Multi-Scale Damage and Mechanical Behavior of Sheet Molding Compound Composites Subjected to Fatigue, Dynamic, and Post-Fatigue Dynamic Loadings

M. Shirinbayan, J. Fitoussi, N. Abbasnezhad, A. Lucas, A. Tcharkhtchi

Abstract**—**Sheet Molding Compounds (SMCs) with special microstructures are very attractive to use in automobile structures especially when they are accidentally subjected to collision type accidents because of their high energy absorption capacity. These are materials designated as standard SMC, Advanced Sheet Molding Compounds (A-SMC), Low-Density SMC (LD-SMC) and etc. In this study, testing methods have been performed to compare the mechanical responses and damage phenomena of SMC, LD-SMC, and A-SMC under quasi-static and high strain rate tensile tests. The paper also aims at investigating the effect of an initial pre-damage induced by fatigue on the tensile dynamic behavior of A-SMC. In the case of SMCs and A-SMCs, whatever the fibers orientation and applied strain rate are, the first observed phenomenon of damage corresponds to decohesion of the fiber-matrix interface which is followed by coalescence and multiplication of these micro-cracks and their propagations. For LD-SMCs, damage mechanisms depend on the presence of Hollow Glass Microspheres (HGM) and fibers orientation.

Keywords**—**SMC, LD-SMC, A-SMC, HGM, damage.

I. Introduction

THE aim of the automobile industries is to produce the most light-weighted vehicles, so it can be more fuel-efficient and in another hand to have more stiffness, for this reason, fiber-reinforced polymer composites have almost replaced with metal parts [1]-[3]. The difference between these two materials is that metal structures respond with folding or buckling when it is under impact loading, whereas the composite materials fail while facing a sequence of damage mechanism, such as cracking of matrix or fiber, debonding between them and crack propagation. SMCs are the materials which are widely demanded by industry especially the automotive industry because of cost-efficient lightweight and large body panels. They are almost consisting of a vinyl-ester or polyester resin reinforced by a high content of chopped bundles of glass fibers. They have almost high energy absorption capacity, so it interests the engineers to use it for absorbing energy, while a car crash happens [4], [5].

In this study, particular interest is given to the aspects related to the microstructural variability of the SMC composite induced by the manufacturing process. Indeed, these aspects (variability of volume fraction and orientation distribution of reinforcements) strongly influence the mechanical properties of the material in the elastic phase but also in the nonlinear phase related to the development of damage phenomena.

The reduction of tensile rigidity is a scalar indicator of macroscopic damage often used for composite materials. It is easily evaluated on the occasion of loading-unloading tests with a progressive increase of the loading. A residual slope measurement is used to define a macroscopic damage variable. It is interesting to define at the microscopic scale, an indicator of damage directly related to the evolution of the density of micro-cracks [6]-[13]. Microscopic damage mechanisms can be identified using SEM observations on polished sample surfaces. One can, in particular, define a relative density of damage at the interface fiber-matrix through the division of the volume fraction of the fibers detached at the interface in the fiber volume content in the Representative Elemental Volume (REV) [6]-[13]. For short fiber composites and for SMC composites, in particular, four types of local damage are likely to develop: matrix cracking, decohesion at the fiber-matrix interface, fiber break, and pseudo-delamination. In order to better understand and identify about the damage behavior, for a suitable choice of damage behavior law and for identification of its parameters whatever the numerical approach is used, a thorough knowledge of the type of local damage mechanisms, their threshold and kinetic is always needed on the other hand [6]-[13]. Moreover, for the effective use of SMC composites, their response under various types of loading should be clearly understood. Comprehending the fatigue behavior is an important role in characterization the cyclic response of the materials. This behavior is usually shown by S-N curve (the value of cyclic stress or strain amplitude versus the number of cycles to failure, N), which is named as a Wöhler curve [14], [15]. The main factors that affect the cyclic behavior of the composite materials are fiber orientations, applied stress or strain, temperature, frequency, and induced self-heating [16]-[21]. As in a study by Wang and Chim [22], they have indicated that by increasing the fatigue stress, σ_{max}, stiffness of the material and in consequence the

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fatigue life of the material decreases.

High strain rate tensile test is known as a classical method for characterizing the crash behavior wherein the mechanical behavior of the material is sensitive to the loaded rate [7]-[13].

In this article we aim to answer the question about the effect of the fatigue loading on the residual dynamic behavior of A-SMC composites.

II. Materials and Methods

A. Architectures of SMC Composites

The components and the microstructures of the three discussed composites are briefly presented in Fig. 1. One can note that standard SMC has the density about 1750 kg/m^3 with 26% of glass fiber content in mass. By considering standard SMC as a reference composite, there are two aims to have different architectures; the first is to increase fiber content using vinyl-ester resin as a matrix. In this case, we can get to a high-performance SMC composite (A-SMC). It has about 50% of glass fiber contents in mass which gives the density of about 1950 kg/m^3. The second aim is to have low-density SMC. In this case, about 22% in mass of hollow glass spheres used to decrease the density to about 1220 kg/m^3. A comparison between a standard SMC microstructure and those of A-SMC and LD-SMC is clearly shown in Fig. 1.

1. Standard SMC

Standard SMC consists of an unsaturated polyester resin which is reinforced with glass fibers and filled with calcium carbonate fillers ($CaCO_3$). Glass fibers have a weight content of 26% and are assembled in bundles in such a way that each one contains approximately 200 fibers. These bundles are randomly oriented in the material with a constant length of 25 mm and the fiber diameter of 15 µm. The random distribution of reinforcement confers to the material a microscopic heterogeneous aspect and an overall transverse isotropic mechanical behavior [9].

2. Advanced Sheet Molding Compound (A-SMC)

A-SMC consists of a vinyl-ester resin reinforced by a high content of chopped bundles of glass fibers (50% in mass which corresponds to 38.5% in volume) [6].

3. Low-Density Sheet Molding Compound (LD-SMC)

LD-SMC is a type of SMC consisting of a polyester resin reinforced with 25-30% of chopped glass fibers bundles (25 mm length) and 22% of hollow glass spheres (in mass) [13].

Moreover, A-SMCs and LD-SMCs were provided in two microstructure configurations of randomly Oriented (RO) and highly oriented (HO) obtaining by an initial charge put only in the left part of a rectangular mold before compression leading to material flow. Plastic omnium auto exterior has provided all of the SMC composites.

B. Characterization Methods

1. Fatigue Tests

Tension-tension fatigue tests have been conducted at various applied maximum stress on MTS 830 hydraulic fatigue machine. Stress ratio in all the tests was chosen to be equel to R = 0.1. In this paper, the experimental results refering to the ferequency of 30 Hz are presented. In order to have the exact measurement of the stiffness reduction due to the first loading stage, each fatigue test was followed by a quasi-static tensile loading-unloading-reloading stage. Self-heating phenomenon was characterized during the tests by measuring the temperature evaluation by the aide of an infrared camera (Raynger-MX4) in a defined area (maximum temperature). The evolution of Young's modulus is also determined.

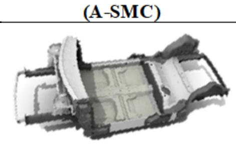
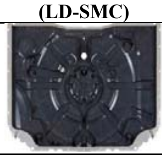
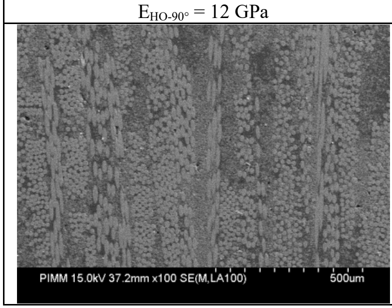
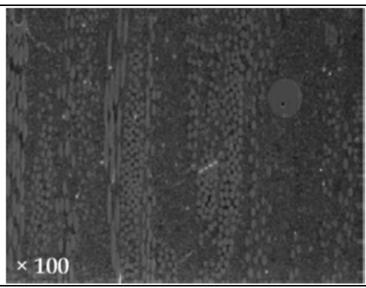
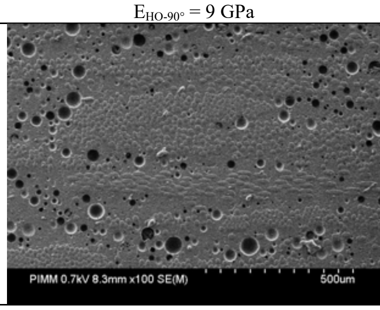
High-performance SMC (A-SMC)	Standard SMC	Low-Density SMC (LD-SMC)
		
Glass fibers 50% in mass	Glass fibers 26% in mass	Glass fibers 25-30% in mass
ρ = 1950 kg/m^3	ρ = 1750 Kg/m^3	ρ = 1220 kg/m^3
$E_{HO\text{-}0°}$ = 18.5 GPa E_{RO} = 14.5 GPa $E_{HO\text{-}90°}$ = 12 GPa	E_{RO} = 11.3 GPa	$E_{HO\text{-}0°}$ = 12 GPa E_{RO} = 10 GPa $E_{HO\text{-}90°}$ = 9 GPa
		

Fig. 1 Architectures of SMC composites

2. Tensile Tests

Quasi-static tensile tests by the speed of 2 mm/min have been achieved with MTS 830 hydraulic machine. High-strain rate tensile tests have been done on a servo-hydraulic test machine (Schenk Hydropuls VHS 5020). This machine can reach a strain rate range from 10^{-4} m/s (quasi-static) to 20 m/s. Also, the load level is measured by a piezoelectric crystal load cell with the capacity of a 50 kN. There is a launching system in this equipment and the sample is placed between the load cell (upper extremity) and the moving device (lower extremity) as drawn in Fig. 2. A contactless technique [6] was used to measure the local deformation using a high-speed camera (FASTCAM-APX RS).

3. Specimen Geometry

In a previous study [9], FE simulations resulted in the determination of optimal geometrical parameters for high-speed tensile tests: L_1, L_2, L_3 and R (Fig. 3). These parameters are optimized for reducing the stress wave effects and of generating homogeneous stress/strain field during high speed tensile tests. The experimental coupled loading of fatigue-crash was performed on the same geometry of the sample.

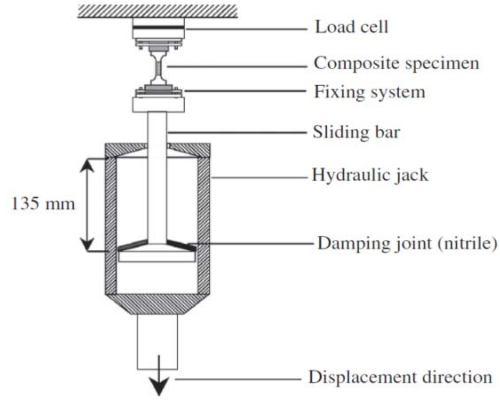


Fig. 2 Experimental device used for high-speed tensile tests

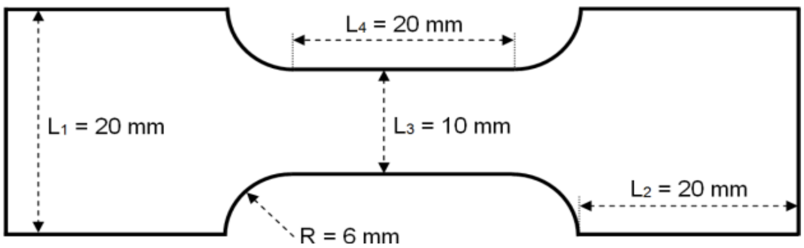


Fig. 3 Obtained specimen dimension from optimization procedure results

III. Influence of the Architecture of the SMC Composites on the Damage Mechanism

All types of SMC composites are sensitive to the rate of loading, which influences their mechanical responses. Hence, for the effective use of these composites, their responses under different strain rates should be clearly understood. During experimental high-speed tests, the composite is generally subjected to rapid accelerations. It has been verified that by increasing the strain rate, a delay in damage onset is followed by a slightly reduced damage kinetic. The notion of visco-damaged behavior which is due to the fiber/matrix interface strength and is also time-dependent has been emphasized for different architectures of SMC composites. Hereby damage mechanisms of the mentioned SMCs are illustrated.

A. Standard SMC: Damage Initiations and Propagation through Debonding of Interface Fiber/Matrix

In the case of standard SMC composites, the initiation of micro-cracks at the fiber/matrix interfaces followed by their coalescence remains the predominant phenomenon. Results showed that the damage threshold in terms of stress and strain increases with increasing strain rate, whereas elastic modulus remains insensitive to the strain rate [9].

B. A-SMC Composite: Damage Initiations through Interface Decohesion and Damage Development by Transverse Cracking in the Matrix

In the case of Randomly Oriented A-SMC, an analysis of the damage phenomenon carried out at quasi-static loading. The first observed phenomenon of damage corresponds to decohesion at the fiber-matrix interface. This phenomenon is the predominant mechanism initiation of micro-cracks. It appears from the first non-linearity. This phenomenon starts first on the interfaces which contain disoriented reinforcements and spreads slowly through the overall volume of the composite. Indeed, the most disoriented fibers in the direction of loading are subjected to a high local normal stress at the interface. At inside each fiber bundle, a fiber-matrix interface failure propagates to its neighbor and quickly spreads from one to another through the matrix. When the crack reaches another bundle, it is deflected according to the orientation of the reinforcements of the bundle encountered. Thus, a network of cracks generally perpendicular to the direction of traction develops. In fact, initiation of damage phenomenon at the fiber-matrix interface followed by a progressive propagation of crack which appears gradually several times on each bundle (Fig. 4). Pseudo-delamination between the bundles of fibers coupled to micro-cracks in the matrix always occurs before final failure and is favored by high strain rates, as well as fiber orientation is in the loading

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direction.

Fig. 5 enables to emphasize that the material elastic modulus measured in the first stage of the stress-strain curve remains insensitive to the strain rate. One can note that the damage threshold, in terms of stress and strain, increases with strain rate.

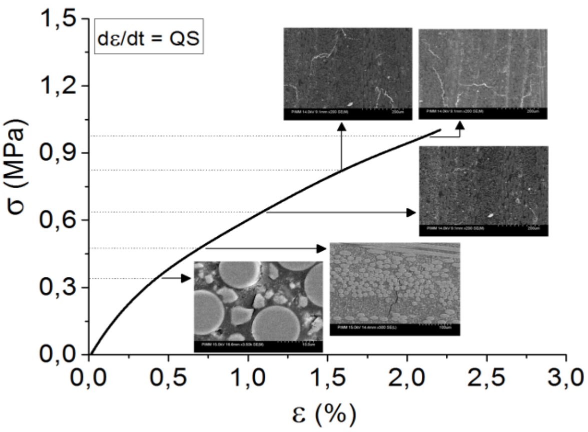

Fig. 4 Damage mechanisms of A-SMC under quasi-static tensile loading

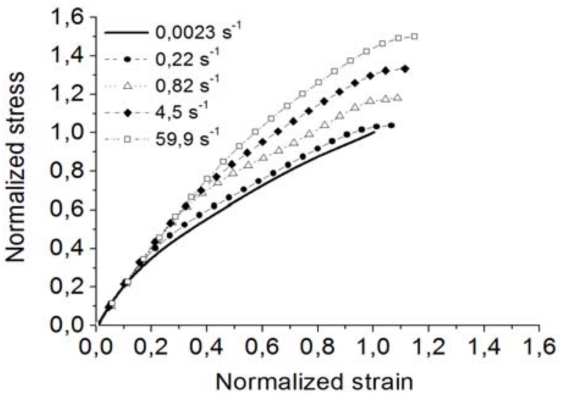

Fig. 5 Experimental high strain rate tensile curves of RO-A-SMC (Normalized stress (resp. strain) = stress (resp. strain)/ultimate stress (resp. strain) obtained in quasi-static

C. LD-SMC Composite: Damage Mechanisms Depends on the Presence of HGM and Fibers Orientation

In the case of standard SMCs, the damage is usually initiated in the fiber-matrix interface which is the main reason for the progressive degradation of the composite. In the case of LD-SMCs, fiber-matrix interface damage is in competition with the damage of the hollow glass-matrix interface, shown in Fig. 6. In the case that the most of the fibers are aligned along with the loading direction (HO-0° configuration) the principal damage mechanism is referred to fiber-matrix debonding, and for the fibers that are perpendicularly oriented to the loading direction (HO-90° configuration), the main damage mechanism is followed by HGM-matrix debonding.

Fig. 7 shows the effect of strain rate on the tensile behavior of RO-LD-SMC. Results show that by increasing the strain rate from quasi-static to high strain rate damage threshold in term of stress and strain increases.

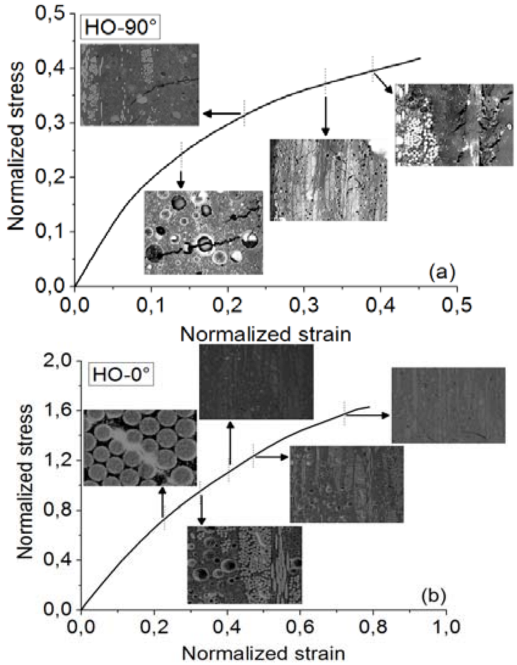

Fig. 6 Damage mechanisms of LD-SMC under QS tensile loading: (a) HO-90° and (b) HO-0°

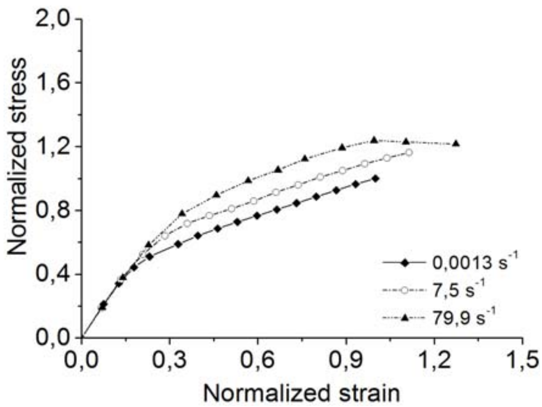

Fig. 7 Experimental high strain rate tensile curves of RO-LD-SMC (Normalized stress (resp. strain) = stress (resp. strain)/ultimate stress (resp. strain) obtained in quasi-static

IV. Fatigue Behavior Analysis

A. Wöhler Curve and Self-Heating Phenomenon

Fig. 8 (a) shows the Wöhler curve of RO-A-SMC samples at a frequency of 30 Hz. It shows a linear logarithmic for the loading amplitudes varying from 0.45 σ_r to 0.62 σ_r. The S-N curve starts deviating for the lowest loading amplitudes. It can be noticed that a variation of the applied stress from 0.45 σ_r to 0.38 σ_r (variation of 15%) leads to 20 times higher fatigue life (resp. 10^5 cycles and 2×10^6 cycles).

Fig. 8 (b) illustrates the variation of temperature during fatigue tests at different amplitudes (f = 30 Hz). One can observe no significant temperature change before 200 cycles. In the case of fatigue tests performed at 0.62 σ_r, the temperature increases rapidly from room temperature to 60°C up to 2000 cycles while temperature variation does not exceed 10°C for fatigue tests of 0.38 σ_r. Self-heating depends directly on the viscoelastic behavior of the polymer. Increasing applied loading amplitude leads to more self-heating and matrix viscosity decreases [19]-[21].

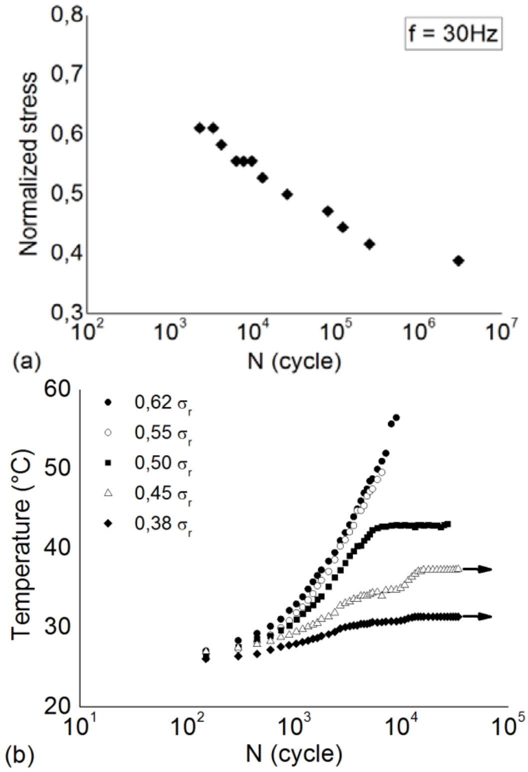

Fig. 8 (a) Normalized Wöhler curve at a frequency of 30 Hz, (b) Temperature variation at different amplitudes and frequency of 30Hz (Normalized value = current value / average ultimate stress value (σ_r) obtained for quasi-static tensile tests performed on RO-A-SMC)

V. Post-Fatigue Dynamic Tensile Behavior

To study on the post-fatigue dynamic tensile behavior of A-SMC, the selected variability parameters will be the fatigue lifetime fraction N/N_r which is directly related to the fatigue damage state characterized by the progressive decrease of the relative stiffness E/E_0. The second parameter is the amplitude of the applied stress in fatigue. The value of applied stress was defined: 0.45 σ_r (σ_r: ultimate stress obtained for quasi-static tensile tests defined as a reference). The cyclic loadings were interrupted at varous lifetime values, N/N_r, i.e. around 3%, 15% and 35% according to Table I.

Tensile tests at different strain rates (from QS to 60 s^{-1}) were performed on several pre-fatigued RO-A-SMC samples. For illustration, post-fatigue stress-strain curves (σ-ε) are plotted in Fig. 9 for different applied strain rates and defined cycles. It should be noted that post-damage tensile curves are established at different applied strain rates. Independently of the applied strain rate, one can observe that the residual Young's modulus decreases when the applied lifetime fraction increases. Note that the normalized stress (respectively strain) corresponds to the ratio between the measured stress (respectively strain) and the ultimate stress (respectively strain) obtained for a quasi-static tensile test chosen as a reference.

TABLE I
Loading Parameters in Trials for the Study of Coupling Fatigue-Dynamic

Fatigue test			Tensile test		
Applied stress	Defined cycles	N/N_r (%)	Strain rate		
	15 000	15			
0.45 σ_r	40 000	35	quasi-static	1 s^{-1}	60 s^{-1}
	60 000	50			

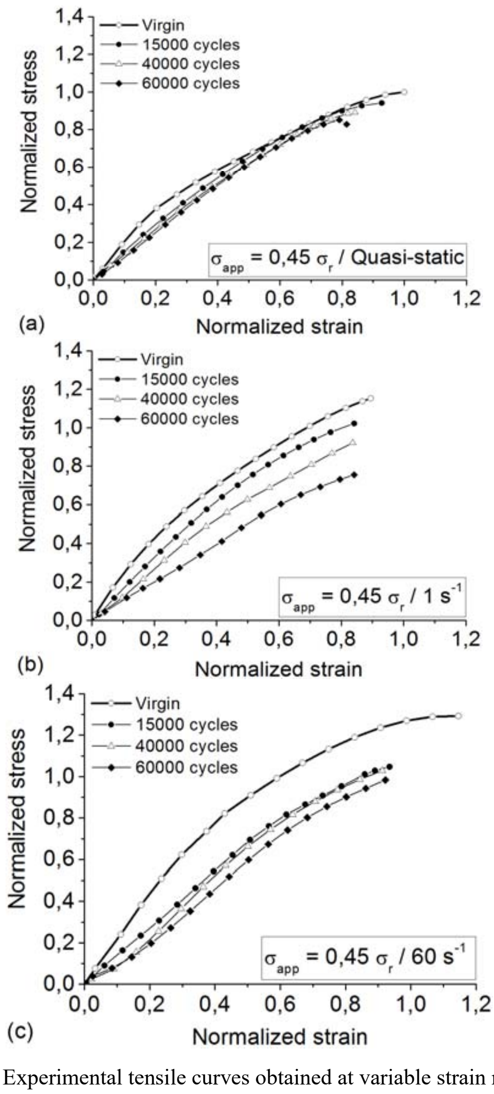

Fig. 9 Experimental tensile curves obtained at variable strain rate on specimens submitted to fatigue applied stress of 0.45 σ_r for different defined cycles: (a) quasi-static, (b) 1 s^{-1} and (c) 60 s^{-1}

VI. Strain Rate Effect on Fatigue Pre-Damaged A-SMC

A. Residual Stiffness

In order to get good precision on the post-fatigue damage state, prior to all dynamic tensile stage the elastic modulus (initial slopes of the stress-strain curves) was measured by quasi-static tensile loading until 50% of the maximum stress applied during the previous fatigue stage. These values are then compared to the virgin material elastic moduli at different strain rates. Fig. 10 shows the evolution of E/E_0 for pre-damaged A-SMC obtained from the dynamic tensile test as a function of strain rate for different fatigue loading conditions and lifetime fractions. As expected, one can observe that the residual Young's modulus decreases when increasing the applied fatigue lifetime fraction. However, it is obvious that, even after the fatigue stages, the strain rate effect remains negligible similarly to the virgin material. It is noticeable too that the stiffness variation with the applied fatigue lifetime is of the same magnitude for all the applied fatigue amplitude. Therefore, one can conclude that the local repeated deformations during fatigue stages do not affect the dynamic macroscopic stiffness.

B. Threshold and Ultimate Characteristics

Post-fatigue material characteristics, namely damage thresholds corresponding to the first non-linearity ($\sigma_{threshold}$; $\varepsilon_{threshold}$) and ultimate stress and strain ($\sigma_{ultimate}$; $\varepsilon_{ultimate}$), are plotted as a function of strain rate in Fig. 11 for applied fatigue amplitude of 0.45 σ_r. Normalized characteristic (strain or stress) is defined to be the ratio between the considered characteristic (strain or stress respectively) under specific loading history (i.e. a given post-fatigue tensile loading) and ultimate quasi-static characteristic (strain or stress respectively). Indeed, the quasi-static tensile response is defined as a reference. Note that the ultimate characteristics correspond to the maximum stress (or strain) level (before delamination when it occurs). It is obvious that the non-linear overall response of both non-damaged A-SMCs and fatigue pre-damage A-SMCs composites are drastically influenced by the strain rate.

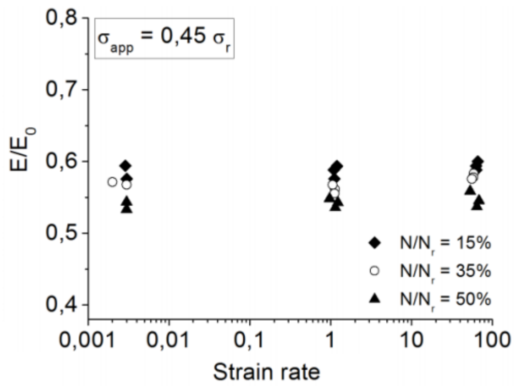

Fig. 10 Influence of strain rate on the elastic modulus; $\sigma_{app} = 0.45\ \sigma_r$

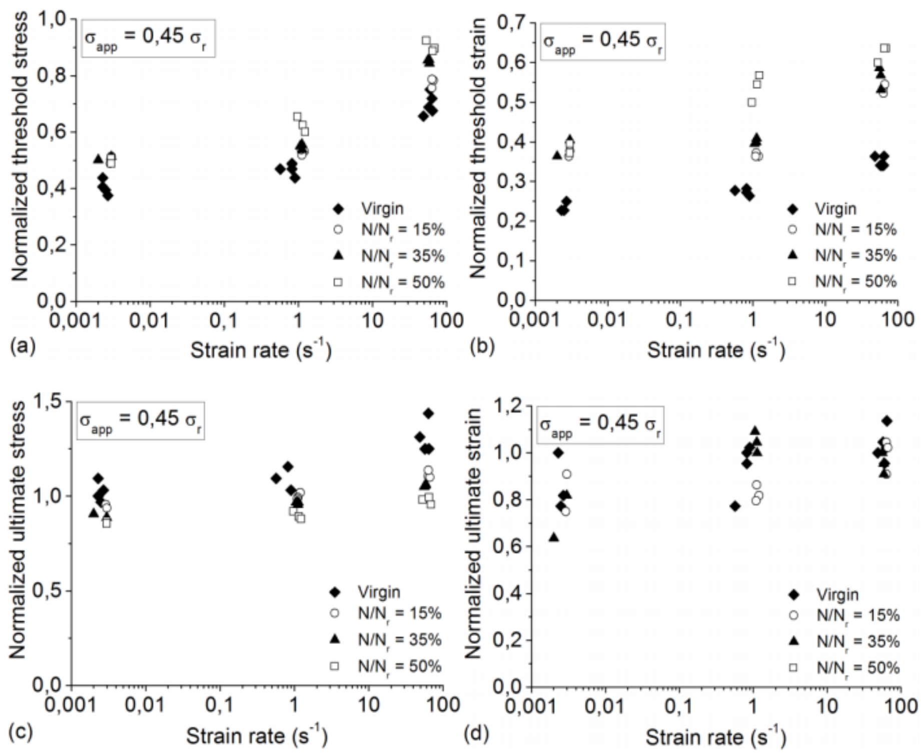

Fig. 11 Influence of strain rate on: (a) Normalized threshold stress, (b) Normalized threshold strain, (c) Normalized ultimate stress and (d) Normalized ultimate strain; ($\sigma_{app} = 0.45\ \sigma_r$)

One can note the particularly high strain rate dependence of the damage threshold independent of the loading conditions. Indeed, one can observe until more than 100% variation of the threshold stress and strain. Moreover, for all tests, no significant strain rate effect is noticed on the ultimate strain.

As mentioned above, according to the curves of Fig. 11, it is observed that the fatigue pre-damaged samples present a remaining monotonic mechanical potential always lower than the virgin samples. One can also notice that this decrease is independent of the strain rate. Indeed, the curves remain parallel and their level is the only function of the lifetime fraction (or in the other words the reached damage level).

From the results, one can note that the effect of fatigue on damage threshold in the quasi-static tensile test is low, also can be considered as negligible, but it comes to be important at high strain rate. This effect is especially noticeable at the high-applied amplitude and more affected pre-damage in the fatigue test.

One can notice that when the damage degree affected in cyclic loading is important, sensitivity to strain rate increases. This remarks that the viscous effect of damage is firmly related to the propagation of micro-cracks pre-existing in the fatigue test. The principal damage mechanism for A-SMC composite is related to propagation of cracks initiated at the fiber-matrix interface.

VII. Conclusions

Referring to the results, the subsequent conclusions can be obtained:

- By comparing the fatigue behavior at the frequency of 30 Hz at different maximum applied stress, once equal to 0.45 σ_r and the other equal to 0.38 σ_r, the fatigue life is obtained about 10^5 cycles and about 2×10^6 cycles respectively. Consequently, one can note that an applied stress variation of 15% leads to a fatigue life 20 times higher.
- This table briefly presents the damage mechanism of different architectures of SMC composites:

TABLE II
RUPTURE MECHANISMS: COALESCENCE AND PSEUDO DELAMINATION IN THREE DIFFERENT SMCS: A-SMC, STANDARD SMC AND LD-SMC

High-performance SMC(A-SMC)	Standard SMC	Low-Density SMC (LD-SMC)
Damage initiation: Decohesion at fiber-matrice interface Damage propagation: Crack pass through the matrix and bundles of fibers	Damage initiation and Propagation: Decohesion at fiber-matrice interface	Damage initiation and Propagation: Depends to the condition of hollow glass spheres and the tendency of reinforcements. ***At 0°*** Decohesion at the fiber-matrice interface ***At 90°*** Decohesion at interface of glass spheres

- Elastic modulus remains insensitive to strain rate after tensile loading of pre-damaged A-SMCs.
- The pre-damaged samples present a remaining monotonic mechanical potential always lower than the virgin samples. This decrease is independent of the strain rate.
- Influence of pre-damage by cyclic loading on the damage threshold is low in the quasi-static loading and becomes important at high strain rate loadings.
- One can note that when the degree of damage affected by fatigue is important, sensitivity to strain rate increases.

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