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EVALUATION OF FORCE-TIME CHANGES DURING IMPACT OF HYBRID LAMINATES MADE OF TITANIUM AND FIBROUS COMPOSITE.

Fibre metal laminates (FML) are the modern hybrid materials with potential wide range of applications in aerospace technology due to their excellent mechanical properties (particularly fatigue strength, resistance to impacts) and also excellent corrosion resistance. The study describes the resistance to low velocity impacts in Ti/CFRP laminates. Tested laminates were produced in autoclave process. The laminates were characterized in terms of their response to impacts in specified energy range (5J, 10J, 20J). The tests were performed in accordance with ASTM D7137 standard. The laminates were subjected to impacts by means of hemispherical impactor with diameter of 12,7 mm. The following values have been determined: impact force vs. time, maximum force and the force at which the material destruction process commences (P_i). It has been found that fibre titanium laminates are characterized by high resistance to impacts. This feature is associated with elasto-plastic properties of metal and high rigidity of epoxy – fibre composite. It has been observed that Ti/CFRP laminates are characterized by more instable force during impact in stage of stabilization of impactor-laminate system and stage of force growth that glass fibre laminates. It has been observed more stable force decrease in stage of stress relaxation and withdrawal of the impactor. In energy range under test, the laminates based on titanium with glass and carbon fibres reinforcement demonstrate similar and high resistance to low-velocity impact, measured by means of failure initiation force and impact maximum force.

Keywords: hybrid composites, titanium-carbon laminates, impact, damage.

1. Introduction

Fibre metal laminates (FML) belong to the group of hybrid composite materials dynamically developed from the beginning of 21st century. They consist of alternatively arranged thin layers of metal and layers of polymer – fibre composite permanently bonded together. Available literature describes already applied laminates consisting of aluminium alloys and glass fibres (GLARE®), carbon fibres (CARALL®) and aramid fibres (ARALL®) [1]. The authors of numerous studies [2,3,4] emphasize that laminates with permanent bonding between aluminium and fibre composite are characterized by favourable strength and anti-corrosion parameters (excluding CARALL® [1,5] laminates) and by resistance to impacts by means of concentrated force [6,7]. Owing to these features and high technological regime as well as manufacturing costs, still it was possible to use FML laminates in aerospace technology for aircraft components (e.g. Airbus A380) only. Increasing availability of components and apparatuses to be used for FML laminates production caused significant interest in this group of materials in automotive and machine industry.

As a result of increasing design requirements in the scope of aircraft structures (materials with higher rigidity, strength, resistance to impacts) and improved resistance to corrosion, intensive works are continued in order to introduce the new types of FML materials, for instance the attempts to introduce the new aluminium alloys (e.g. Al-Li alloy) [1], magnesium and titanium alloy. Up to the present time, titanium and its alloys seem to be the most successful application. The initial problems associated with effective adhesive bonding between metal and composite can be considered resolved, among others through the development of titanium surface chemical preparation techniques [8,9]. It should be emphasized that the laminates consisting of titanium and carbon fibres do not suffer from galvanic corrosion in operation conditions which gives the opportunity to use them in aircraft structures. Furthermore these types of materials are characterized by excellent strength parameters [10]. However, in the opinion of authors of the present study, supplementary research works in the scope of more advanced influences in a material in operation environment (low and high velocity impacts, the influence of temperature and the influence of its cyclic changes, humidity etc.) are necessary to fully explore titanium FML laminates.

The assessment of resistance to low velocity impacts in composite materials and sandwich structures consists in controlled simulation of impacts in laboratory conditions in a manner enabling the assessment of destruction mechanisms and scale in determined impact conditions [6,11]. The variations of material response force on impacting body vs. time (*f-t* curves) [12] belong to the results obtained from the experiment. The force vs. time curves represent the information about the values of forces causing gradual degradation of material as well as about the intensity and scale of initiating and developing damages. The authors of studies [12,13,14] demonstrated that

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force vs. time curve encompasses characteristic points and stages on the basis of which it is possible to draw conclusions e.g. concerning the mechanisms of progressing destruction. Laliberté et al. [13] presented four stages of GLARE® laminates degradation. Their description encompasses plastic deformation stage, delaminations initiation and propagation stage occurring thereafter, further destruction process in composite matrix and fibres as well as laminate cracking. Guan and Yang [14] characterized five stages of GLARE® laminates response to the impact. The first stage consists in the contact of impacting body with the material and vibrations resulting therefrom. The second stage consists in initiation of local damages causing successive reduction of laminate rigidity. The third stage is characterized by integration of local damages and by the sudden loss of laminate stability. The growth of global destruction is observed in course of the fourth stage. The growth of destruction is ceased in the fifth stage and the return strain of laminate in the elastic range takes place. The authors have also found that the occurrence of individual stages is associated with impact energy. On the basis of their experiments, Caprino et al. [12] demonstrated six stages of FML laminates degradation and based their theory on measurement data. The authors characterized early stage of delaminations initiation and propagation, further process of fibres cracking, initiation stage of lower aluminium layer cracking, stage of intensive fibres cracking and penetration. Simultaneously they indicated that each stage occurs in certain range of impact energy [12].

The prior knowledge about force – time relationship in case of impact in laminates consisting of aluminium and fibre composite [6,7,15], facilitates the assessment of new materials in this regard by means of identical methods, which constitutes the scientific problem currently being addressed intensively [16,17].

The aims of the present study are: interpretation of force vs. time curves for low velocity impacts in FML laminates consisting of titanium and glass – epoxy laminate as well as carbon – epoxy laminate and comparison of their responses to impacts within various energy ranges.

2. Materials and methods

The subject of research covered FML laminates consisting of two layers of GRADE2 titanium sheet 0.5mm thick (Sumitomo Metals, Japan) subjected to anode oxidizing processes in sulphuric acid water solution with so called primer layer applied thereafter. The primer consists of synthetic polymer resins and corrosion inhibitor activating titanium layer. Titanium layers have been separated by means of polymer – fibre composite layer 0.5mm thick. Two types of composite have been used i.e. pre-impregnated tape made of epoxy-glass composite on the basis of R type glass fibres (Hexcel, USA) (Ti/GFRP laminate) and epoxy – carbon composite on the basis of AS7 high strength fibres (Hexcel, USA) (Ti/CFRP laminate). The laminates have been made in unidirectional fibres layout (Ti/CFRP (0) and Ti/GFRP (0)). The lay up (0) used in FMLs means that all fibres in composite layers were arranged in the same direction (along the longer side of a sample).

The laminates have been produced in autoclave process using vacuum package developed in the Material Engineering Department in Lublin University of Technology [18,19]. The laminates were cured at the temperature of 135°C for 2h (heating and cooling at 2°/min) at the pressure of 0.35MPa and negative pressure in vacuum package -0.08MPa.

Samples with dimensions of 150 x 100 mm were subjected to low-velocity (< 10 m/s) impact in room temperature by using a drop-weight impact tester (INSTRON Dynatup 9340) with a possibility to record load-time history. A hemispherical impactor tip with a diameter of 12.7 mm (0.5") was applied. All the conducted low velocity impact tests were based on ASTM D7136 standard [11]. The impact was tested for three different energies - 5, 10 and 20J.

On the basis of obtained results, force – time curve illustrating selected impact was subjected to detailed analysis and the variations of force vs. impact time were compared for two types of laminates at various impact energies.

3. Results and discussion

Figure No 1 illustrates an example of force vs. time curve (*f-t*) after the impact with energy of 20J for Ti/CFRP laminate.
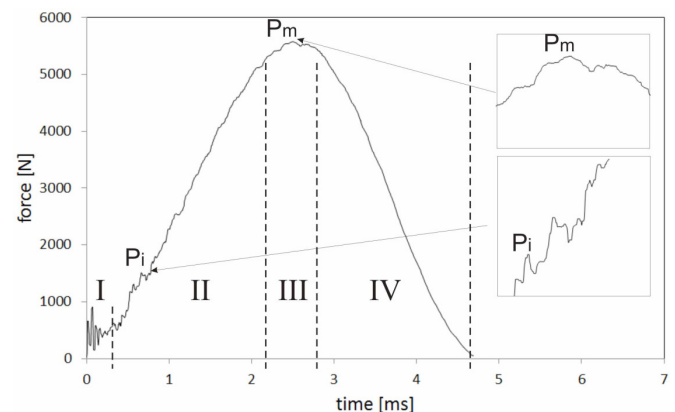

Fig. 1. Force-time curve after low-velocity impact with 20J impact energy in Ti/CFRP laminate

On the basis of the review of obtained curves and data available in literature it has been found that the shape of *f-t* curve for titanium – composite laminates does not differ from the shape of *f-t* curves obtained for other types of laminates and for conventional composite materials [20,21]. The curve consists of force growth section, achievement of maximum force and stable reduction of force. Force oscillations vs. time, particularly prevailing in the initial stage of diagram, are the significant features of the diagram. On the basis of the research carried out by the authors [6,7] and on the basis of literature review [22], it has been found that obtained curve is relatively smooth at energy of 20J. In case of some materials (e.g. aluminium / carbon fibre laminates), the energy of 20J causes significant degradation reflected on the diagram in the form of significant (even by hundreds N) periodical reductions of force [6,7]. The curves with relatively smooth shapes belong to the group of curves illustrating the material without any perforation. There was no perforation in the described case. Obtained curve has been subdivided into four stages (I – IV)

(Fig.1). The initial period of impactor – material contact (stage I, Fig. 1) is the period of intensive force oscillations as the result of system vibrations. The sudden acceleration of panel and rigidity of table – material – impactor system generates the vibrations mainly depending on rigidity of the material under test. In the studies of authors describing these phenomena for aluminium laminates, the initial vibrations were also observed but their level was significantly lower i.e. force oscillations were included within ±100N [6,7]. The observed case is characterized by force oscillations within ±400N. Probably such intensive oscillations are caused by high rigidity of Ti/CFRP laminate. The second stage (Fig. 1) consists in relatively stable force growth vs. time until the forces close to maximum force are achieved. This area is characterized by impactor displacement of composite plate deformation [23]. However insignificant force oscillations are noticeable (Fig. 1). The first visible disturbance of force is interpreted as the damage initiation moment in composite [14]. In many scientific studies e.g. [12,13,14], the authors suggest that it is the damage initiation moment in polymer matrix which is the weakest component of composite in terms of strength and formability. The first damage initiation moment is defined as P_i point (Fig. 1) and often considered as composites resistance to impacts. As indicated by Guan et al. [14] and by Bienias et al. [7], further oscillations of force in this stage may result in the occurrence of next local structural damages or in development of already occurred matrix damages. However continuous growth of force suggests that the material is still capable to carry the loads associated with impact and to absorb the energy transferred by the impactor. The stage III is the impact stage characterized by the achievement of maximum force (P_m) (Fig.1). Force oscillations occurring in this area indicate to further material degradation. The value of these force fluctuations is determined by the value of progressing destruction. In observed case, insignificant force fluctuations indicate to the lack of significant loss of composite plate rigidity. Other authors of studies [21,24] presented f-t curves illustrating forces reductions in P_m area reaching several tens of percents of maximum force. Such significant reductions of forces may indicate to fibres cracking as a result of impactor penetration and metal cracking (perforation). Some small damages occurred in Ti/CFRP laminate being tested. These phenomenon was demonstrated by insignificant force reductions (between a few and several tens N) indicating relatively high resistance to impacts in this type of laminate. The last stage (IV) (fig.1) consists in compactor withdrawal and force reduction to zero level. Owing to lack of perforation, stable force reduction was observed. No force oscillations were observed in this stage. Probably it is an indication of maintained rigidity and lack of any significant degradation of material under test.

Figure No 2 illustrates the summary of force – time curves for Ti/CFRP and Ti/GFRP laminates after impacts with energies of 5-20J.
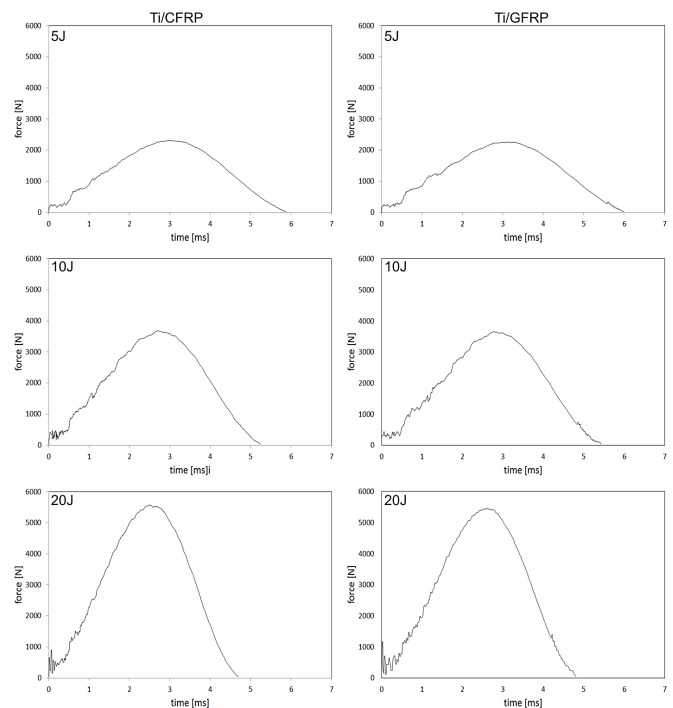

Fig. 2. Force-time curves of tested titanium-composite laminates

On the basis of comparison of f-t curves after impacts in the laminates being tested, no significant differences in curves shapes have been observed between Ti/CFRP and Ti/GFRP laminates. Only insignificantly longer times of contactor – material contact have been denoted for glass fibre laminates (differences not exceeding 10%). This fact may be caused by lower rigidity and higher formability in the elastic range of glass fibres (about 3% of glass fibres, about 1,5% of carbon fibres) [6]. Insignificant difference between the types of reinforcement in laminates is indicated by the curves in stage IV of the f-t curve. The oscillations occur in glass fibre laminates only (Fig. 2). This fact may be associated with so called membrane effect at the impact [15,23] which applies to elastic materials (energy accumulated in the form of elastic strain is return and gives some material reaction into impactor tip). The carbon fibres are characterized by lower flexibility and the membrane effect probably did not occur in Ti/CFRP laminates in experiment conditions.

It has been observed that the influence of energy value on f-t curve in case of impact is significant (Fig. 2). The reduction of material – impactor pair contact time is accompanied by the impact energy growth. It is directly associated with the impactor velocity determined by preset impact energy. Therefore, the process dynamic is increased affecting the value of laminate influence force on the impactor.

The Figure No 3 illustrates the value of specific forces: P_i damage force and P_m maximum force for laminates under test for energy range of 5-20J.
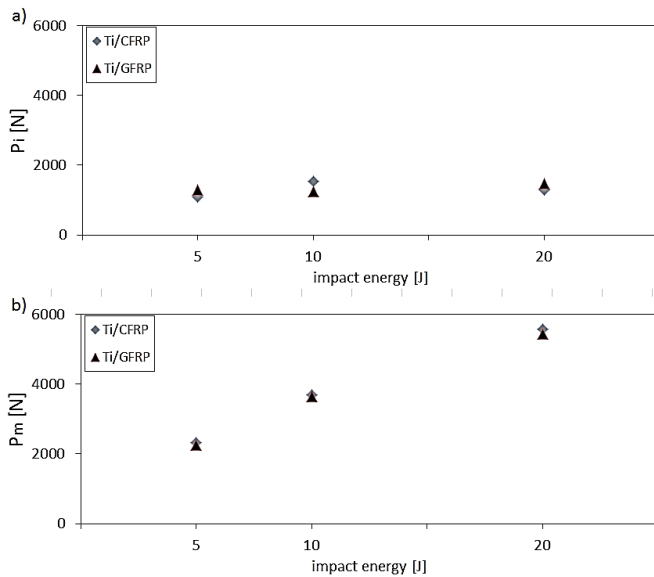
Fig. 3. P_i (a) and P_m (b) values vs. impact energy and type of laminate.

It has been found that the values of specific forces i.e. P_i and P_m are similar for the both types of laminates. Similar shapes of *f-t* curves and similar values of specific forces may indicate to significant contribution in loads carrying process i.e. loads resulted from impact. Among others, Chai et al. [15] indicated to significant contribution of metal in impact energy absorption. At higher impact energies – causing at least metal cracking – laminate reinforcement and its resistance to dynamic effects can be of significant importance. In observed energy range, the resistance of unidirectional Ti/GFRP and Ti/CFRP laminates is equivalent.

In accordance with observations of *f-t* curves, the energy growth is accompanied by the value of maximum force (Fig. 3b). It has been found that it is possible to anticipate the increment of these values owing to clear almost linear trend of maximum force increment related to impact energy in energy range under test. Similar trends have been indicated in other studies describing impacts in conventional composites and FML laminates containing aluminium [25].

The noticeable relatively constant P_i value regardless of impact energy (in range under test) (Fig. 3a) confirms that P_i point may represent the damage initiation moment in polymer matrix i.e. the laminate component with the lowest resistance to impacts.

The stable shapes of presented *f-t* curves for Ti/CFRP and Ti/GFRP laminates may also result in certain extent from unidirectional layout of fibres. The research carried out by the authors and others [23,25,26] indicate that the layout of fibres in FML laminates and composites may have influence on degree of their degradation as a result of impacts due to their properties anisotropy (mainly in case of Young modulus) in individual composite layers. However, it is required to carry out further thorough research in this scope.

4. Conclusions

The following conclusions have been drawn on the basis of completed research:

1. The shape of *f-t* curves generated in course of impact for FML laminates with titanium layers reflects their degradation process with quality identical to degradation process for laminates with aluminium alloy.
2. Relatively insignificant force oscillations in stage III, even at the highest energy, indicate to limited phenomenon consisting in fibres degradation and lack of perforation (in laminates with carbon and glass fibre).
3. In energy range under test, the laminates with the both types of unidirectional reinforcement demonstrate similar and high resistance to low-velocity impact, measured by means of P_i and P_m values as well as by means of force oscillation value in stage III.

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