearity of the thermoelastic effect has been noticed for a stress level below the yielding strength of the material. The analysis of the temperature trend evolution may be a useful aid in order to identify damage initiation within the material that would lead to failure, especially under fatigue load, even adopting a simple and rapid static tensile test.

1. Introduction

In the recent years, infrared thermography has been adopted to monitor the fatigue behavior of several class of materials [1–3], even composite material [4–6]. In 2013, Risitano and Risitano [7] proposed the Static Thermographic Method (STM) as an innovative test procedure able to estimate the onset of damage processes within the material evaluating the energetic release during a static tensile tests. The macroscopic stress level at which a deviation from the linearity of the thermoelastic trend is observed correspond to the stress that introduce in the material irreversible damage. Clienti et al. [8] for the first time observed such behavior and correlates it to the fatigue limit of plastic materials. The same behavior has been observed also in basalt fiber composites [9] and glass fiber reinforced materials [10].

It is difficult to model the internal micro structure of the materials, especially for metals, and correlate it to the macroscopic behavior; but, on the other hand, the internal structure of composite material is well known. The material under study is a composite material of the class PA66GF35, which has been investigated by several authors in literature. Sato et al. [11] analyzed the damage evolution on this class of composite under static and fatigue tests and proposed a micro failure model. Bernasconi et al. [12] analyzed the influence of the fiber orientation on the fatigue behavior of short glass fiber reinforced PA6 composites. De Monte et al. [13] studied the influence of the temperature and thickness of specimens retrieved at several orientations respect the Mold Flow Direction (MFD).
Adopting the infrared thermography, Belmonte et al. [14] studied the damage mechanism on plain and notched specimens of reinforced polyamide. Several authors have focused their study on modelling the fiber-matrix interaction of composites material [15]. Horst et al. [16] created a finite element model to investigate the stresses at fiber and matrix interface of glass fiber reinforced polyamide composites and compared it to experimental results.

In this work, a first attempt to understand the link between the internal micro structure and its micro failure mechanism on the overall energetic release of a composite material is performed. Numerical simulations are carried out in order to predict the onset of damage within the material while the STM is applied on dog-bone specimens in order to verify the damage model.

2. Theoretical background

2.1. Temperature trend during static tensile test

In this section, a simplified temperature model for engineering materials under static tensile condition is exposed. It is based on the fundamental assumption that fatigue failures occur within the material where the local stress distribution, amplified by structural or superficial micro defects, is capable of producing local micro plastic deformation [7]. The local stress state can be linked to a macroscopic nominal stress value (load/area) that introduce in the material the first micro plasticization.

The relationship between the applied stress, or strain, and the corresponding temperature change in solid material consist of two contributions due to a thermoelastic and a thermoplastic effect (Equation (1)) [17].

\[ \Delta T = \Delta T_e + \Delta T_p \]

The thermoelastic effect is a well known phenomenon adopted in stress analysis to evaluate the distribution of the first invariant stress tensor, i.e. the sum of the principal stresses [18,19]. Under adiabatic conditions and for a linear isotropic homogeneous material, the variation of the material temperature, follows the Lord Kelvin’s law:

\[ \Delta T_e = -\frac{a}{\rho \cdot c} T_{1u} = -K_m T_{1u} \]

Where \( K_m \) is the thermoelastic coefficient.

After the material locally reaches a stress condition beyond its yielding stress, the irreversible plastic deformations lead to an increase in temperature. From the first principle of thermodynamics (energy conservation), the rise in internal energy could be addressed to the heat generated by plastic deformation (Equation (3)).

\[ \rho c \frac{\partial T}{\partial t} = \frac{\partial Q}{\partial t} \]

The generated heat due to plastic deformation can be linked to the mechanical energy by means of the Taylor-Quinney coefficient, defined as the percentage of plastic deformation energy dissipated into heat \( Q = \beta W_p \). Despite this coefficient varies in different metallic materials [20], for sake of simplicity it can be assumed constant and equal to 0.9. Under these hypothesis, the temperature increment due to plastic deformation can be estimated with Equation (4).

\[ \Delta T_p = \frac{1}{\rho \cdot c} \int Q dt = \frac{\beta}{\rho \cdot c} \int \sigma_p \varepsilon_p \]

In the elastic phase the temperature experiences a linear decrease due to the thermoelastic effect. If a plasticity condition is reached locally in some internal defect point of the material, Equation (1) is no longer valid and a heat amount leads to a deviation from the linear trend.

2.2. Static Thermographic Method

During a uniaxial traction test of common engineering materials, the temperature evolution, detected by means of an infrared camera, is characterized by three phases (Figure 1): an initial approximately
linear decrease due to the thermoelastic effect (phase I), then the temperature deviates from linearity until a minimum (phase II) and a very high further temperature increment until the failure (phase III).

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

$$\Delta T_i = -K\mu T\sigma_i$$

(5)

![Figure 1. Temperature trend during a static tensile test.](image)

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. [8] 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. Risitano and Risitano [7] proposed a novel procedure to assess the fatigue limit of the materials during monoaxial tensile test. 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 Methods
The material under study was a composite obtained by injection molding process of the type PA66GF35. In this kind of material, the matrix phase in composed by aliphatic polyamide 66 while the fiber is made of glass and it is dispersed in the matrix with a weight percentage of 35%. Three specimens of the Type 1Aaccording to ISO527 standard where retrieved from a plate along the mold flow direction (MFD, 0° orientation) (Figure 2a). The specimens were subjected to natural ageing at room temperature for about 4 years. In Table 1 are reported the mechanical properties as declared by the manufacturer. The specimens were tested under displacement control, with a crosshead speed of 5 mm/min, adopting a servo-hydraulic test machine ITALSIGMA 25kN (Figure 2b). During the tests the superficial temperature was monitored with an infrared camera FLIR A40 with a sample rate of 1 image per second. The superficial strains were assessed by means of a stereo cameras Digital Image Correlation (DIC) system, with a resolution of 4000 x 3000 pixels and focal length of 50 mm. The system accuracy for the strain measurement is up to 0.01%, and the images were acquired at 1 Hz.
Table 1. PA66GF35 mechanical and thermal properties as declared by the manufacturer.

| Property                        | Value          |
|---------------------------------|----------------|
| Tensile Strength $\sigma_R$ [MPa] | 150$\div$210  |
| Tensile Modulus $E$ [GPa]        | 8.7$\div$11.4 |
| Fiber length $l_f$ [μm]          | 280            |
| Fiber Diameter $d_f$ [μm]        | 10             |
| Density $\rho$ [kg/m$^3$]        | 1410           |
| Specific heat $c$ [J/kg.K]       | 1670           |
| Linear expansion coefficient $\alpha$ [K$^{-1}$] | 2.5 x 10$^{-5}$ |

Figure 2. a) specimen geometry according to ISO527; b) Experimental setup.

In order to assess the micro failure behavior of the composite, a 2D finite element model was created with Ansys APDL. The material properties of the fiber and matrix adopted are reported in Table 2. The fiber-matrix system was modelled as a cylinder (fiber) within another one (matrix) taking into account the volume percentage of the fiber respect to the matrix ($V_f= l_d^2/L_S^2$) [21]. The geometrical characteristics of the model are reported in Figure 3, were a total number of 6900 PLANE183 elements were adopted. Axial symmetry boundary condition was adopted for the system, while the bottom elements were fixed and a displacement for the top ones was imposed in order to achieve the 3% of strain. As regards the right matrix elements, in order to avoid the formation of internal cracks, the displacement along the x direction were coupled together and equal to the matrix node far away from the fiber tip [16].

Table 2. Material properties of fiber and matrix for FE model.

| Material        | Mechanical behaviour | E [GPa] | $\sigma_y$ [MPa] | $\nu$ | $\rho$ [kg/m$^3$] |
|-----------------|----------------------|---------|-----------------|------|------------------|
| Fiber (Glass)   | Linear elastic       | 72      | -               | 0.22 | 2.54             |
| Matrix (PA66)   | Von Mises Yielding   | 3.1     | 51              | 0.4  | 1.16             |
The stress-strain behavior was evaluated with the same procedure proposed by several authors [21,22], where the stress and strain are estimated as average values over the element volumes according to the following equations:

$$\bar{\sigma} = \frac{1}{V} \sum_{i=1}^{N} V_i \sigma_{ij}$$

$$\bar{\varepsilon} = \frac{1}{V} \sum_{i=1}^{N} V_i \varepsilon_{ij}$$

(6)

A 3D macro mechanical model of the Type 1A specimens were also modelled adopting 1/8th of the geometry (Figure 4), in order to apply the temperature model developed in section 2.1. Hexahedral 20-node SOLID186 elements were adopted and after a calibration procedure, a total number of 1536 elements were chosen. In order to emulate the static traction tests, an imposed displacement to the grip nodes was applied. The composite material was modelled as a homogeneous isotropic material with elasto-plastic behavior. The engineering curve coming from the DIC system was adopted and it was corrected taking into account the damage mechanisms assessed by the micro mechanical FE model. As regard the fiber orientation, the injection molding process creates a typical sandwich structure, where the fibers in the shell regions (near the mold walls) are directed along the MFD, while in the core region they are almost perpendicular to the MFD. Since it was observed by several authors that the core region is about the 5% of the specimen thickness [23,24], taking into account the small thickness of the adopted specimens, the core region was neglected and all the fibers within the composite were considered aligned to the MFD and hence to the load direction. The first stress invariant and the plastic work per volume unit of a volume of about 2 mm region of the specimens reduced section were retrieved.
Figure 4. Macro mechanical Finite Element model of the PA66GF35 Type 1A specimen.

4. Results and discussion

4.1. Experimental tests

Static tensile tests were performed on three specimens adopting a crosshead velocity of 5 mm/min. The crosshead velocity has to be choose properly in order to assure adiabatic test conditions, i.e. the specimens are not allowed to exchange heat with the environment. The superficial temperature trend was monitored with an infrared camera and the obtained temperature signal was filtered with a lowess filter, with a data span of 10%, in order to reduce the outliers and highlights the thermoelastic trend. In Figure 5, the nominal stress versus the specimen’s surface temperature variation, estimated as the difference between the instantaneous temperature and the initial temperature of the surface recorded at time zero \( \Delta T = T_i - T_0 \) are reported. In the initial part of the \( \Delta T \)-t curve it is possible to clearly distinguish the linear trend of the temperature, then it deviates from the linearity reaching a plateau region. It is possible to draw two linear regression line, the former for the first linear phase (early stage of the temperature signal, \( \Delta T_1 \) fit point series) and the latter for the second phase (last stage before the sudden increase in the temperature signal, \( \Delta T_2 \) fit point series), not taking into account the temperature values near the slope change (Experimental Temperature series). Solving the system of equations, it is possible to determine the intersection point of the two straight lines. The corresponding value of the applied stress could be related to the macroscopic stress that leads to irreversible damage phenomena in the composite material. The limit stress has been evaluated on three tests, obtaining a value equals to 34.1±3.8 MPa.
4.2. Micro failures within the material

Prior to modelling the micro mechanical failure of the composite material, it is important to observe the damage evolution during a static traction test. Sato et al. [11] observed the progression of the damage within a composite with PA66 matrix and dispersed glass fibers during static tensile and fatigue tests adopting the SEM technique. They observed as the fiber tip does not contribute to the load transfer between the fiber and the matrix, hence the matrix can be thought as not bonded with the fiber ends. For low stress levels, micro voids at fiber end regions are observed and, as the load increases, interfacial micro failure of the matrix along the fiber length arises. Then the micro cracks propagate within the matrix up to reach a very large plastic deformation with catastrophic failure of the whole composite. From the micro mechanical FE model the stress-strain curve has been evaluated, as well as the plasticity evolution within the matrix phase. As done by Kang et al.[21] for metal matrix composite material, in Figure 6 are reported the engineering stress-strain curve obtained from the micro mechanical FE model up to 1.7% of strain (for higher deformation, FE values were not reliable) and from the static traction test performed on a specimen, assessed with DIC method. The experimental PA66GF35 curve exhibits, for the same strain level, higher stress values compared to the FE curve. The estimated elastic modulus (29.7 GPa, according to ISO527 standard) is considerably higher compared to the manufacturer data. On the other hand, the estimated elastic modulus of the FE curve (11.3 GPa) is almost near the upper bound value of the range declared by the manufacturer. The differences in the mechanical behavior of the experimental and simulated stress-strain curve may be due to not have taken into account, in the FE model, the viscoplastic behavior of the matrix and to the excessive ageing of the tested specimens. In the same figure are reported some images extracted from the FE model with the representation of the “stress ratio” parameter, i.e. the level of plasticity of one element, as estimated by the ANSYS software (blue=fully elastic, red=fully plastic). As the strain level increases, the plastic area in the matrix increases. For a strain level of about $\varepsilon = 0.002$, the fiber matrix debonding region reaches the 5% of the fiber length. Such a strain level can be considered as
the limit strain level where irreversible micro failure arises within the material. For higher strain levels, the plastic area increases in a similar way as observed by Sato et al.

![Graph](image-url)

**Figure 6.** Comparison between Experimental and Numerical (FE) engineering curve for PA66GF35. Evolution of the plasticization within the matrix.

4.3. **Predicting the temperature evolution**

From the micro mechanical FE model, the minimum strain level at which damage begin within the composite material has been assessed; hence, in order to model the overall plastic behavior of the specimen, the experimental stress-strain curve of the material has been redefined considering the material as isotropic elastic till $\varepsilon = 0.002$, then it has been considered as a plastic material adopting an isotropic multilinear plasticity model. The core region generated by the injection molding process (fiber aligned perpendicularly to the MFD) has been neglected, considering its small presence in the specimen volume, while the overall specimen has been considered as oriented along the MFD. A displacement on the grip section nodes has been imposed and the first stress invariant and the plastic work per unit of volume have been evaluated from the finite element simulation of the specimen. Due to the ageing of the material under study, the thermoelastic constant $K_m$ has been directly evaluated from experimental data performing a linear regression of the relative temperature variation versus the stress. In Figure 7 are reported the experimental filtered temperature and the numerical prediction of the temperature according to the model presented in section 2.1. By observing the experimental trend, the three different phases are evident. In the first phase the temperature trend is perfectly linear, then for a stress level of 31.5 MPa it deviates from the linearity reaching a plateau region where it is almost flat. When the stress level is equal to 95 MPa, a very high further temperature increment is experienced till the specimen failure. The temperature trend predicted by the FE simulation adopting
The corrected stress-strain curve for the same specimen of the experimental test, perfectly follow the linear trend of the experimental temperature up to the stress level of 32.7 MPa, where the specimen experiences the first micro failure. From that point, the temperature slightly increases and, in the third phase, it experiences the same asymptotical increase of the experimental trend. The limit stress assessed by the FE simulation is in good agreement with the experimental value. The knowledge of the micro failure within the material has allowed a good prediction of the macro failure of the composite material analyzing the energetic release.

![Figure 7](image.png)

**Figure 7.** Energetic release of PA66GF35. Comparison between experimental and simulated temperature trend.

5. Conclusion
Understanding the internal micro structure of the material and the micro failure mechanism under static loads is fundamental in order to predict failures. In this chapter, moving from the observation of the micro damage mechanism of a PA66GF35 composite material, a finite element simulation has been carried out in order to assess the strain level at which irreversible damage begin within the material. This information has allowed to redefine the stress-strain curve of the material assessed experimentally, taking into account the plastic behavior of the material. Numerical simulation has been carried out at macroscopic scale in order to predict the energetic release of the material. The simulated temperature trend has been compared with the experimental ones, performed on the same specimen geometry, showing good agreement between the limit stresses, i.e. the stress level at which the temperature trend deviates from the linearity. The adoption of the Static Thermographic Method could be a useful aid in order to identify, with a rapid test procedure, the onset of irreversible micro damage within the material that lead to the failure of the structure.

References
[1] Corigliano P, Cucinotta F, Guglielmino E, Risitano G and Santonocito D 2020 Fatigue assessment of a marine structural steel and comparison with Thermographic Method and Static Thermographic Method *Fatigue Fract. Eng. Mater. Struct.* 43 734–43
[2] Rigon D, Ricotta M and Meneghetti G 2017 An analysis of the specific heat loss at the tip of
seriously notched stainless steel specimens to correlate the fatigue strength *Theor. Appl. Fract. Mech*. 92 240–51

[3] Ristiano G, Guglielmino E and Santonocito D 2018 Evaluation of mechanical properties of polyethylene for pipes by energy approach during tensile and fatigue tests *Procedia Structural Integrity* vol 13 (Elsevier B.V.) pp 1663–9

[4] Crupi V, Guglielmino E, Ristiano G and Tavilla F 2015 Experimental analyses of SFRP material under static and fatigue loading by means of thermographic and DIC techniques *Compos. Part B Eng*. 77 268–77

[5] Colombo C, Libonati F and Vergani L 2012 Fatigue damage in GFRP *Int. J. Struct. Integr.* 3 424–40

[6] Palumbo D, De Finis R, Demelio P G and Galietti U 2016 A new rapid thermographic method to assess the fatigue limit in GFRP composites *Compos. Part B Eng*. 103 60–7

[7] Ristiano A and Ristiano G 2013 Determining fatigue limits with thermal analysis of static traction tests *Fatigue Fract. Eng. Mater. Struct.* 36 631–9

[8] Clienti C, Fargione G, La Rosa G, Ristiano A and Ristiano G 2010 A first approach to the analysis of fatigue parameters by thermal variations in static tests on plastics *Eng. Fract. Mech*. 77 2158–67

[9] Colombo C, Vergani L and Burman M 2012 Static and fatigue characterisation of new basalt fibre reinforced composites *Compos. Struct*. 94 1165–74

[10] Harizi W, Chaki S, Bourse G and Ourak M 2014 Mechanical damage assessment of Glass Fiber-Reinforced Polymer composites using passive infrared thermography *Compos. Part B Eng*. 59 74–9

[11] Sato N, Kurauchi T, Sato S and Kamigaito O 1991 Microfailure behaviour of randomly dispersed short fibre reinforced thermoplastic composites obtained by direct SEM observation *J. Mater. Sci.* 26 3891–8

[12] Bernasconi A, Davoli P, Basile A and Filippi A 2007 Effect of fibre orientation on the fatigue behaviour of a short glass fibre reinforced polyamide-6 *Int. J. Fatigue* 29 199–208

[13] De Monte M, Moosbrugger E and Quaresimin M 2010 Influence of temperature and thickness on the off-axis behaviour of short glass fibre reinforced polyamide 6.6 - Cyclic loading *Compos. Part A Appl. Sci. Manuf*. 41 1368–79

[14] Belmonte E, De Monte M, Hoffmann C J and Quaresimin M 2017 Damage mechanisms in a short glass fiber reinforced polyamide under fatigue loading *Int. J. Fatigue* 94 145–57

[15] Goh K L, Aspden R M and Hukins D W L 2004 Review: Finite element analysis of stress transfer in short-fibre composite materials *Compos. Sci. Technol.* 64 1091–100

[16] Horst J J, Salienko N V. and Spoormaker J L 1998 Fibre-matrix debonding stress analysis for short fibre-reinforced materials with matrix plasticity, finite element modelling and experimental verification *Compos. Part A Appl. Sci. Manuf*. 29 525–31

[17] LY H A, INOUE H and IRIE Y 2011 Numerical Simulation on Rapid Evaluation of Fatigue Limit through Temperature Evolution *J. Solid Mech. Mater. Eng*. 5 459–75

[18] Pitarresi G and Patterson E A 2003 A review of the general theory of thermoelastic stress analysis *J. Strain Anal. Eng. Des.* 38 405–17

[19] Biot M A 1956 Thermoelasticity and irreversible thermodynamics *J. Appl. Phys.* 27 240–53

[20] Rittel D, Zhang L H and Osovski S 2017 The dependence of the Taylor–Quinney coefficient on the dynamic loading mode *J. Mech. Phys. Solids* 107 96–114

[21] Kang G Z and Gao Q 2002 Tensile properties of randomly oriented short δ-Al2O3 fiber reinforced aluminum alloy composites: II. Finite element analysis for stress transfer, elastic modulus and stress-strain curve *Compos. - Part A Appl. Sci. Manuf*. 33 657–67

[22] Houshyar S, Shanks R A and Hodzic A 2009 Modelling of polypropylene fibre-matrix composites using finite element analysis *Express Polym. Lett*. 3 2–12

[23] Arif M F, Meraghi F, Chemisky Y, Despringre N and Robert G 2014 In situ damage mechanisms investigation of PA66/GF30 composite: Effect of relative humidity *Compos. Part
[24] De Monte M, Moosbrugger E and Quaresimin M 2010 Influence of temperature and thickness on the off-axis behaviour of short glass fibre reinforced polyamide 6.6 - Cyclic loading

*Compos. Part A Appl. Sci. Manuf.* **41** 1368–79