Archives of Materials Science and Engineering
Volume 51
Issue 1
September 2011
Pages 48-54
International Scientific Journal published monthly by the World Academy of Materials and Manufacturing Engineering

Fretting wear damage-I: numerical study of composite steel sheets reinforced with TiB_2

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Received 22.06.2011; published in revised form 01.09.2011

ABSTRACT

Purpose: of this paper is based on the damage analysis by fretting wearing occurred on the composite steel sheets reinforced with TiB_2 ceramic particles. There is a real lack to find a reliable data and detail research in literature that makes the purpose of this manuscript.

Design/methodology/approach: Fretting is a surface degradation process in which removal of material is induced by small amplitude oscillatory movement between contacting components, such as flexible coupling joint structures etc. The main parameters affecting fretting wear are reported to be normal load, slip amplitude, frequency of the oscillatory movement, contact geometry, surface roughness and material properties. In this study, a finite element-based method is presented for simulating the contact of a rigid cylinder on flat fretting wear for the composite steel sheets reinforced with TiB_2 ceramic particles.

Findings: The general purpose commercial code ABAQUS was employed; this model can be used to facilitate generalization of the present approach to more complex applications. In this study a particular mesh technique was used to optimize the computation time, especially when dynamic analysis is used. In fact, two-dimensional, four-node, plane strain (linear) elements are employed throughout. The mesh (element size) in the contact area is very fine to capture the complicated variation of the surface and subsurface stresses and relative slip. The contact surface is constituted with a rigid hard steel cylinder material and a flat plate of composite steel sheets reinforced with TiB_2 ceramic particles.

Practical implications: This manuscript concerns a typical contact with the cylindrical plan geometry as it models the major problems and also stress distribution due to the contact was well defined. Our assembly is then, composed with a cylindrical contact with a plan substrate. An elastic - plastic analysis of fretting stress using a finite element ABAQUS is enhanced. The cylindrical pad is made of a rigid material and a flat plate the composite steel sheets reinforced with TiB_2 ceramic particles. A bilinear elastic - plastic isotropic hardening model with a von Mises yield surface is employed to characterize the material behaviour of these composite steel sheets reinforced with TiB_2 ceramic particles.This manuscript give a real and practical usage as a friendship notice concerning this subject.

Originality/value: is very well shown that this model is firstly verified through comparison with an analytical elastic solution. Various parameters, such as friction coefficient, the normal force applied on the top of the pad, tangential force applied to the left side of the pad, and bulk tension applied on the right edge of the substrate are adopted to study the influences of these parameters on fretting stresses to understand the implication and importance of elastic-plastic analysis in fretting fatigue experiments.

Keywords: Fretting wear; Slip; Contact; FEM; Mesh refinement; Composite steel sheets; Reinforcement of TIB_2

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

F. Ayari, E. Bayraktar, Fretting wear damage-I: numerical study of composite steel sheets reinforced with TiB_2, Archives of Materials Science and Engineering 51/1 (2011) 48-54.

METHODOLOGY OF RESEARCH, ANALYSIS AND MODELLING

1. Introduction

Metal Matrix Composites (MMCs) have most extensively expected in manufacturing engineering (aeronautical and also automotive-transport applications) as potential structural materials due to their high specific strength and stiffness [1-23]. 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 particles 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, 4-6]. 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 steel 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, remarkably weldability and the ductile brittle transition temperature of these steel matrix composites reinforced with TiB_2 sheets recently invented and developed by the ARCELOR Research Group in France [1]. Introducing these new composite steel sheets in cars and/or in transport area as well as in aeronautical applications the weight can be reduced whereas the stiffness – rigidity (Elastic modulus increased and the density decreased) can be improved on the manufactured pieces. 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.

In fact, in several previous works, very thin contact layers were used with various material properties to overcome the severe fretting conditions in order to improve the contact behaviour of particular components, [1, 3-6, 8-12]. Considerable progression has been made for well understanding of fretting fatigue over the last decade. During the time elapsed, quasi all of the experiments have become more standardized and carefully controlled and this has provided the data necessary for the development of methods for predicting fretting fatigue performance. Among them, certain authors report the presence of fretting debris, deduced as iron oxide, in the neighbourhood of a contact interface. Although fretting fatigue is not specifically mentioned, the contact in question was between grips and specimen in a simple fatigue test. Indeed, fretting phenomenon between the specimen and grips has been used the basis of a fretting fatigue test. Following the early investigations, fretting was recognized as being associated with a reduction in fatigue life [3, 4] and the term fretting fatigue came into common use to describe situations where micro slip between contacting surfaces appears to give rise to a reduction in fatigue life when compared to a plain component.

In fact, in crucial contact zones of transmission between components the contact zone can be illustrated, with different couple of geometries (sphere-plan, cylinder-cylinder etc.). The present research is interested with the cylindrical plane geometry contact as it models the major problems. Thus, the main objective of this study is to define a Finite Element Model (FEM) that can describe real loading conditions. In this study, first time, a particular technique of mesh is used to optimize the computation time, especially when a dynamic analysis is used. In fact, two-dimensional, four-node, plane strain (linear) elements are employed throughout. The mesh – element size in the contact area is very fine (about 0.01 mm) to capture the complicated variation of the surface and subsurface stresses and also the relative slip. The sharp transition from coarse mesh, remote from the contact region to fine mesh, in the contact region, is achieved via multi-point constraints (MPCs). This is necessary to achieve the contact balance of detailed contact region mesh refinement, for modelling microscopic wear depth increments and for accurate prediction of the significant fretting variables, and minimum CPU time for the total wear simulation. The contact surface is constituted with a rigid hard steel cylinder material and composite steel sheets reinforced with TiB_2 as a flat horizontal plate material. Results of the numerical simulation were compared to existing test fretting wear data of the same materials show a good capability of the FEM model to reproduce the test conditions.

2. Experimental results and discussion carried out on the composite material

2.1. Materials, microstructure and measurement of micro hardness values

As well given larger details in former papers [1], composite steel sheets reinforced with TiB_2 were developed and actually manufactured by ARCELORMITTAL – FRANCE. All of manufacturing steps follow the conventional steel production methods [1, 3, 4].

Firstly, 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.

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 wettability 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. The details of microstructure evolution were discussed in the former papers [1, 3]

Micro hardness measurement was given in the Figure 2. The mean values for the composite steel sheets, without welding (only base metal), have been given 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.

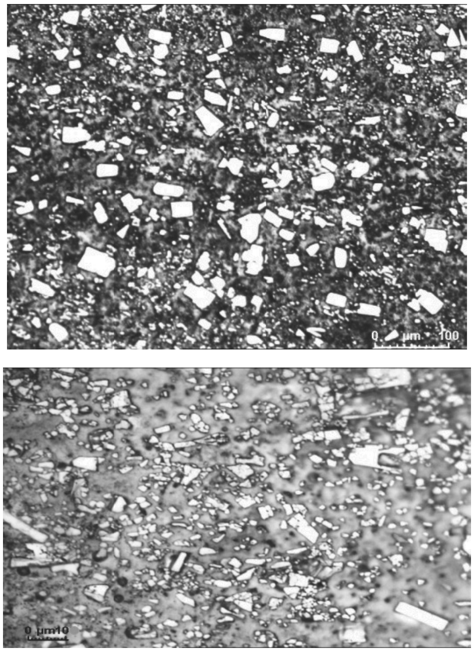

Fig. 1. Microstructure of steel matrix composites reinforced with TiB_2 specimens in base metal

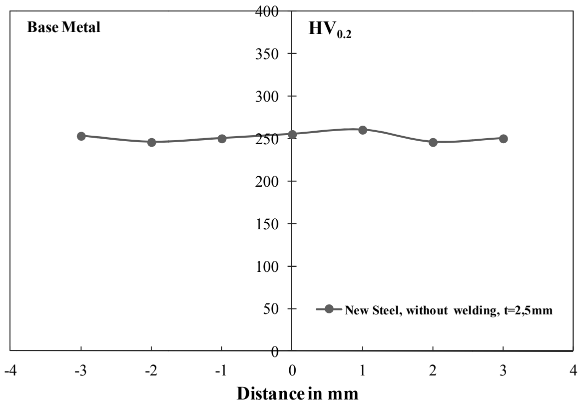

Fig. 2. Hardness evolution of Base Metal

2.2. Ductile/brittle transition temperatures and fracture surfaces

Impact tensile choc tests results were given in the Figure 3. All the details with this special test technique can be found in former works [3, 4]. Briefly, this test is based on the use of a specially designed two-body tensile specimen, including a smooth part and a notched section. This specimen is mounted in a special device called crash simulation device and the whole setting is brought to the desired testing temperature by means of a cooling system (in liquid nitrogen). Afterwards, this set is rapidly placed in a pendulum device having a quick locking system where special housing has been arranged (<3 s) and fractured.

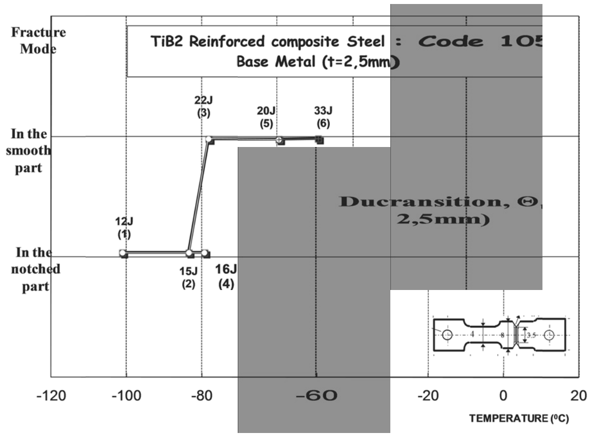

Fig. 3. Impact tensile choc test results for the base metal

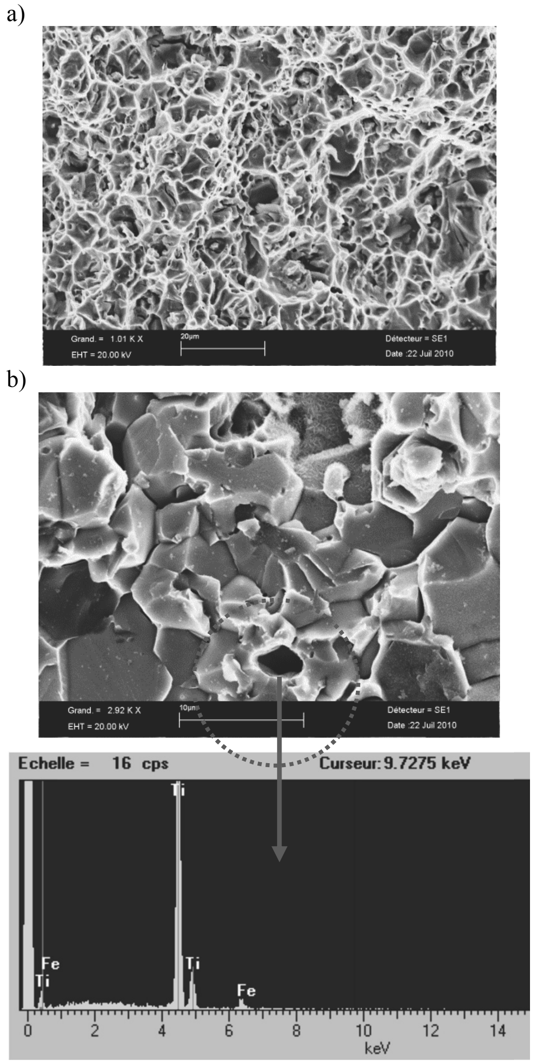

Fig. 4. Impact tensile choc test results for the composite steel sheet specimen failed in ductile (a) and brittle (b) fracture conditions with EDS analysis on the fracture surface

The special geometries of the specimen to be tested is composed of two different parts, a smooth and a notch section adapted to welds and base metals and or only base metal. As indicated in the ductile – brittle transition behaviour of the test specimens are deeply different. Specimens from base metal without welding give a satisfaction transition values (around – 80°C). These results are very successful results for steel matrix composites reinforced with ceramic particles.

Fracture surfaces of the test specimens taken from Scanning Electron Microscopy (SEM) were given in Figure 4. Evidently, fracture surfaces of these specimens verify these experimental results in case of the ductile and brittle failure conditions as indicated in the same figure.

According to these observed pictures, the particle sizes and the dispersion of ceramic particles of TiB_2 in form of hexagonal shape in iron matrix are seemed almost homogenous. Thus, the structure of the material will be considered in the FEM model as homogenous taking into account the equivalent mechanical properties of the material. In the same way, it should be noted that the geometry of TiB_2 particles is regular but different form essentially they are in the form of hexagonal geometry. The former paper [3] gives more information about this material.

3. Analysis with Finite Element Model (FEM)

A finite element-based method is presented for simulating both the fretting wear and the evolution of fretting in a cylinder on flat fretting configuration. An elastic plastic analysis of fretting stress using a finite element is enhanced. The general purpose, non-linear code, ABAQUS was employed for the FE modelling [9]. The FE model is shown by Figure 5, where the radius of the cylinder is the same as the cylindrical specimen in the fretting tests. The cylindrical pad is made of a rigid material and the substrate is made with composite steel reinforced with TiB_2. A bilinear elastic-plastic isotropic hardening model with a von Mises yield surface is employed to characterize the material behaviour of the composite steel. This model is firstly verified through comparison with analytic solutions.

Two-dimensional four nodes, plane strain elements are employed (linear elements). The mesh element size in the contact area is very fine to capture the variation of strain and stress field and also relative slip. The sharp transition from coarse mesh to fine mesh, in the contact region, is achieved with special optimization mesh technique as it is shown by Figure 6. Optimization of the mesh has led to important reduction of the total time calculation. The contact surface interaction is modelled with the contact pair approach (which uses the master-slave algorithm to enforce the contact algorithm). A stabilizing technique and correction via control parameters was also used in order to minimize the perturbations along the loading paths. The nodes on the slave surface are permitted to penetrate the master surface by a used controlled maximum penetration depth e (sliding). The cylindrical surface is chosen as the cylindrical slave contact surface and a value of approximately 1 is fined to be satisfactory.

The basic Coulomb friction model with isotropic friction is employed. The frictional contact conditions are introduced via the Lagrange multiplayer approach, rather than the most approximate penalty method, in order to enforce exact sticking (slip zero) constraints between the bodies when the equivalent shear stress is less than the critical shear stress. During the loading scheme, linear constrain equations are employed to ensure uniform displacement of the nodes on the top surface of the cylinder. The bottom of the substrate plate is restrained from movement in the x and the y directions. Results are obtained in a discredit form, and with the assumption of plane strain. However, this technique provides a convenient tool for providing an understanding of this type of fretting contact, which will be proved useful when more complex geometries are analysed.

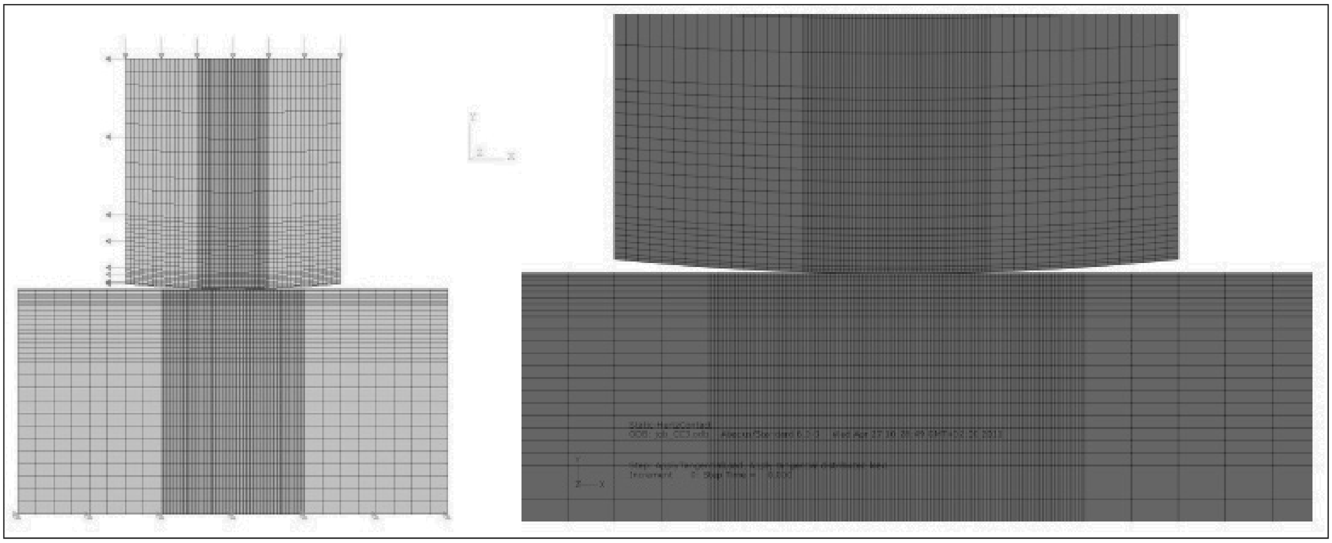

Fig. 5. a) Geometry of the model and boundary conditions, b) capture of the mesh at the contact zone

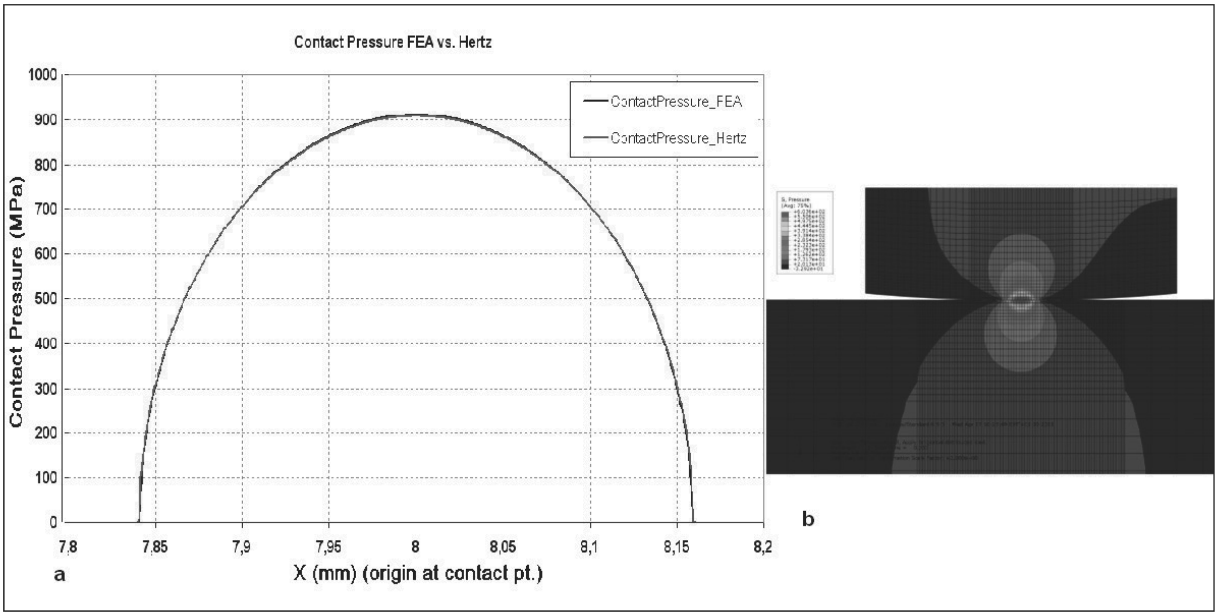

Fig. 6. a) Contact pressure, b) capture of the mesh at the contact zone under normal pressure

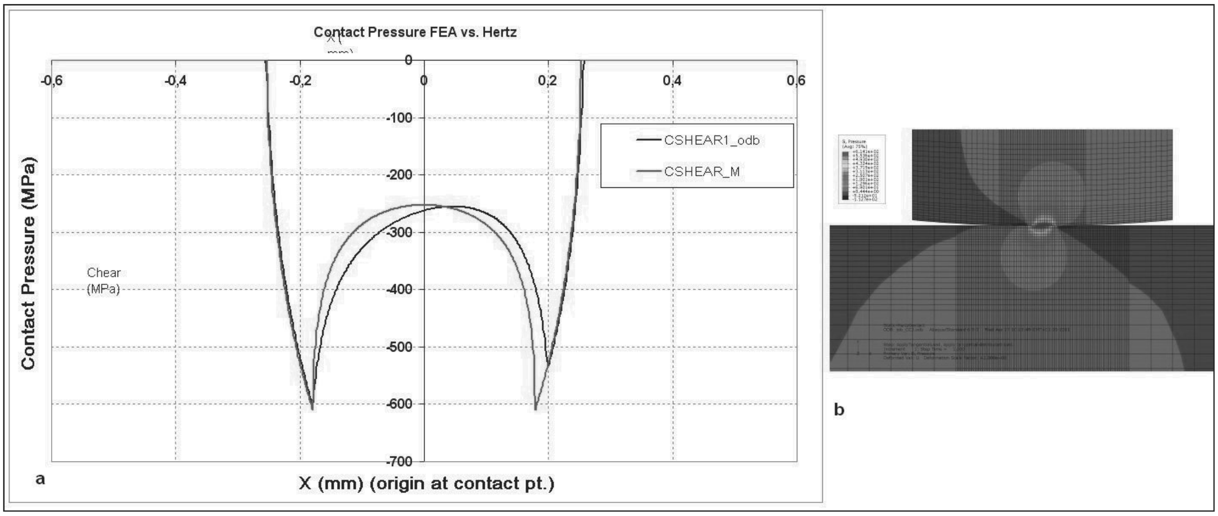

Fig. 7. a) C-shear (FEM and theoretic values), b) capture of the C-shear at contact zone

4. Results and discussion for FEM

The mechanism of wear of the basic substrate composite steel strongly depends on the energy deployed in friction. For weak energies wear by adhesion is dominating, and wear remains weak. When energy exceeds a hundred joules one records an adhesive wear also accompanied by an abrasive wear.

Abrasive wear comes from the remains of wear which were initially manufactured, their number and their geometrical form make that the flow accelerates and wear becomes important. By increasing the energy deployed in friction, the dominating mechanism of wear becomes wear by oxidation. This is due to the fact that the gradient of the temperature of the contact became very high what supports oxidation and degradation becomes catastrophic.

Figure 6 a, indicates the distribution of pressure in the contact zone; this distribution is almost superimposed to the analytic curve defined with the Hertz contact as it is shown by Figure 6a and Figure 6b. According to Figure 7 the FE results and the theoretical results of the C-Shear contact pressure is almost the same, this result is deduced after slip of the cylindrical pad. For this reason, distribution of the different stresses in the contact area were illustrated in Figure 8. The present results are being in accordance with theoretical hypothesis developed previously with different authors as Hertz, Cattaneo and Mindlin.

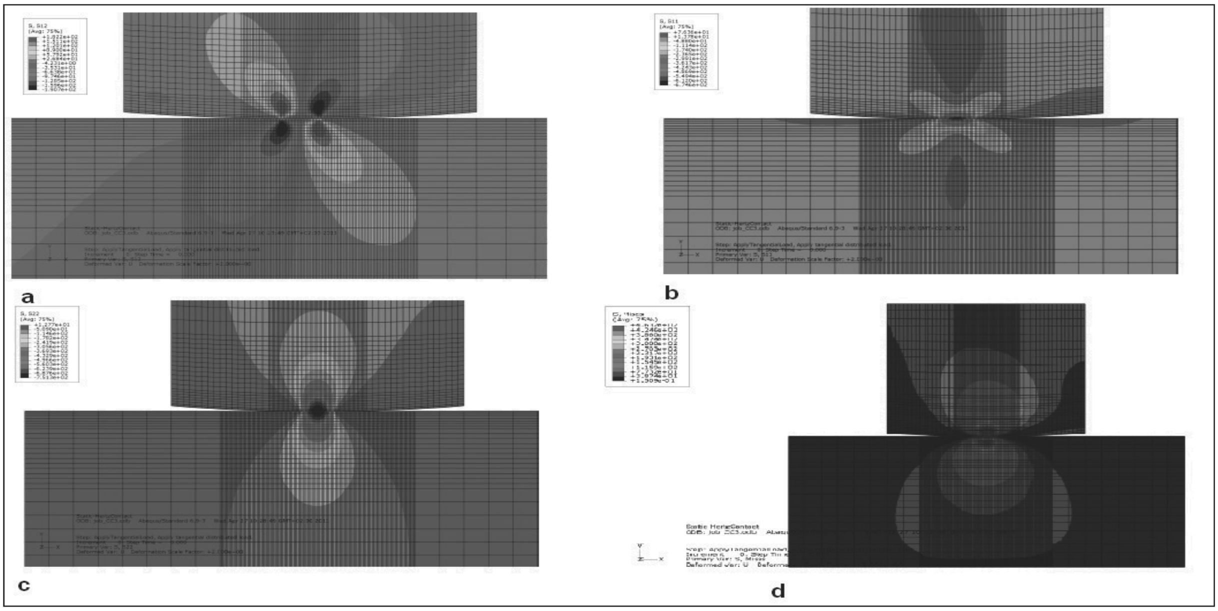

Fig. 8. a) S_{12} distribution, b) S_{11} distribution, c) S_{22} distribution, d) Von Mises equivalent stress

5. Conclusions

General conclusions driven from this research are given as follow:

- composite steel sheets reinforced with ceramic TiB_2 particles were successfully manufactured as proposed in the Patent;
- usage of this material as a base metal and also the welded parts has a big potential success in manufacturing engineering (Aeronautical-Automotive/Transport area);
- it shows a finer structure and the ceramic TiB_2 particles were distributed in a homogeneous way and their sizes are also homogeneous in hexagonal form;
- in the case of the numerical study; a preliminary work was made here because this product should find other applications for all of the structures designed by stiffness such as energy domain, road transport and railway etc. When a contact surface suffers from a repeated shear of small amplitude due to vibration, surface degradation like wear damage develop. These damage phenomena, termed fretting wear and fretting fatigue, can decrease the design life of components and structures;
- it is important to understand and evaluate the stress state of our fretted material, in order to analyse and predict fretting its failure. The first step in this procedure is to define the interfacial tension distribution, and this is practiced in the present paper, for the specific geometry of a cylinder, pressed to a flat plate substrate, and subject to both transverse and axial shearing forces. It is needed also to provoke sliding. We can independently evaluate this problem, for the particular case when the shearing force is applied transversely (dynamic loading). The intention in the present paper is to extend earlier results, and to investigate the effects of sequentially applied shearing forces. The first part of this presented work has been useful to validate results issued within this FE model, so far we can solve the dynamic problem by enforcing the stick conditions in the x- and y-directions, this fact will be coupled in a complicated way.

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