Microstructure dependent fatigue life prediction for short fibers reinforced composites: Application to sheet molding compounds

M.A. Laribi[a,b,*], S. Tamboura[c], J. Fitoussi[b], M. Shirinbayan[b], R.Tie Bi[d], A. Tcharkhtchi[b], H. Ben Dali[c]

[a] Institut Clément Ader ICA, CNRS UMR 5312, 3, Rue Caroline Aigle, 31400 Toulouse, France
[b] Arts et Metiers Institute of Technology, CNAM, PIMM, HESAM University, F-75013 Paris, France
[c] Ecole Nationale d'Ingénieurs de Sousse, LMS, Pôle technologique, Route de Ceinture, 4054 Sousse Tunisie
[d] Zero Emission, FAURECIA CLEAN MOBILITY, Bois sur Prés, 25550 Bavans, France

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A B S T R A C T

Because of the high variability of SMC microstructure due to material flow during thermoforming, fatigue life prediction in real automotive structure represents a huge challenge. In this paper, we present a two-step microstructure selection involving an original ultrasonic method which is briefly presented. Then, on the basis of four selected microstructure configurations, an accurate experimental damage analysis is performed including both monotonic and cyclic loading. The high microstructure dependence of the obtained Whöler curves is demonstrated. Moreover, an experimental link between monotonic damage and fatigue life is emphasized. Then, a new fatigue life prediction methodology based on the later is proposed. This methodology also uses a micromechanical damage model in which a local damage criterion is involved for monotonic loading damage prediction. A very good agreement between experimental and predicted Whöler curves is demonstrated for all studied microstructures and three working temperatures. Finally, the model allows building a microstructure dependent Whöler curve abacus which may be very useful for SMC structures design.

1. Introduction

The use of composite materials is strongly conditioned by the ability of manufacturers or subcontractors to design automotive structures under various complex loading such as fatigue or crash. However, in real automotive parts, composite microstructures are always determined by the shaping process which always involves strong material flow during molding. Consequently, real structure parts inevitably contain multiple microstructures extremely variable from one location to another. In the case of SMC composites, semi-product sheets are manufactured by dispersing long bundles (usually 25 mm) of chopped fibers (commonly glass fibers or carbon fibers) on a bath of thermoset resin (commonly polyester resin, vinyl ester or epoxy resin). After a storage period while it matures, the material is cut into charges which are placed on specific areas of the mold depending on the required shape. Compression molding at high temperatures (usually around 160 °C) allows the charge to fill the mold by flowing. Once fully cured, the finished product is then removed from the mold. Therefore, the specific placement of the SMC semi-product and material flow during hot pressure molding will determine the spatial distribution of the microstructure in the composite structure. An illustration of the latter variability is given [1] where microstructure measurement results are obtained from an original ultrasonic technique (briefly presented in paragraph 2.2.1). For comparative purposes, it can be shown that microstructure scattering observed in SMC structures is far greater than that observed in the case of a thermoplastic matrix composite structure obtained by injection molding [2,3]. To a lesser extent, this variability is also observed within a plate processed for the purposes of the study (see Fig. 2).

In addition, it is well known that the mechanical properties of short fiber reinforced composites are highly dependent on microstructure [4,5]. The latter must be considered as a major input to behavior laws and limit criterion (failure or damage) used in finite elements calculation for structure design [6,7]. All the parameters used in the latter constitute the "material card" which determines the mechanical response including the threshold and kinetic of damage and failure. Given

* Corresponding author.
E-mail addresses: Mohamed-Amine.Laribi@ensam.eu, mohamed-amine.laribi@iut.tlse3.fr (M.A. Laribi), sahbi.tamboure@gmail.com (S. Tamboura), joseph.fitoussi@ensam.eu (J. Fitoussi), mohammadali.shirinbayan@ensam.eu (M. Shirinbayan), bob.valor-ext@faurecia.com (R.T. Bi), abbas.tcharkhtchi@ensam.eu (A. Tcharkhtchi), hachmi.bdaly@gmail.com (H.B. Dali).

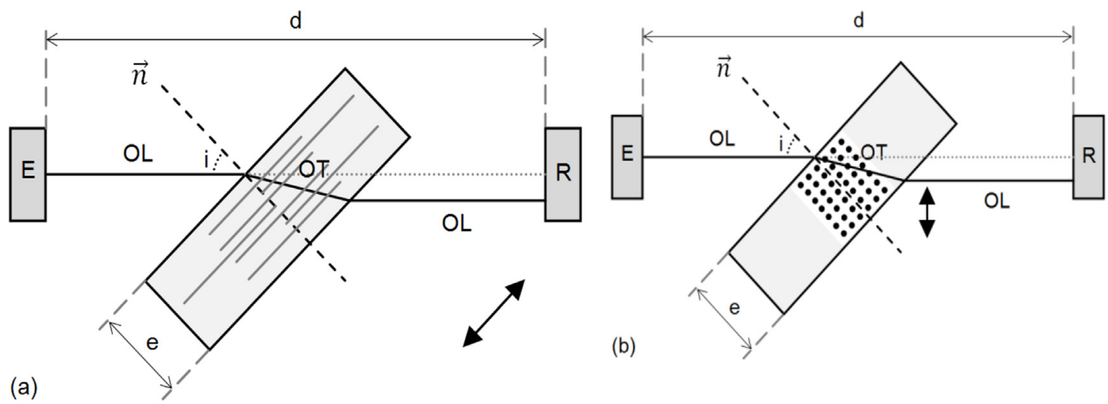

Fig. 1. Methodology of determination of the fiber orientation (a) High V_{OTmax} (b) Low.V_{OTmax}

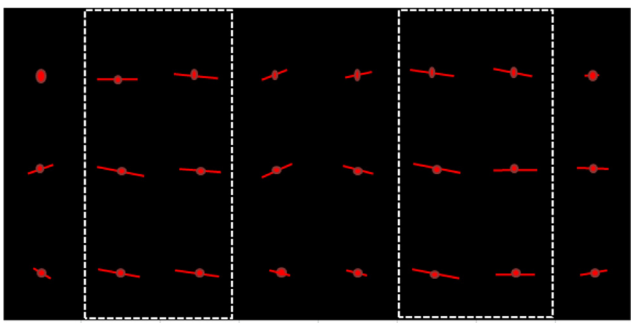

Fig. 2. Ultrasonic test for a HO SMC Plate.

Table 1
Average values of the birefringence factor measured for the three selected microstructures.

Microstructure	HO	RO	TG60°
K%	7.5 ± 1	3.5 ± 0.5	5.6 ± 0.8

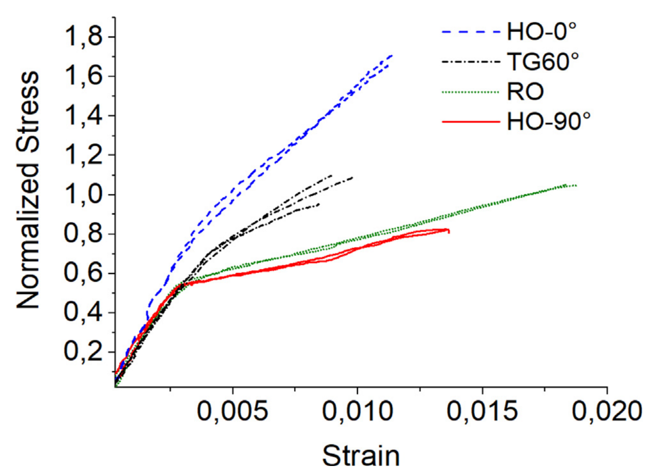

Fig. 3. Tensile test for the selected specimens.

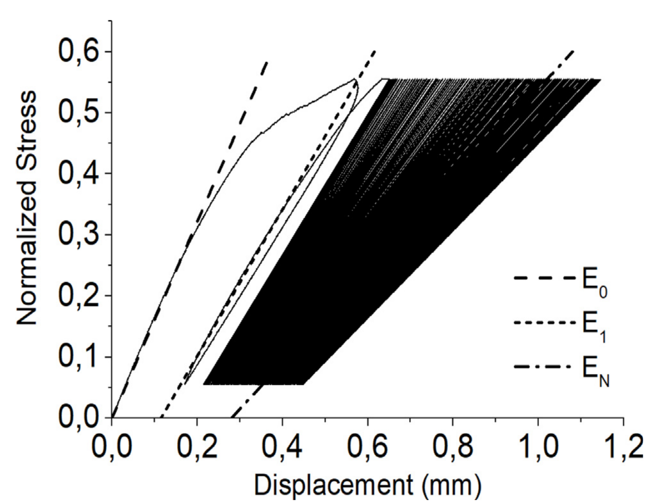

Fig. 4. Mechanical characterization procedure; preliminary loading-unloading-elastic reloading and fatigue.

the extreme microstructure variability in SMC parts, it should be necessary, in absolute terms, to develop one material card per zone. In the case of fatigue loading, it supposes costly and time consuming experimental campaigns.

In order to address this difficulty, micromechanical modeling can be a suitable tool.

Several authors have proposed different micromechanical models including damage at the local scale. In Short Fiber Reinforced Composites (SFRC), fiber-matrix interface debonding is frequently presented as the predominant local damage mechanism [8]. Matrix micro-cracking can also participate in composite degradation and sometimes fiber breaking and pseudo-delamination [9,10,11]. Therefore, a damaged state can be described as a matrix in which are distributed reinforcements and micro-cracks. When microstructure and local damage state are known, it is possible to use homogenization technique to compute step by step macroscopic response of the considered composite [12,13] until final failure. Several micromechanical models introduce fiber–matrix interface [12] and matrix micro-cracks through local damage criteria put in competition. Sometimes, fiber breakage can also be taken into account [9] but is generally presented as a secondary local damage mechanism in SFRC. These local criteria are given in a statistical form in order to take into account the local variations of the microstructure [12,13,14,15]. They also can be strain rate dependent in order to take into account the effect of high speed loading [1,16,17,18]. The different populations of micro-cracks are introduced in the form of zero stiffness heterogeneities [19]. Some approaches propose models taking into account the progressive debonding of the interface [14,15,20]. Despringre & al. [21] have recently proposed to take into account the effect of fiber-matrix debonding through a decrease in the load transfer rate at the interface. Earlier, interface damage effect had been described by replacing a debonded fiber by an equivalent volume of matrix [14,15,22]. Jendli [12] considers that interface debonding effect is well described by both partial reductions of the fiber volume fraction and introduction of zero stiffness heterogeneity. To the same objective, Fitoussi & al. [14] proposed the

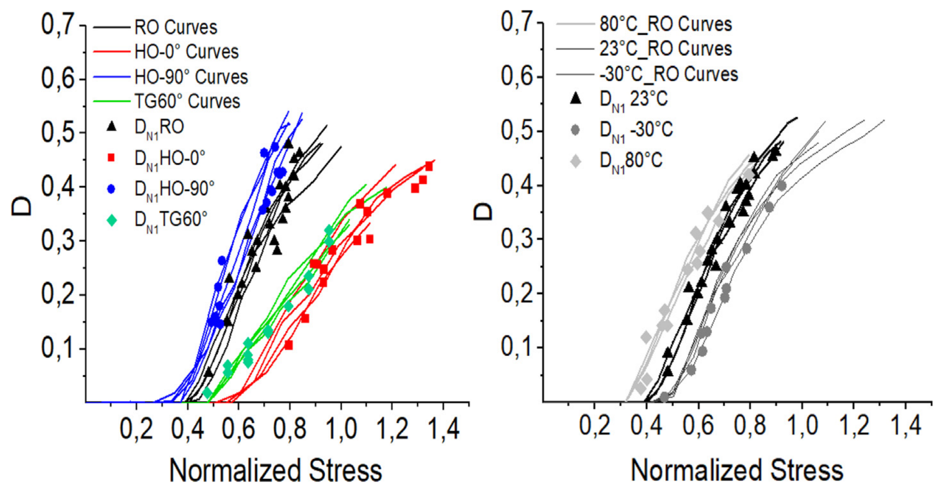

Fig. 5. Macroscopic damage parameter (a) for different microstructures (b) for RO microstructure at different temperatures.

concept of an equivalent anisotropic damage inhomogeneity.

It must be noticed that it is also possible to introduce local damage by using continuum damage mechanics at the local scale [23–26]. Two or four order damage tensors allow progressive weakening of the matrix, the fibers and the interface. Macroscopic behavior is then obtained by homogenization.

Generally based on the Mori and Tanaka approach [27], homogenization is performed in one or several steps. Two steps homogenization is used in order to take into account the effect of specific damage mechanisms at one phase scale such as in the work of Desrumaux & al. [28] in which a first homogenization is performed at the matrix scale by introducing zero stiffness heterogeneities. Fibers are then introduced into an equivalent homogenized damaged matrix and fiber-matrix interface debonding is taken into account during the second step homogenization. In the case of SMC composites in which fibers are introduced in the form of bundles, Jendli & al. [12] choose to performed homogenization at the bundle scale. Then, homogenized damaged bundles are introduced in the matrix by a second homogenization. In a similar way, Doghri & al. [26] introduced the concept of pseudo-grain regions which always contain only one family of heterogeneity. In a second step macroscopic behavior is obtained by Mori and Tanaka homogenization considering each pseudo-grain as one phase.

SFRC fatigue damage and fatigue life prediction are some of the most critical subjects in automotive structure design. As in the case of monotonic loading, fatigue damage can also be described by local damage criteria or local damage laws [29,30] which parameters depend on the number of imposed cycles. Despringre & al. [21] have recently proposed a micromechanical model of fatigue behavior of short glass fiber reinforced polyamide (PAGF30) based on the Mori and Tanaka approach. The authors proposed several local damage laws describing fiber-matrix debonding, matrix micro-cracking and fiber breakage. These local damages laws act simultaneously to describe the evolution of damage at the microscopic scale during fatigue loading. Mori and Tanaka homogenization scheme allows determining the macroscopic response of the composite. The principal interest of this kind of approach lays in its strong physical content which allows taking into account explicitly the microstructure variations due to damage. However, the use of these models, when implemented in industrial finite element tools, implies time consuming numerical procedures which restrict the practical applicability of this approach in the case of fatigue loading.

Another specific difficulty of fatigue life characterization and prediction lays in the long and costly experimental campaigns involved in fatigue characterization. Marco and al. used thermal measurement during self-heating and analyzed heat energy to predict Whöler curves [31]. This method provides good results in the case of polymers and rubbers [32]. In the case of composites, changing microstructure characteristics such as fiber or matrix nature or reinforcement spatial distribution imposes a new characterization. In order to avoid this problem, Jain & al. [30,33], propose a methodology based on a master Wöhler curve established using specimen presenting a specific known microstructure. The authors used this master curve together with a Mori and Tanaka based micromechanical model including plasticity and damage in order to predict the Wöhler curve of each new targeted microstructure. This approach builds on an experimental observation which leads to the assumption that, for similar number of cycles to failure, the loss of stiffness curves for different microstructures can be considered as equivalent. However, experimental evidence shows that this assumption is not verified in the case of thermoset based composites such as SMC.

However, Laribi & al. [29] have recently developed a fast fatigue life prediction of short fiber reinforced composites using a hybrid damage approach. The authors applied with success this new methodology to a standard SMC composite. This methodology is built on the existence of a link between damage developed under monotonic loading and that developed under cyclic loading. This link is emphasized by an equation of state relating local damage state to macroscopic damage state. The local damage is described by a global damage rate while macroscopic damage is characterized by the loss of stiffness. This equation of state is identified using the micromechanical model developed by Jendli & al. [12] and is generalized to the case of cyclic loading. The fatigue damage model is described by six parameters. Five parameters can rapidly be identified by the simulation of a simple tensile test and/or by loading-unloading tensile tests. The model was validated for different microstructures. However, the parameter describing the macroscopic damage kinetic must be evaluated experimentally for each new microstructure. Therefore, in order to avoid this limitation, it is necessary to develop a complementary methodology which can be able to predict SN curves as a function of the microstructure. Therefore, the aim of this paper is to extend the applicability of Laribi's approach. The present approach is also inspired by the Jain's master curve approach [30].

After the presentation of SMC microstructure and two experimental microstructure selection methodologies used in this study, this paper emphasizes an important experimental result showing the existing link between monotonic loading damage and fatigue life. This relation, appearing to be independent of microstructure, is used together with micromechanical simulations of monotonic loading (tensile), to establish Whöler curves for any other targeted microstructure. The model is finally used to study fatigue life sensitivity to the distribution of orientation.

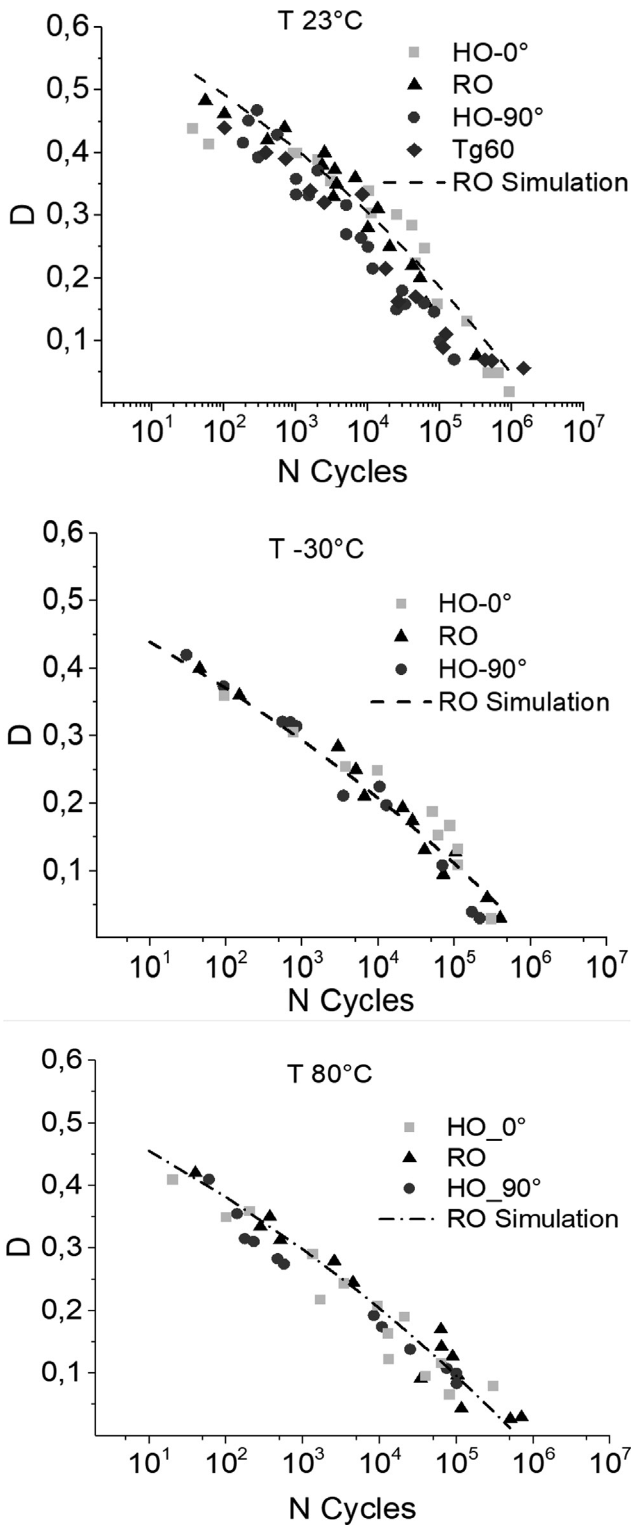

Fig. 6. Relation between monotonic first loss of stiffness and fatigue life at different temperatures.

2. Material and microstructures

2.1. Standard SMC composites

The studied material is a Sheet Molding Compound composite (SMC) used in automotive industry. It consists of an unsaturated polyester matrix reinforced by 28% weight content of glass fibers and 37% of Calcium carbonate (CaCO3) particles. Fibers are presented in the form of bundles of fibers with constant length (L = 25 mm). Approximately, each bundle contains 250 glass fibers of about 15 µm diameter. Before compression molding, the bundles are randomly oriented in the plane of the non-reticulate SMC sheet. For the need of the study, three types of microstructure have been provided by Faurecia Automotive. Two of them are presented in the form of plates. The third one is extracted from a real automotive SMC part. During plate's elaboration, it is possible to control the average distribution of fiber orientation by placing the non-reticulate SMC sheets in specific area of the mold. High Oriented (HO) plates and Randomly Oriented (RO) plates have been elaborated. HO plates have been obtained by placing the non-cured SMC only in half of the surface of a rectangular mold (120 × 250 mm^2). Due to the thermo-compression process, fibers tend to be oriented parallel to the Mold Flow Direction. RO plates were obtained by filling 80% of the mold surface. SMC sheets have been placed in the middle of the mold in order to limit material flow. These plates are obtained under an average temperature of 165 °C and a pressure of 60 Bars. Reticulation time is less than two minutes. The third used microstructure corresponds to specimens extracted from the PSA 3008 tailgate in a specific location dedicated to quality control during production.

2.2. Microstructure selection

SMC composites mechanical behavior is known to present high dispersion. In a early study of Fitoussi & al. [34] has distinguished two types of mechanical scattering in SMC composites. In this study, we focus on scattering coming from microstructure variations due to a local variations of the volume fraction and distribution of orientation of fibers. These local variations bring to a local stresses variations which finally lead to macroscopic variation of damage threshold and kinetic. Under fatigue loading, damage behavior and fatigue life are generally more sensitive to these local variations [35]. Therefore, it is of first importance to select specimens presenting different well identified microstructures in order to validate the proposed approach. To this aim, we propose two rapid assessment methodologies. The first one is based on ultrasonic measurements while the second use damage analysis.

2.2.1. Ultrasonic method for rapid microstructure selection

Several studies have shown that ultrasonic techniques are an easy and efficient methods to identify the fibers orientation through the shear wave velocity evolution. Indeed, the use of an original ultrasonic was recently illustrated by Shirinbayan & al. [1] and Meftah & al. [2]. Two probes, transmitting (E) and receiving (R), are immersed into a water flank at a fixed distance d. The sample is placed with an angle i (angle on incidence) of about 45° between the two probes in order to generate a shear waves. These waves propagate through the specimen width in a direction which is determined by the Snell-Descartes law. Consequently, one can define two limit cases: Longitudinal fibers orientation (OL) (Fig. 1(a)) and Transverse fibers orientation (OT) (Fig. 1(b)). When the fibers are oriented at 0°, they are contained in the shear plane and they offer a high section to shear (Fig. 1a). Consequently, the measured shear wave velocity value, V_{OT}, will be maximal. On the other hand, when fibers are oriented perpendicularly to this plan, the sheared section is reduced to a minimum and defines a lower value of velocity (Fig. 1b).

Thus, by a simple rotation from 0° to 360° around the normal axis of the plane of the sample ($\vec{n}$ in Fig. 1), V_{OT} evolution can be plotted in order to evaluate the fibers orientation distribution. An acoustical bi-refringence coefficient, K%, related to the fiber orientation rate can be defined as:

$$K\% = \frac{V_{OTmax} - V_{OTmin}}{\langle V_{OT} \rangle} \qquad (1)$$

where $\langle V_{OT} \rangle$ is the average of V_{OT} values. The ultrasonic analysis was

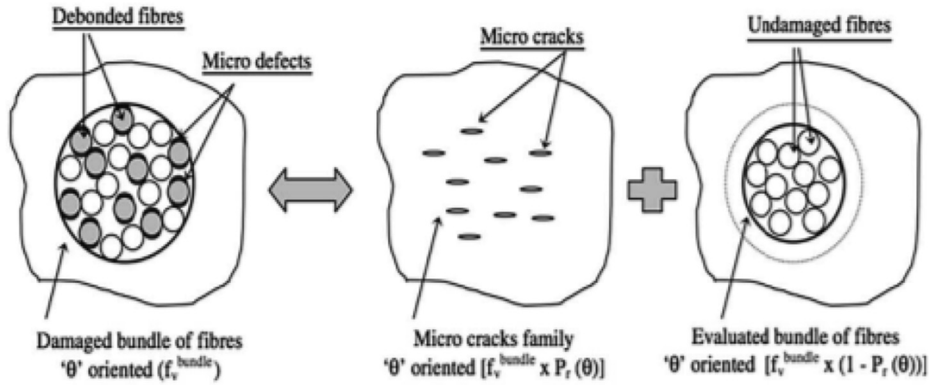

Fig. 7. Micromechanical damage description. (From Jendli & al. [12]).

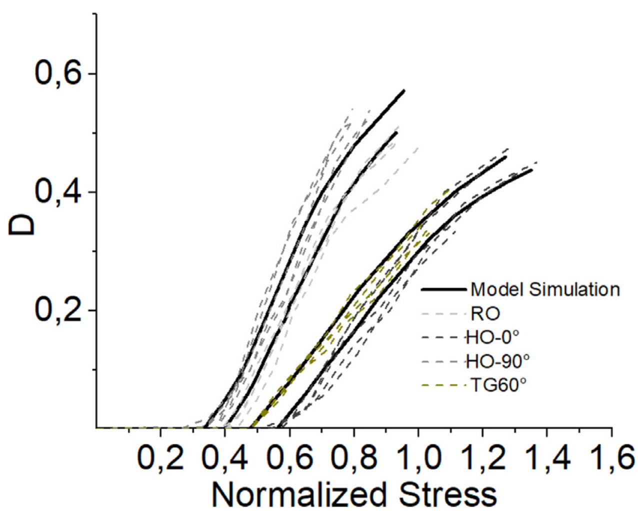

Fig. 8. Prediction of the macroscopic damage parameter evolution for differents microstructures submitted to tensile loading.

performed on specimens extracted from both SMC plates and SMC tailgate part.

2.2.2. *Application*

As an illustration, the Fig. 2 presents the ultrasonic results obtained on a high oriented SMC plate. One can observe a global orientation of the fibers in the mold flow direction. However, a relatively high scattering is emphasized (birefringence factor varying from 2 to 8.5). Moreover, to reduce the variability of the mechanical tests results, two equivalent microstructures zones have been selected. These zones are mentioned in white dotted lines in the Fig. 2. In these selected zones, specimens present the higher birefringence value and a global orientation at 0° versus the mold flow direction.

The same kinds of results are obtained with specimens extracted on RO plates and on different specimens extracted from the same location of PSA 3008 tailgates. Note that in the last cited case a preferential direction at 60° was emphasized with a good repeatability. Thereafter, this specific microstructure is noted TG60°. Table 1 summarizes these results.

2.2.3. *Selection validation by damage analysis*

In this study, quasi static and fatigue characterizations of the SMC behavior have been performed on a MTS 830 hydraulic machine. Tensile and fatigue samples were extracted from HO and RO plates. In the case of HO configurations, specimens were cut in two chosen orientations: in the flow direction (HO-0°) and perpendicularly to it (HO-90°).

In this paragraph are presented the experimental tests and their respective protocols. Then, we present a selection method based on damage analysis and dedicated to verifying that the microstructures of the selected fatigue specimens are representative of one of the three identified microstructures (HO, RO and TG60°).

Several kinds of test have been performed:

a. Tensile tests until failure on the three typical microstructures: RO, HO (0° and 90°) and TG60° (see results in Fig. 3). In Fig. 3, one can verify that specimens presenting similar ultrasonic results show similar mechanical proprieties.

b. Tension-tension fatigue tests at several levels of maximum applied stress. The operating frequency and stress ratio is f = 10 Hz and R = 0.1. One can define the loss of stiffness under fatigue loading: $\left(\frac{E}{E_0}\right)_N$. For a better identification of E_0 and the residual stiffness after the first cycle, E_1, each performed fatigue test was preceded by a quasi-static tensile loading–unloading-elastic reloading cycle. (see Fig. 4). Therefore, for each fatigue specimen, one can determine a value of the macroscopic damage parameter after a first cycle: $D_{N1} = 1 - \left(\frac{E}{E_0}\right)_{N=1}$.

Because the Young's modulus is directly related to microstructure, this preliminary procedure allows verifying that each used fatigue specimen presents the appropriate microstructure. Indeed, the measured values of D_{N1} must be consistent with the average evolution of D_σ determined by loading-unloading tensile tests until failure for the corresponding microstructure. Otherwise, the specimen is not used in the fatigue campaign. See Fig. 4where the preliminary values of D_{N1} measured on the selected fatigue specimens at different maximum applied stress appear to be consistent with the evolution of D_σ determined by loading-unloading tensile test until failure.

Therefore, the selection of the three identified microstructure specimens used in the fatigue campaign is performed by both ultrasonic measurements (birefringence factor) and the first loss of stiffness under cyclic loading (D_{N1}). Such an approach enables a better control of the microstructure and contributes to a strong reduction of scattering. In the following, we only present results obtained using the selected specimens.

c. Loading-unloading tensile tests with progressive increase of the maximal load in order to determine the evolution of the loss of stiffness: $\left(\frac{E}{E_0}\right)_\sigma$ where E is the actual Young's modulus and E_0 is the non-damaged composite Young's modulus. Therefore, one can plot the evolution of the macroscopic damage parameter defined by Kachanov [36]: $D_\sigma = 1 - \left(\frac{E}{E_0}\right)_\sigma$. See typical result in Fig. 5. Note that the proposed methodology was applied for different temperatures (−30 °C, 23 °C and 80 °C) corresponding to classical automotive requirements.

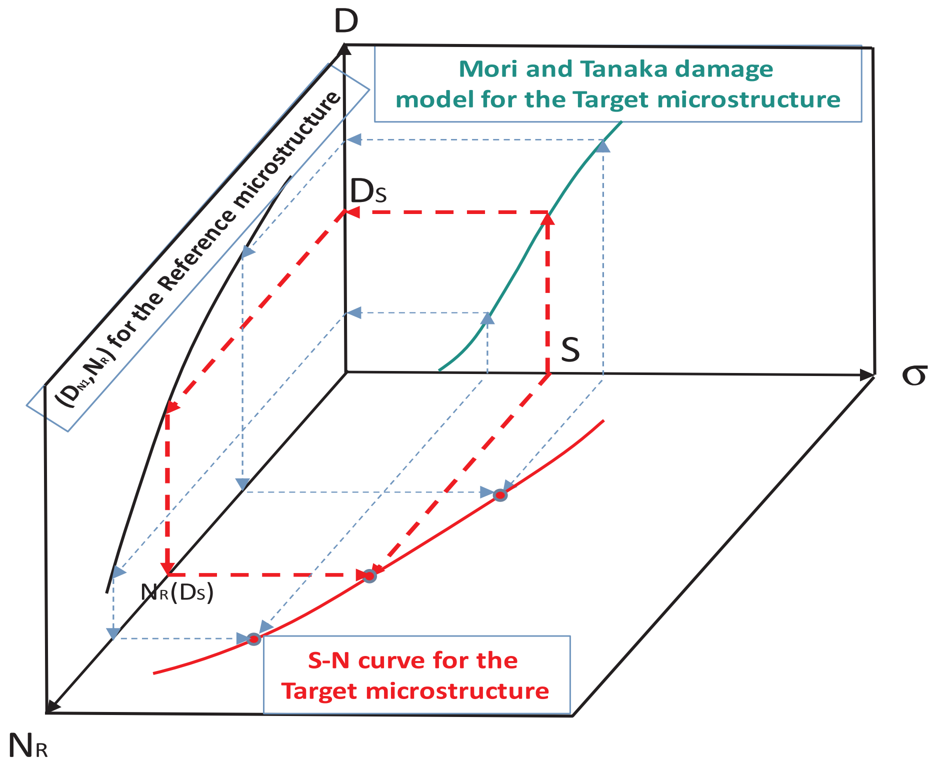

Fig. 9. Schematization of the proposed predictive methodology.

3. Experimental link between monotonic loading damage and fatigue life

3.1. *Intrinsic relationship between monotonic first damage and fatigue life*

Several authors have emphasized an existing link between monotonic behavior and fatigue life of composite materials [29,30,33]. Besides, some fatigue life predictive models are based on the residual monotonic strength [34,37]. This is due to the fact that, generally, the same damage mechanisms occur for both monotonic or fatigue loading. Except for very local effects such as strain localization around fiber-matrix interface [34,38], one can assume equivalent local damage states. Therefore, one can assume that a given local damaged microstructure state, globally described by a certain content of micro-cracks, can be reached under several types of loading history (including monotonic, fatigue, creep, high strain rate or thermal loading). Moreover, the local damage is directly related to macroscopic residual properties such as loss of stiffness. Indeed, Laribi & al. [29] have recently proposed an equation of state relating the local damage to macroscopic loss of stiffness. They demonstrated that this equation, established under monotonic loading, is also valid when adapted to cyclic loading. Therefore, one can postulate the existence of a unique multi-scale relation between local and macroscopic damage which is independent of the macroscopic loading history. When microscopic and macroscopic damage is expressed as relative values, this intrinsic relation is also independent of microstructure. In other words, we assume that two composite specimens submitted to an equivalent relative loss of stiffness by applying monotonic loading (for the first one) and fatigue loading (for the second one), will also develop an equivalent local damage rate.

Moreover, Laribi & al. [29] established that final failure occurs when a critical value of the local damage rate is reached. Indeed, one can consider that failure occurs when the residual resistant surface reaches a critical rate. Then, micro-cracks interconnect to form a macroscopic crack. Therefore, one can assert the existence of an intrinsic link between damage and failure under monotonic loading and fatigue life. This relation can be emphasized by plotting the evolution of the first loss of stiffness (D_{N1}) versus the number of cycle to failure (N_R) for each performed fatigue test (see Fig. 6 where this intrinsic relation is emphasized for three working temperatures). As suggested above, this figure shows that this relation can be considered as an intrinsic relationship relatively independent of the microstructure as it can be observed in Fig. 6. One can note that this intrinsic relation exists for all studied temperatures. This evolution can be traduced by the following expression:

$$D_{N1} = 1 - C * {N_r}^{P} \tag{2}$$

where C and P, are material parameters which can be identified on the RO microstructure by fitting experimental results in Fig. 6.

4. Micromechanical damage prediction

4.1. *Micromechanical damage modeling*

In this paragraph, we briefly remind the micromechanical model used for this work which is derived from Jendli & al. [12] in its adapted form by Laribi & al [29].

Fiber-matrix interface debonding is considered to be the predominant local damage mechanism in SMC composites [14]. Thus, a local statistical interface damage criterion is proposed:

$$P_r = 1 - \exp\left(-\left(\left(\frac{\sigma}{\sigma_0}\right)^2 + \left(\frac{\tau}{\tau_0}\right)^2\right)^m\right) \tag{3}$$

where P_r is the interface failure probability, α and τ are the local normal stress and shear stress at the interface calculated using Mori and Tanaka approach localization. α_0, τ_0 and m are the fiber matrix interface normal and shear strengths. m is a statistical parameter allowing to take into account local microstructure fluctuations. At each loading step, an interface failure probability is calculated for each fiber orientation family in order to determine the amount of created micro-

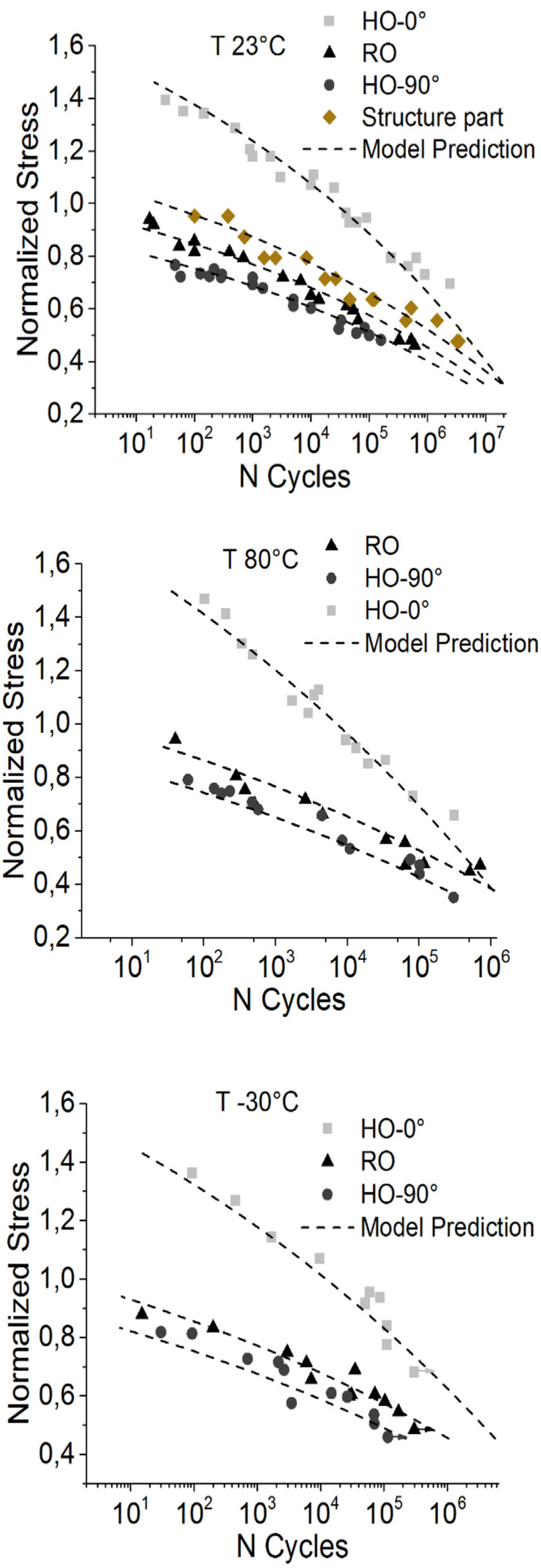

Fig. 10. Comparison between experiment and simulation results for different microstructure configurations and three working temperatures.

cracks. The effect of fiber–matrix debonding is then represented by both partial reduction of the fiber volume fraction, and introduction of zero stiffness heterogeneity (see Fig. 7).

Therefore, at each loading step, microstructure is defined by non-damage fibers, active fibers (including non-damaged fibers and a part of damaged fiber) and micro-cracks whose volume fractions are respectively given by:

$$f_n^{ND} = (1 - P_r^n) * f_{n-1}^{ND}$$

$$f_n^{act} = f_n^{ND} + k \sum_{i=1}^{n} P_r^i . f_{i-1}^{ND}$$

$$f_n^{mc} = f_{n-1}^{mc} + h. P_r^n . f_{n-1}^{ND} \tag{4}$$

where k presents a reduction coefficient applied to fibers partially damaged and h is the ratio between the volume of the introduced penny shape (representing interfacial micro-crack) and the fiber evaluated by geometric considerations. Subsequently, a homogenization procedure integrating matrix, reinforcements and micro cracks can be achieved using the Mori and Tanaka approach. Therefore, the evolution of the residual stiffness tensor of the composite during a monotonic tensile loading can be determined. Once the model parameters are identified (see [12] for the identification procedure), macroscopic damage evolution can easily be predicted in the case of monotonic tensile loading. Fig. 8 shows a comparison between prediction and experimental measurements.

5. Methodology of structure fatigue life prediction versus microstructure

5.1. From the reference microstructure for any other one

Once the micromechanical damage model identified and the (DN_1,N_R) curve established using the chosen reference microstructure, one can propose the following numerical procedure in order to established SN curve for every other targeted microstructure (Note that the procedure is graphically illustrated in Fig. 9):

Step 1: An experimental campaign is realized using selected specimens presenting a specifically chosen reference microstructure - randomly oriented if possible:

a. Loading-unloading tensile tests in order to establish the experimental $(D, \sigma)^{Ref}$ curve.
b. Fatigue tests until failure preceded by a loading–unloading reloading quasi-static test are performed at different maximum amplitude in order to establish the $(DN_1,N_R)^{Ref}$ curve.

Step 2: The identification of the local fiber–matrix interface failure criterion parameters is conducted using an inverse method on the basis of the $(D, \sigma)^{Ref}$ experimental curve as described in [12,29].

Step 3: A Targeted microstructure (Targ) is chosen. Monotonic tensile test is modeled until failure using the damage modelling based on the Mori and Tanaka approach: $(D, \sigma)^{Targ}$ curve is established for the targeted microstructure until a chosen macroscopic stress, $\sigma = S$.

Step 4: The macroscopic damage value D_S reached for $\sigma = S$ is read on the modeled $(D, \sigma)^{Targ}$ curve.

Step 5: The corresponding number of cycle to failure, N_R, is read on the (DN_1,N_R) curve.

Step 6: Recording the couple of value (S,N_R)

Step 7: Steps 1 to 6 are repeated for another chosen value of S as many times are needed to establish the SN curve of the targeted microstructure.

Note that mathematically, once D_S is determined by the Mori and Tanaka based damage model, the number of cycle to failure for an applied macroscopic stress S can be calculated by:

$$N_R = \left(\frac{1 - D_S}{C}\right)^{\frac{1}{P}} \tag{5}$$

Therefore, once the parameters, C and P, are determined for one reference microstructure (RO in our application) a simple monotonic tensile simulation enables deducing rapidly the SN curve for any other

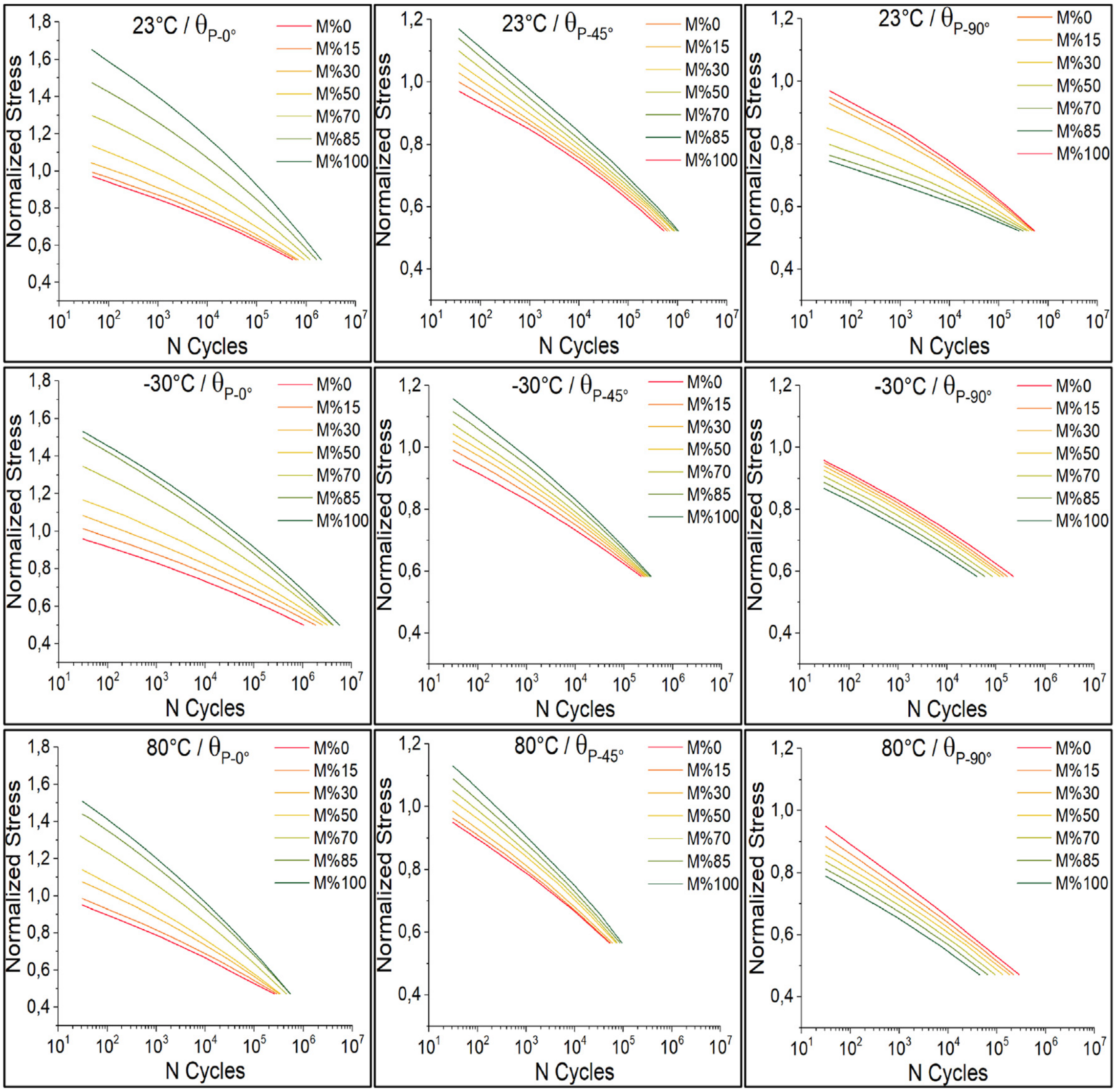

Fig. 11. Predicted Whöler curves according to the fiber orientation parameters (M, θ_P) and temperature.

targeted microstructure.

5.2. Application to SMC composites

Because it represents the average microstructure, RO SMC is chosen as reference material. Then, the micromechanical damage model parameters (α_0, τ_0 and m) are identified on the basis of the experimental $(D, \alpha)^{RO}$ curves. Similarly, C and P parameters are identified on the $(D_{N1}, N_R)^{RO}$ curves. Then, the numerical procedure described above has been applied to the three SMC microstructures in study (RO, HO (0° and 90°) and TG60). Comparison between experimental results and modeling show very good agreement for all microstructure configurations (see Fig. 10).

6. Numerical study

Once the methodology validated, it is possible to determine the SN curve for several other SMC microstructures. Indeed, the use of the identified micromechanical model allows the influence of the distribution of fiber orientation on the Whöler curves to be studied numerically. One can propose the following orientation distribution function:

$$\frac{f^{\theta}}{f} = \frac{k}{n} * (1 + M * \cos(2(\theta - \theta_P))) \tag{6}$$

where $f^{\theta}$and f are the volume fraction of the fibers oriented at θ° (versus a principal in-plane axis corresponding to the tensile direction) and the total fiber volume fraction respectively. n is the number of orientation families used in the Mori and Tanaka approach, M is the orientation rate (related to the birefringence parameter) and $\theta_P$is the main orientation of the fibers (corresponding to the mold flow direction). k is a normalizing parameter. This function has been shown to be representative for SMC composites. Indeed, fiber orientation distribution is represented by two scalar parameters (θ_P, M) corresponding to the principle direction and randomness. In the case of SMC composites, material flow during process remains limited because of the large size of the reinforcements. Indeed, fibers are presented in the form of 25 mm long bundles which implies high interactions between them and a limitation of the orientation variations. So that the variation of the scalar parameter M from 0 to 1 allows describing properly all real SMC orientation distribution through the proposed sinusoidal function. Note that the proposed methodology can be easily adapted to injected material for which the higher randomness should be described by the 2nd-order orientation tensor [39] which may be introduced in the Mori and Tanaka approach. Fig. 11 shows obtained Whöler curves for different microstructure parameters (M, θ_P) at different temperatures. Independently of the temperature, a greater influence of the orientation rate M may be noted when the fibers are oriented in the tensile direction ($\theta_P = 0^{\circ}$) and for the higher values of the applied maximum stress. As expected, when the fibers are mainly oriented in the loading direction, fatigue life increases with the orientation rate while it decreases when the fibers are oriented perpendicularly.

Therefore, the proposed methodology allows predicting the fatigue life for any microstructure. In a future paper, a Tsai-Wu criterion abacus built on the basis of the presented methodology will be presented and used to optimize the design of a real SMC structure.

7. Conclusion and perspectives

This paper proposes a fatigue life predictive model for SMC composites in which microstructure is an input data. Indeed, the high variations of the microstructure observed in real structures are due to material flow during process. Therefore, in order to build an accurate experimental database, a two-step selection method involving an original ultrasonic method and damage analysis is presented. A complete experimental damage analysis has been performed on several selected SMC's microstructures. The high influence of SMC microstructure on fatigue life has been demonstrated. Moreover, an experimental link between monotonic loading damage and fatigue life has been emphasized. It has been shown that this relation is independent of microstructure. Therefore, a new fatigue life predictive approach based on this intrinsic relation and a micromechanical damage model has been built. This approach has been applied for four microstructure configurations. Very good agreement between experimental and numerical results confirms the validity of this approach. Finally, a numerical study shows how the proposed methodology should be useful for structural design through the establishment of microstructure dependent Whöler curves abacus. Ideally, this abacus should be used in a finite element analysis coupled to process simulation allowing prediction of material flow during thermoforming of SMC composites.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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