Journal of Achievements in Materials and Manufacturing Engineering

VOLUME 49
ISSUE 1
November
2011

Damage analysis of the ceramic reinforced steel matrix composites sheets: experimental and numerical study

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Received 23.09.2011; published in revised form 01.11.2011

Analysis and modelling

ABSTRACT

Purpose: of this paper reports damage analysis of TiB_2 (ceramic particles) reinforced steel matrix composite sheets. This new steel composite receives much attention as potential structural materials due to their high specific strength and stiffness. The goal of the research described in this paper is to study the usage of this new steel family in the manufacture of light structures.

Design/methodology/approach: therefore in this study is focused to the titanium diboride TiB_2 reinforced steel matrix composite sheets that they were characterized by optical and scanning electron microscopes after the mechanical tests carried out on the base metal and welded specimens under dynamic and static test conditions.

Findings: The non homogeneity of the structure in this type of composites makes deeply complexity of their numerical and analytical modelling to predict their damage during the loading. For example, the interfaces essentially play a key role in determining mechanical and physical properties. For this reason, a Finite Element (FEM) analysis is used for modelling to simulate the macroscopic behaviour of this material, taking into account the relevant microscopic scales.

Practical implications: defined in this research is based on the impact dynamic behaviour of this steel sheets by using a special impact tensile test developed formerly that all details were published in this journal. This type of test gives more comprehensible information about special steel sheets (welded or base metal) in case of dynamic crash conditions.

Originality/value: The present research gives detail information on the new steel matrix composite sheets reinforced TiB_2 ceramic particles. This new composite was developed by ARCELOR research group and impact dynamic behaviour and weldability of the welded parts and base metals from this composite steel are discussed here in order to give practical and useful solution for industrial applications.

Keywords: Steel matrix composites; Ceramic particles-TiB_2; Crash test; Welding; Weldability

Reference to this paper should be given in the following way:

E. Bayraktar, F. Ayari, D. Katundi, J.-P. Chevalier, F. Bonnet, Damage analysis of the ceramic reinforced steel matrix composites sheets: experimental and numerical study, Journal of Achievements in Materials and Manufacturing Engineering 49/1 (2011) 53-61.

1. Introduction

Metal Matrix Composites (MMCs) have recently received considerable attention in manufacturing engineering as potential structural materials due to their high specific strength and stiffness [1-6, 8-12]. While most work on MMCs is directed towards producing novel and lightweight engineering materials, there is also considerable interest in developing iron and steel matrix composites. Iron and steel matrix composites reinforced with TiB_2/TiC ceramic particulates have been the focus of intensive investigation due to their ease of fabrication, low costs and isotropic properties. These materials potentially have good wear resistance with an excellent combination of low density and high toughness values [1, 4, 5]. For this reason, MMCs with fresh, ultrafine and stable ceramic reinforcements can demonstrate outstanding mechanical properties [6]. Among various ceramic particulates, titanium carbide (TiC) and titanium diboride (TiB_2) are good candidate materials because of their excellent properties such as high hardness, low density, high melting temperature, high modulus, good wear and corrosion resistance [5, 7, 10-12]. These materials are highly attractive for automotive applications, because their lightness and high toughness make them conducive to the production of environmentally friendly cars. However, several limitations associated with the use of pure TiC and TiB_2 were found in the literature [5-7, 9-12].

The first theme concerns the microstructural evolution of the composite sheets as base and welded structures due to their potential use in the automotive industry. The second theme is the relationship between microstructural and mechanical properties, notably weldability and the ductile brittle transition temperature of these steel matrix composite (TiB_2-RSMCs) sheets recently invented and developed by the ARCELOR Research Group in France [1]. Introducing these new composite steels in cars will reduce the total vehicle weight. This is a major topic of interest in support of the general goal of reducing fuel consumption and CO_2 emissions in future car designs.

2. Experimental conditions

Initially, the plate materials with a thickness of 2, 2.5 and 3 mm were made of special continuous casting and hot and cold rolling (classical steel manufacturing method) by ARCELOR Research Group-France. The values of carbon and manganese are 0.04% and 0.40% respectively. Some of the steel sheets were welded only one fusion weld line by Gas Tungsten Arc (GTAW) process. Basically TiB_2 ceramic particulates were used as reinforced materials in the iron matrix. All other details can be found easily in the documents [1, 2].

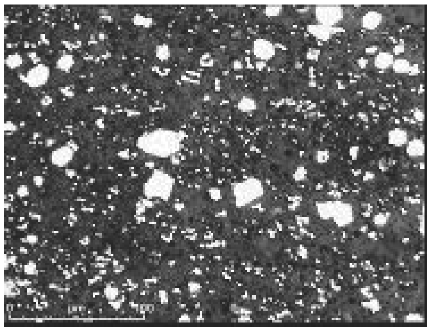
First of all, a detail metallographic analysis has been carried out. Evolution of TiB_2 ceramic particulates were observed in the welded and base-metal parts. Secondly, micro hardness tests have been done on the polished metallographic specimens. In order to evaluate the toughness properties of the TiB_2-RSMCs, impact - crash- tensile tests (ITT) have been carried out at different temperatures on the test specimens with a special geometry containing a smooth part (BM) and notched part (WM) with a special device mounted on an impact pendulum [7, 8]. Finally, static compressive tests, under a rigid spherical indenter with fixed radius (r = 3 mm) have been carried out and the results were compared with that of the numerical analysis carried by using ABAQUS Code. Fracture and deformed surfaces of the sheet specimens were analysed by means of Scanning Electron Microscope (SEM) for understand the damage behaviour of the TiB_2-RSMCs specimens under crash and static compression tests.

3. Results and discussion

3.1. Microstructural evaluation

Different mechanisms due to the reinforcements in steel matrix were effective in the microstructure. This evaluation indicates the size effect and distribution of the ceramic particulates in the matrix. The morphology of the ceramic particulates and the matrix has been evaluated in metallurgical point of view. This information has allowed understanding the cohesion and wetability of the ceramic particulates with matrix. Generally, TiB_2 ceramic particulates grew in hexagonal prismatic or rectangular shape. The micrograph given in Figure 1 shows the morphology and distribution of TiB_2 reinforcements produced in steel matrix and eutectic structure in the weld bead. The details of microstructure evolution in Weld Metal - WM, and Heat Affected Zone, HAZ were discussed in former papers [2].

a)



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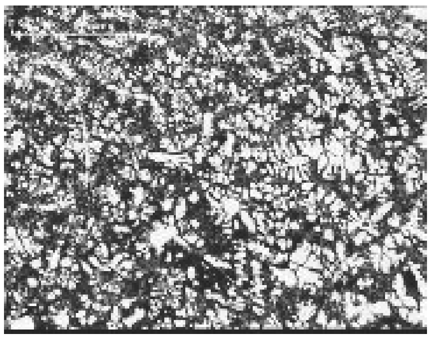

Fig. 1. Evolution of the microstructure of TiB_2-RSMCs specimens in base metal (a) and weld bead (b)

In fact, solubility of iron in the TiB_2 remains less than 4% it means that system Fe/TiB_2 keeps intact the mechanical properties of TiB_2. In the system Fe-B-Ti, TiB_2 precipitates in steel by eutectic solidification (this avoids the primary precipitation of borides in the liquid metal). (Volume fraction is around 15%, eutectic composition). These values were found with the surface percentages of the TiB_2 ceramic particulates calculated by image analysis. Weld Bead, after solidification, gives regularly a dendritic structure. This type of structure is always developed around the ferrite nuclei.

3.2. Evaluation of micro hardness and impact tensile test behaviour

Micro hardness measurement was given in the Figure 2 as the mean values for three different zones (BM, HAZ, and WM). The values for the new steel sheets, without welding (only base metal), has been added in this diagram. The population of TiB_2 particles distributed in the matrix plays an important role on the hardness evolution in the steel sheets.

Impact tensile tests results were given in the Figure 3. All the details with this special test technique can be found in former works [2]. As indicated in the ductile - brittle transition behaviour of the test specimens are deeply different. As the base metal without welding specimens in Figure 3a) gives a satisfaction transition values (around -80°C) the welded specimens show a transitions varying between -40 and -10°C depending on the thickness and also steel grades (Figures 3a and 3b). However, these results are very successful results for a steel matrix reinforced ceramic particles.

Evidently, fracture surfaces of these specimens verify these experimental results in case of the ductile and brittle failure conditions as indicated in Figure 4.

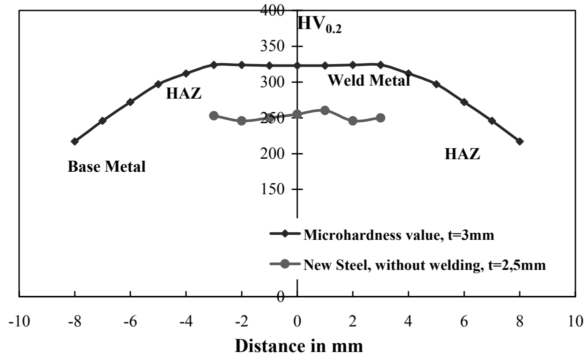

Fig. 2. Hardness evolution in different parts of the steel sheets (WM, HAZ and Base metal)

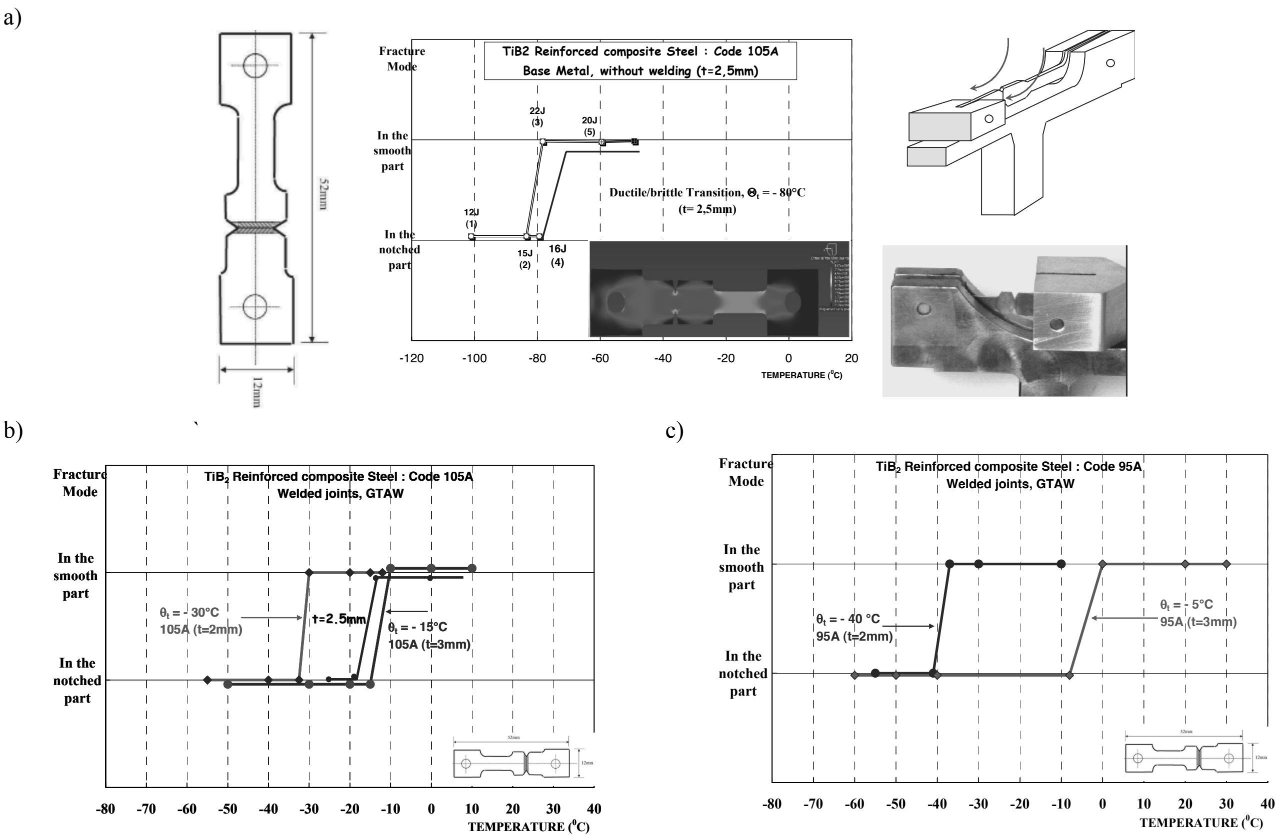

Fig. 3. Impact Tensile Test (ITT) results for the base metal a) and welded specimens with test device b, c) and developed specimen geometry and also FE stress distribution model with Abaqus stress analysis

a)

b)

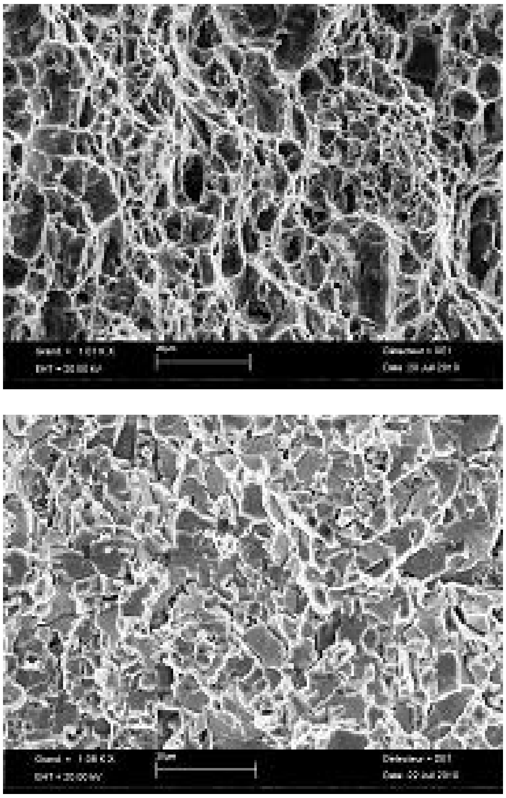

Fig. 4. Impact tensile test results for the specimen failed in ductile (a) and brittle (b) fracture conditions

3.3. Compressive tests, under a rigid spherical indenter

Static compression tests have been carried out under a rigid spherical indenter (r=3 mm) and deformed zone areas were measured for each test specimen (only base metal) and fractography analysis were also made for each specimen. This test is a typical damage test to understand the behaviour of the steel sheets containing ceramic reinforcements (Figure 5). The development of this product requires a better understanding of the relationship between crack propagation and microstructure. For this reason, a finite element based model was build which is inspired from the microstructure of the material. The micro hardness testing and the compressive tests are thus selected to compare between performances of this material based on experimental tests results and also numerical macro FE structural study. The dispersion of TiB_2 particles in iron matrix is somewhat heterogeneous containing relatively regular shape of TiB_2 particles.

Naturally, ITT and compression test carried out here as similar to the deep drawability tests cannot be positioned on the same plane. In other words, ITT characterises a ductile-brittle transition mode in fracture in dynamic loading conditions. So, it is sensitive to the physical parameters, which play a role on the cleavage (grain size, other defects, etc.). However, static compression test, of which ultimate stage is mostly the plastic failure, is mainly sensitive to the flow rule of materials during the deformation and also to the presence of particles of the second phase as indicated in these sheets reinforced with TiB_2 ceramic particles. Meanwhile, to make a correlation between these two different test variables should be considered as an indicative presentation, because both of these tests reflect micro-structural parameters which influent both of these two type of tests.

All of the parameters give practical information about the damage behaviour of these materials.

4. Microstructural model and Finite Element (FE) simulations

In order to understand well the stress strain mechanism of steel matrix composites reinforced with TiB_2 ceramic particles, a finite element model (FEM) based on the actual microstructures was build. This model is stimulated from the micromechanical composition of the Fe-TiB_2 as MMC material. Also, this model can provide the distribution of von Mises effective stress, strain and the maximum principal stress in the matrix and particles. The model is used to perform a comparison between experimental results and numerical results of compression tests. Figure 6 describes schematically the conditions of experimental compression tests, under a rigid spherical indenter with fixed radius (r=3 mm). Geometric variables were illustrated used in this model and the geometry and mesh parameters were also used to analyse these experimental tests.

The ideal microstructure considered in this study consists of a random arrangement of cylindrical inclusions (quasi hexagonal) embedded in a continuous steel matrix containing low carbon (Figure 7). The volume fraction of inclusions can vary from 10% to 20% and the micro-macro transition schemes are evaluated in many cases. However, when the volume fraction increases, nearby inclusions start to interact and this case influences the overall mechanical behaviour. Simulations must then be performed on a Representative Element Volume (REV) of the microstructure. Indeed, the spread of the macroscopic response for several distributions of various inclusions is lower than 5%. The generation of the random distribution follows rectangular cylinders filled with identical and aligned cylindrical inclusions.

The RVE microstructure is periodic along the 3 directions, allowing us to apply periodic boundary conditions to the external faces of the specimens.

The inclusion positioning is constrained by the practical limitation of generating an acceptable FE mesh. A criterion is applied to the minimal distance between each inclusion surface and the external faces of the specimen. The volume of one particular cell inclusion is less than 1 mm^3.

The representative cells are then meshed with quadratic tetrahedral elements. FE simulations are performed using ABAQUS (2008) and the whole volume is meshed using 4-node C3D4 tetrahedral in ABAQUS), enabling us to better capture the strain gradients in the matrix [12-14]. After that, a convergence study was successfully conducted by comparing the predictions (effective response and average inclusion response) to those obtained with finer meshes. The macroscopic stress predicted by the FE analysis is computed from a volume average of the stress tensor given at each integration point over the REV of domain “i”:

$$\bar{\sigma} = \frac{1}{V(i)} \sum_{k=1}^{N_K} \sigma_k V_k \quad (1)$$

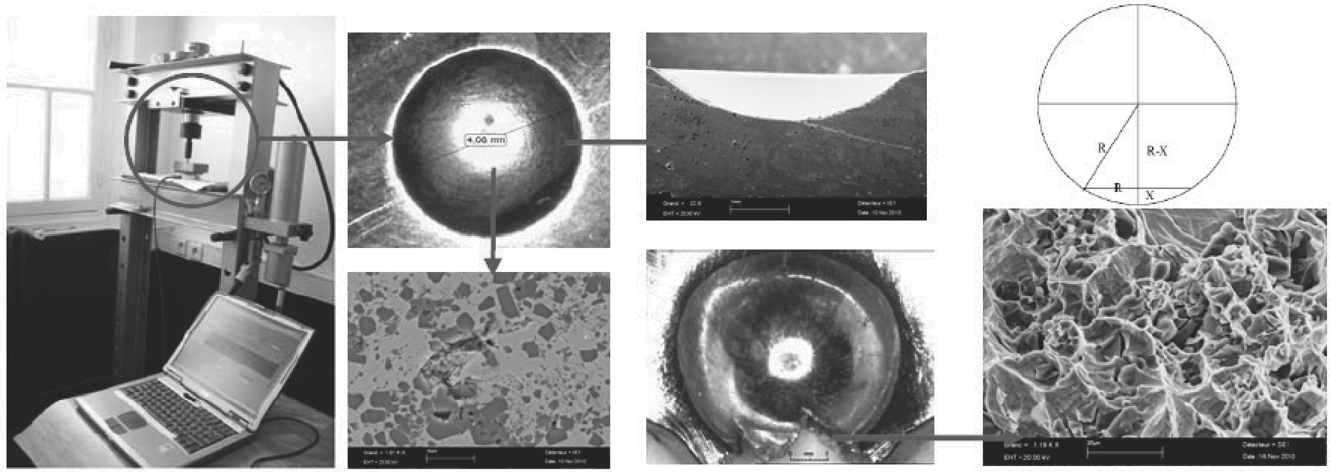

Fig. 5. Static compression test under a rigid spherical indenter: deformed area on the sheet and fracture surface after deformation

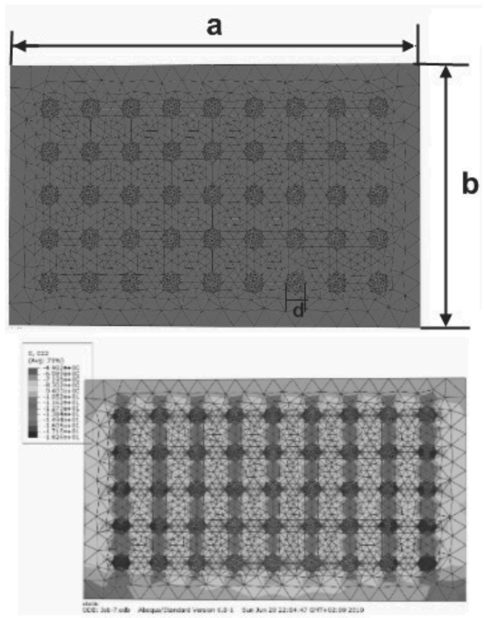

Fig. 6. Two-phases of steel matrix reinforced with TiB_2 ceramic particles under deformation

4.1. Numerical procedure

The macroscopic stresses and strains values were aimed to compute using a homogenization procedure according to the Mori-Tanaka (M-T model) [12]. In fact, the computations of the matrix average stress and the macroscopic stresses are identical to the M-T model. The procedure is fully history-dependent, the deformation state at each integration point in the FE discretion as well as the current matrix average state depends on the corresponding state at the previous step time. Therefore, for any loading condition, even non-monotonic or non-proportional may be considered. The Mori-Tanaka scheme coupled with a FE solution of the equivalent inclusion problem. FE analysis provides an alternative approach for estimating the material properties. A FE model for the heterogeneous test is constructed in which the material parameters to be determined are considered as variable. The simulation is then performed and results are compared to data from a comparable experiment data set. The agreement between the model predictions and the data is quantified and judged to be sufficient or insufficient. If the agreement is not adequate, the parameter values are updated, a new FE model is created and run, and the process continues. Development of an effective parametric FE procedure requires automation of model creation, submission, results extraction, and comparison with experimental data. Within the context of Abaqus, the Python scripting language allows for such automation. The inclusion average stress may be directly extracted from the FE simulation using a Python script file. The computation of the average stress in each phase affects only the effective response of the composite, not the prediction of the stress-strain partitioning. This holds provided that all components of the macroscopic strain are given.

Here, a combination of tools was used to drive the optimization process. A Matlab interface was developed to create the Abaqus input file with all the necessary geometries, material parameter assignments, and also FE results acquisition. Python scripts were used to extract reaction forces, displacements and other variables from the output database, which were fed back into the Matlab process for comparison with the experimental data.

The FE solution is used to simulate two-phase composites consisting of an elasto-plastic matrix reinforced by linear elastic inclusions. The predictions of the mean-field models are compared to reference results from FE computations on representative cells containing a random arrangement of multiple inclusions (Figure 7). Uniaxial and plane strain loading are successively applied to the multi-particle cells. The average of the macroscopic strain over a representative equivalent volume (REV) computed at each time step provides the loading history for the corresponding MF models. Therefore, results corresponding to the same macroscopic strain history, consistently with a strain homogenization procedure.

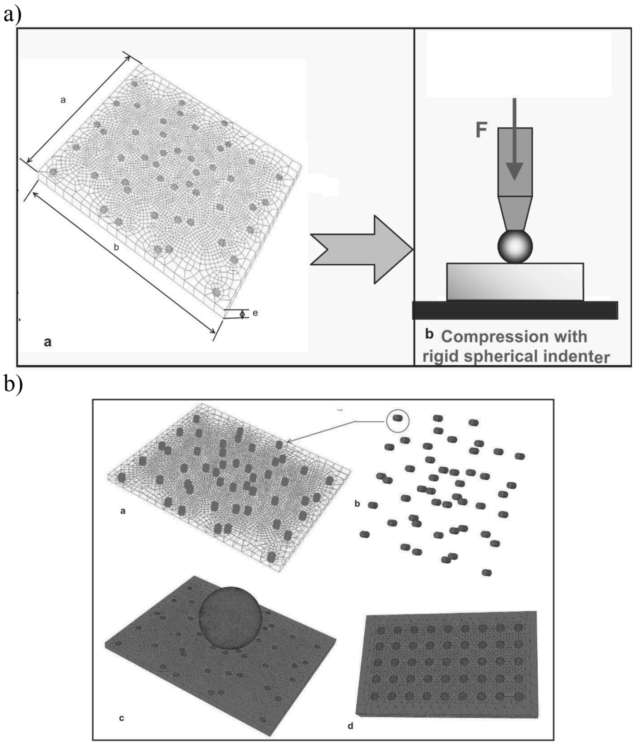

Fig. 7. MMC Fe-TiB_2 under compressive test a) FE model, with the compressive scheme and b) different model parts and mesh representation

Average equivalent stress in the inclusions of two phase MMC material is determined for different volume fractions of the reinforcing phase. The multi-particle, FE predictions (FE with 20% volume fraction) correspond to a uniaxial compression test, while the predictions of the FE model are obtained imposing the same strain history as in the multi particle simulation.

4.2. Boundary conditions and material properties

The boundary condition is so set that at the bottom border as U_x, U_y, U_z = 0 and at the upper face of the specimen is imposed a negative displacement load U_y in y-direction via the rigid spherical or the plate indenter. A static step with small step time is used to assess the gradual evolution of stresses and strains in the elements model, the equivalent reaction force is calculated and used to furnishes the maximum load, when the deformation at the contact zone riches comparable value with the considered limited experimental one.

The mechanical Fe-TiB_2 MMC material properties are derived from the particle inclusion properties of the TiB_2 and those of pure iron as matrix. The inclusion material is assumed to be linearly elastic with elastic modulus E_p=300 GPa and Poisson's ratio table υ = 0.3. In the same way, iron is selected to be the metallic matrix with elastic modulus E_m=210 GPa, Poisson's ratio υ= 0.33. The inclusion average stress may be directly extracted from the FE simulation using a Python script file. The computation of the average stress in each phase influences only the effective response of the composite, not the prediction of the stress-strain partitioning. This holds provided that all of the components of the macroscopic strain are given. At this stage, a combination of tools was used to drive the calculation process.

4.3. Results for FEM model

The FE solution used to simulate two-phase composites consisting of an elasto-plastic matrix reinforced by linear elastic inclusions. The predictions of the mean-field models are compared to the reference results from FE computations on representative cells containing a random arrangement of multiple inclusions. Uniaxial compressive loading are successively applied to the multi particle cells embedded in the metal iron matrix. The average of the macroscopic strain computed at each time step provides the loading history for the corresponding FE models.

Average equivalent stress in the inclusions of two phase MMC material is determined for 2 volume fractions of the reinforcing phase 10 % and 20%. For comparison, the predictions of the compressive results, by mean of deformation and maximum loading are shown for uniaxial compression Figures 8, 9 and Table 1. The average volume fraction for specimens in Table 1 is taken to be 15%. Only the results due to compressive tests using a rigid sphere are presented here.

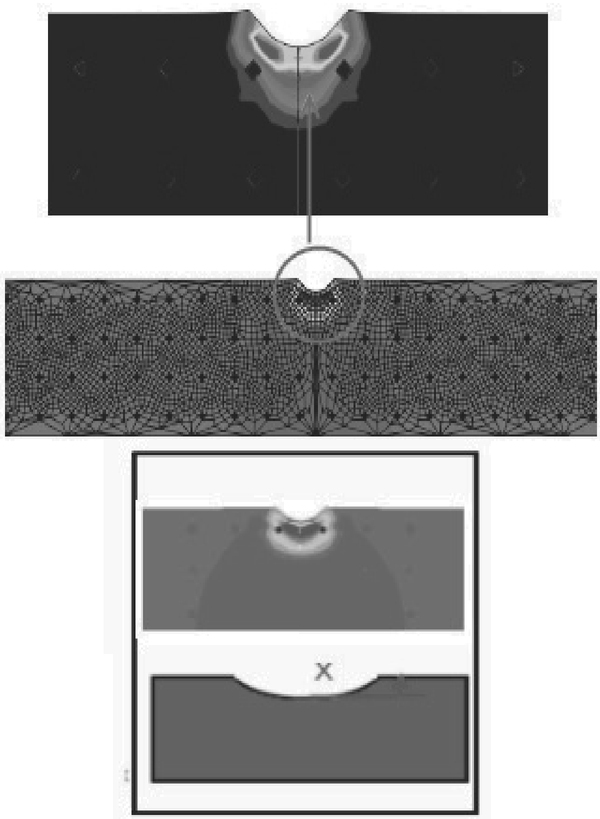

Fig. 8. FEM measurements of the deformation depth under compression of the MMC under compressive tests (Equivalent plastic strain distributions in the contact area)

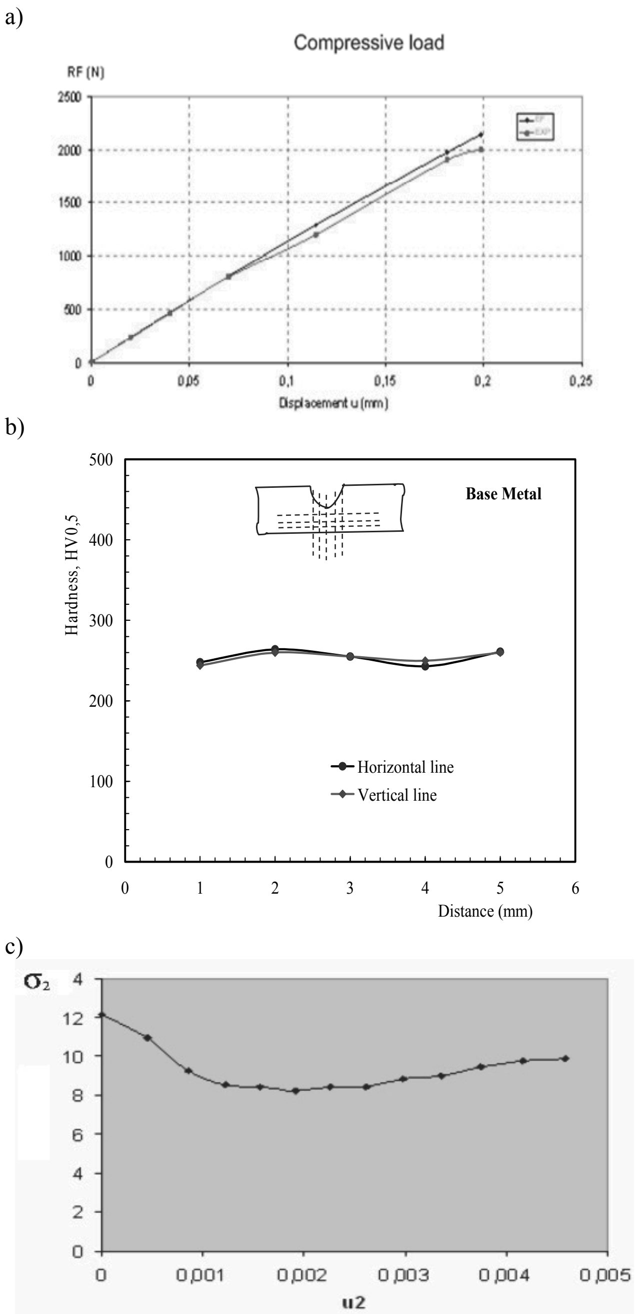

Fig. 9. a) Experimental and FEM variation of the compressive load as a function of displacement of the MMC under compressive tests and b) Hardness evolution in different direction after compression test (experimental) and c) FEM variation of the stress σ_2 as a function of displacement of the MMC under compressive tests

In fact, Figure 9 gives comprehensive evaluation of the deformation behaviour of this material as noted form experimental and FEM variation of the compressive load as a function of displacement under compressive tests. However, interesting results have been obtained from hardness measurements carried out in vertical and horizontal direction under the deformed area due to compression test (experimental) and also very similar results were obtained from variation of the stress σ_2 as a function of displacement due to compression test (FEM).

These results show clearly that a strain hardening mechanism does not occur in this material what ever the deformation level (from small stress levels up to stresses induced failure).

First of all, the structure of the matrix is similar that of the pure iron. It contains very low carbon and the microstructure contains very low dislocation density that does not increase during the deformation even if the microstructure with small grain size. Most probably, the hardness values around the deformed area and also variation of the stress σ_2 as a function of displacement do not change during the deformation and the materials does not show a noticed work hardening phenomenon.

4.4. Partial discussion of FE results

The inclusions response is predicted based on the solution of inclusions in a finite medium having the properties of the matrix. This equivalent inclusion problem is solved by the FE method, allowing field heterogeneities to take place in the made up matrix. In this model the scheme of Mori-Tanaka model is used, the average of the strain in the actual matrix of the composite is taken as far-field strain. The new method is applied to this composite made of an elasto-plastic iron matrix reinforced by spherical or cylindrical elastic TiB_2 inclusions. Macroscopic deformation histories corresponding to non-monotonic uniaxial and plane strain tension/compression are successively considered. In all cases, predictions of the approaches are compared to reference results obtained by FE simulations on cells containing inclusions.

This FE study showed that the M-T assumption is able to simulate the effective response of such composites almost for less than 20% of inclusion volume fraction. However, the predicted inclusion response is, in general, less accurate than the macroscopic real one so that the stress level in low inclusion fraction is underestimated by the mean-field model, this fact was well discussed in a number of previous works [15-17]. This effect is due to a certain extent, compensated by the matrix prediction which raises the stress level in the effective response. This is due to a slight overestimation of the matrix average strain combined with the present comparison material for the matrix. For higher volume fractions (from 20%) the single inclusion modelling yields very poor predictions of the inclusion response. This can be explained by plastic localization taking place between inclusions in the real composite, which is overlooked by the FE model (Figure 9).

Figure 10 illustrates the history of energy for the same plate, both total energy and strain energy figure a and c show the same shape at the loading step, then the energy falls to low values and this sharp drop can join the experimental results obtained with Charpy choc test as the energy transition was dropped sharply from the ductile to the brittle zone. This sudden jump is due to the repartition and the size of the TiB_2 particles.

Development of a new iron matrix, composite reinforced with TiB_2, needs more investigations to attempt a high accuracy between experimental results and their equivalent FE predictions.

Table 1.
General evaluation to compare experimental and FE results from compression test

Test n°	N° of specimen	Specimen size, mm	FE. Max force, N	Exp. max force, N	R	Rayon R_1, mm	FE. x, mm	Exp. x, mm
1	AC-x	25x30x3			3	2.04	0.82	0.80036367
2	AC-1	24x28x2	31104	31025.4	3	2.15	0.91	0.9077524
3	AC-2	21x21x2	29800	29038.5	3	2.03	0.78	0.79113151
4	AC-3	25x30x3	31600	31570.4	3	2.3	1.14	1.07386397
5	AC-4	21x7x3	25700	25636.2	3	2.97	2.56	2.57679792
6	AC-5	28x26x2	26800	26735.6	3	2.01	0.771	0.77291671
7	AC-6	12x27x2	24400	24334.6	3	2.17	0.95	0.92850296
8	AC-7	25x30x3	14400	14334.5	4.75	1.74	0.33	0.33016969

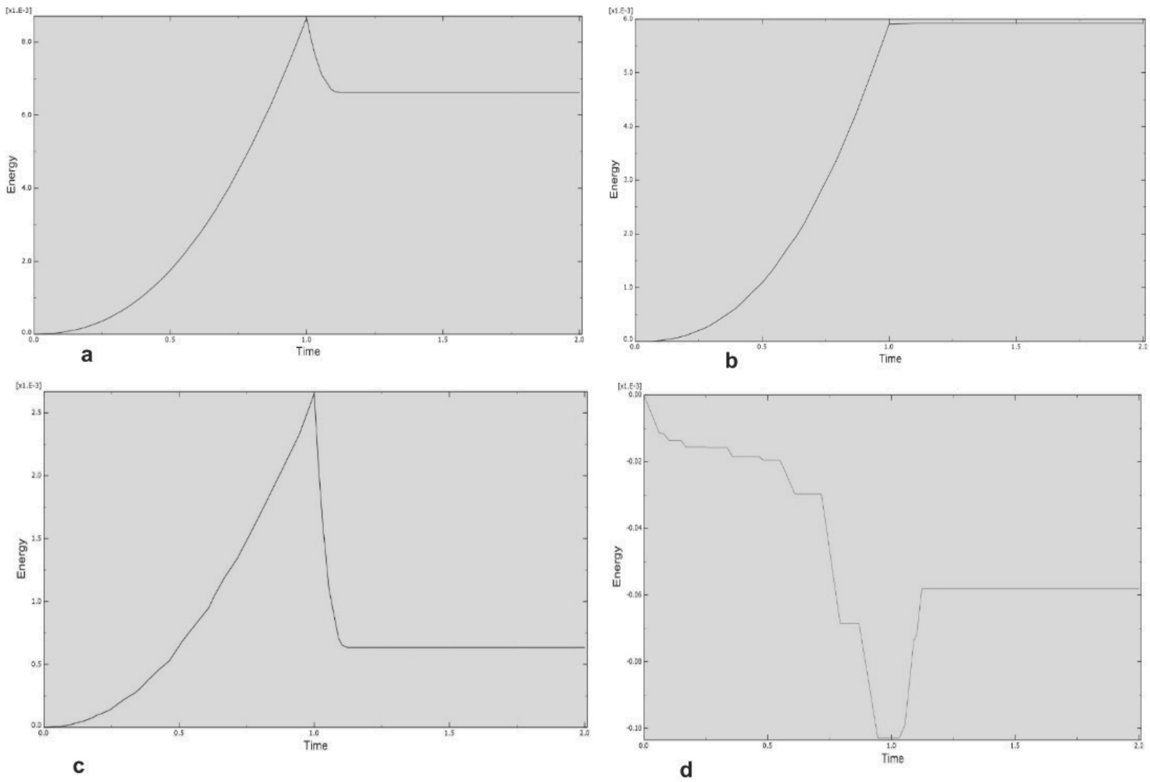

Fig. 10. FEM variation of the stress energy history of the MMC under compressive tests

The best choice of the volume fraction and the size particle is a competitive compromise that could be defined accordingly to the industrial destination of the MMC material. In fact, a larger investigation in the development of these materials can lead to the development of a smart strategy that can be easily used in the future to design smart MMC materials that can be adapted to the functionality of this latter. So that the material composition and the geometry design of the phase distribution in the MMC matrix could be monitored from an application to other.

5. General conclusion

Some of the conclusions can be driven from partial results of this study:

- TiB_2 particulate reinforced MMC_S sheets were successfully manufactured as proposed in the Patent.
- Weldability of this new steel family has a big potential success in manufacturing engineering (Formability of tailored welded blanks, TWBs).

- Weld bead shows finer structure.
- There is no abnormal evolution in HAZ during the welding (e.g. grain growth).
- The weld bead shows a fine eutectic structure.
- There is no abnormal evolution in the HAZ (e.g., grain growth).
- Preliminary work suggests that this product (originally developed for the car industry) should find other applications for all of the structures designed by stiffness (ex: energy domain, road transport and railway).
- A finite element model of the MMC material has been developed using a specimen with specific geometry and material properties. Accurate determination of material parameters is an integral component of developing a Fe-TiB_2 MMC. For most direct estimation, parameters would be determined using standard experimental test techniques (e.g. uniaxial tension or compression). For intention of modelling MMC iron composites, preparation of excised samples presents a number of difficulties. If insertion of inclusion particles is not well designed, it could affect the final result of simulation and it can induce false correlation between external and internal variables. Finally, even if uniaxial properties are precisely measured, the applicability of such data, and resulting material parameters, need a robust simulation to reach the satisfactory conclusions about the mechanical behaviour of those materials.

In general, the development of this MMC material is enhanced for many causes, in particular as far as we are looking for improving some roughness properties, we can associate particular attention to the grain size, because when it is reduced at a large scale, the presence of stresses and imperfections introduced by mechanical alloying enhance the roughness property; the overall roughness property is a competition between decrease in grain size and increase in strain. An enhancement of the numerical model to a nano scale can be with a great utility to bring more light and answers on the mechanical improvement of this material.

Acknowledgements

This study contains partial results of "ANR-ADRERA" project that is going on. Technical and financial support from ARCELOR-MITTAL Research Group, France is gratefully acknowledged.

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