DEVELOPMENT OF ADVANCED LAMINATES FOR AIRCRAFT STRUCTURES

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Fibre Metal Laminates, Metal Laminates, Adhesion Bonding, Modelling

Abstract

The technical focus of this project is the development of new generations of Fibre Metal Laminates - FML (thin metal sheets bonded by fibre-reinforced adhesives) and Metal Laminates - ML (thin metal sheets bonded by structural adhesive) that provides significantly improved strength and stiffness properties for tailored fuselage applications. The fatigue properties of these innovative Laminates, which are not yet available, are required to match those of the GLARE® material. The objective of significantly increased static behaviour and a well-balanced combination of mechanical properties will be achieved by the use of alternative constituents such as new fibres, advanced metals and modified pre-preg systems. The high manufacturing costs of FML will be reduced by using less expensive material systems such as high performance ML. Appropriate manufacturing and joining technologies require validation for the progressive laminates. Corrosion is a problem to be quantified and resolved with new sizings and treatments. A further essential task is the development of material models and static failure criteria for the prediction of the material behaviour of FML and ML in both the microscopic and the macroscopic scale. Finally, optimisation criteria for the design of coupons and structural elements will be developed and experimentally verified for laminates with the aim to reduce the overall weight of the aircraft fuselage. The technological objective is a fuselage skin weight reduction of up to 30% when compared to GLARE®. This is achieved by an increase in static properties of 10 to 100%, depending on the specific value considered. The strategic objectives are an increase in the operational capacity of 10%, a reduction in the direct operating cost of 10% and finally a reduction in the fuel consumption of 10% and therefore a reduced environmental impact with regard to emissions and noise. The strategic and economic objective is a reduction in the product cost of 5% derived from a fuselage skin material cost reduction of 20%.

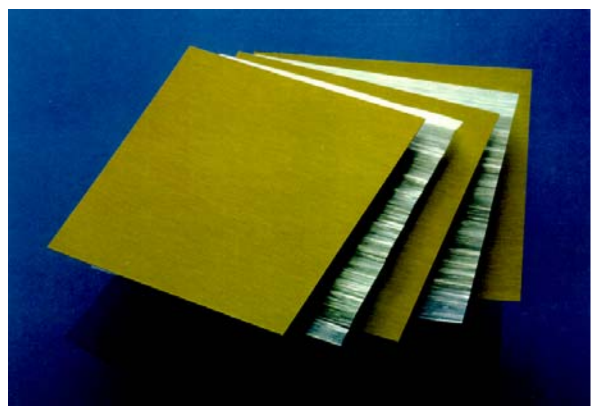

Figure 1: Typical GLARE® lay-up

1. State of the Art

1.1 Fibre metal laminates (FML)

The intensive work on Fibre Metal Laminates (FML) started in the early 80's. These investigations resulted in an optimised material called ARALL® (Aramid Reinforced ALuminium Laminates). The layout was based on 0,3 or 0,4 mm aluminium sheets which were made from AA2024 or AA7475. AA7475 showed a relatively poor fatigue behaviour and AA2024 a low strength, but superior fatigue behaviour. During the late 80's/early 90's, applications in wing structures (Fokker F27) or cargo doors (McDonell Douglas C-17) were discussed and investigated. Several demonstrators and about thirty C-17's with ARALL® cargo doors were built.

A new FML was patented in 1987 where glass fibres instead of aramid fibres were used (fig. 1). This new material showed superior impact behaviour and was called GLARE® (GLAss REinforced laminate). In the early 90's it seemed realistic that GLARE® would be applied on the floor structures of the Boeing 777. In 1997 a GLARE® Research Program (GRP) was launched. This program was funded by the Dutch Ministry for Economic Affairs. Within this research program, the technology readiness of GLARE® was achieved. GLARE® is now used as skin material in approx. 470 m^2 of the new Airbus A380-800 (fig. 2). The application of GLARE® is mainly realised in single and double curved upper shells of sections 13, 15 and 18 (including both window rows). The maximum panel size is up to 10.5 m x 3.5 m.

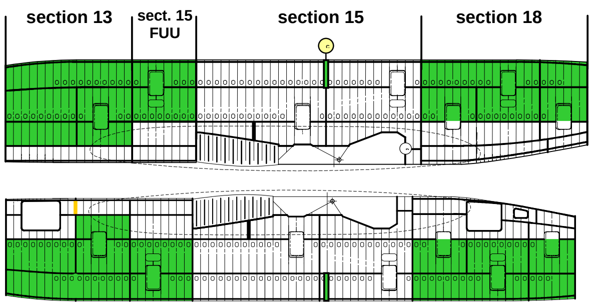

Figure 2: GLARE® (green) application at Airbus A380 [11]

Todays FML-standard is GLARE®, which is qualified as a material for Airbus Aircraft Programmes. This standard is made from 2024 T3 and an unidirectional pre-preg which is based on s2-glass fibres. An epoxy adhesive curing at 120°C is used. The pre-preg will result in a fibre volume content of 59 % and a nominal pre-preg layer thickness of 0,127 mm. GLARE® is made from 0.3 and 0.4 mm aluminium sheets. The metal volume fraction is between 50 and 70%. Today GLARE® has six standard grades with different fibre directions and a varying number of pre-preg layers.

The name FML includes already that additional combinations are possible than just aramid-aluminium and glass-aluminium. For these new materials only limited research results are available. An overview is given by *de Boer* [1].

Alternative constituents are described for a next generation of GLARE®. For example, *de Boer* shows results for the use of 2024 T81 where the properties, especially the static ones, increase by several percent. It is also possible to cure this alloy at 180°C. The combination of carbon fibres with aluminium sheets was mentioned.

Developments in carbon fibre production resulted in a large variety of fibres with many different mechanical properties. Strength and stiffness dominated structural applications can be covered in this way. As potential applications *de Boer* mentioned space applications, impact absorbers for helicopter struts and aircraft seats. He also mentioned the galvanic corrosion problem which could occur if carbon fibres get into contact with aluminium.

Since the early 90's carbon titanium laminates have been developed. These FMLs were developed for service temperatures of up to 300 °C and were made from Ti-6Al-4V and IM 600 carbon fibres.

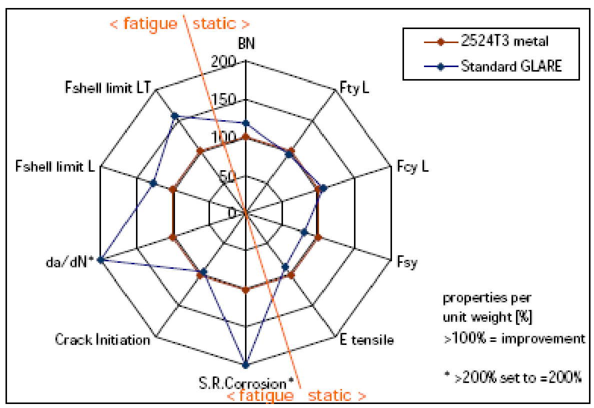

Figure 3: Improved properties of GLARE® in comparison to 2524 T3

Positive properties of ARALL® and GLARE® are, that they both have outstanding fatigue properties. Crack growth is almost not observable compared to other commonly used aluminium alloys (fig. 3). Corrosion is due to the aluminium sheets, not a problem. They have an excellent fire resistance as the epoxy is burnt, after the outer aluminium sheet is molten away, and then isolates the second aluminium layer from the heat. If properly manufactured humidity has almost no effect on GLARE® components. However, the production costs of both materials are high. ARALL® and GLARE® are extensively protected by patents.

To date, the pressurised fuselage of commercial transport airplanes generally consists of a built-up structure where the skin to stringer connection may be riveted or bonded. For new aircraft (A380) the introduction of FML leads to significant weight saving and laser beam welded panels to significant cost saving. The dimensioning criteria may vary depending on the type of aircraft (short, medium or long range), the materials applied, the detailed design (integral or built-up, stiffening ratio) and the applicable regulations and industry standards. The damage tolerance criteria dominate the design in large areas. In these areas the FML will allow a significant weight reduction as a consequence of an improved structural efficiency resulting from an increase in the allowable stresses for crack growth and residual strength.

1.2 Metal laminates (ML)

Bonding technologies provide the opportunity for weight reductions and less conservative design solutions. Advanced adhesive bonding has been used for both wing and fuselage structures in regional aircraft with excellent operational experience [2, 3] and offers advantages for large civil aircraft structures as well (bonding of stringers and doublers at Airbus since the 70´s).

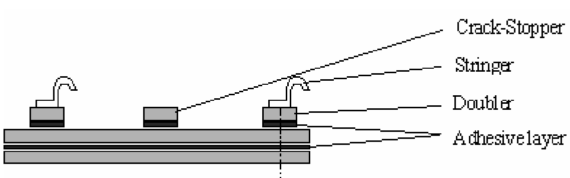

Figure 4: Design principle of Metal Laminates

Metal Laminates are produced by adhesive bonding of a number of thin sheets (fig. 4). In the past comparative fatigue tests on laminated sheet material and solid material of AA2024-T3 Alclad were carried out in the department of Aerospace Engineering of Delft University [4]. The superior behaviour with respect to fatigue crack growth and fracture toughness is related to the following arguments [6]:

- Thickness argument (fatigue crack growth is slower in thin sheet compared to thick plate)
- Peak load delay argument (the thickness argument will be more significant under spectrum loading due to plane stress plastic zone)
- Crack arrest argument (adhesive layers will arrest crack growth for some time)
- Fracture toughness argument (toughness is higher for a thin sheet compared to a thick plate [7, 8, 9])
- Crack stopper argument (highly fatigue resistance crack stopper bands (strap) are needed [10])

1.3 Analysis methods

Over the past ten years, a limited number of dissertations, mainly carried out at the TU Delft, have made considerable progress in the numerical modelling/simulation of Fibre Metal Laminates and Metal Laminates [5]. However the damage behaviour has not been backed up experimentally with the same efforts as for the numerical modelling/simulation. In industry, a comparable progress has not yet taken place and fibre metal laminates are commonly computed numerically using the modified properties of aluminium structures. This may work reasonably well as long as no significant excursions are made into the non-linear regime. Furthermore, this approach is not relevant for the damage behaviour of FMLs and MLs. The project adds for the first time an industrial capability to simulate FML structures on a level close to the best available basic research developments, and in addition will validate the models in a systematic manner by experimentation particularly geared at the model.

2. Scientific and technological objectives

The grades of GLARE® used today are optimised for fatigue and damage tolerant (F&DT) properties. That is the reason for the application of this material in the upper shells of the A380. Due to the outstanding F&DT performances the dimensioning factors are the static properties. Therefore a new generation of Fibre Metal Laminates (FML) with significantly improved static but equivalent fatigue characteristics, which is not yet available, could lead to better performance and a wider range of applications of FML. It is necessary to obtain a balanced behaviour between static and fatigue and damage tolerant (F/DT) properties. Such a well-balanced material could lead to significant reductions in terms of weight and operating cost.

To enable future high-performance structures for aircraft a new tailored and cost-effective material is absolutely needed. With the general aim of reducing structural weight, manufacturing costs and direct operating costs, the improvements from innovative FML/ML have to be combined with advanced design and structural weight optimisation. These design concepts will lead to an optimised balance between structural weight and production costs while maintaining the structural performance and ensuring the stringent safety requirements.

Proposed research areas include the use of different types of fibres and different light metal alloys or metal matrix composites. A further research topic is a different layer build-up. Such variations could include the use of different metal-alloys and different fibre orientations in fibre metal laminates, as well as mixed metal layer combinations including metallic fibre substitutes, such as perforated metal plates, metallic meshes or local reinforcements, when focusing on Metal Laminates (ML). Metal Laminates could be regarded as a cost effective alternative to the Fibre Metal Laminates.

For improved environmental protection surface treatment without chromate has to be investigated, while maintaining adequate environmental durability of the material. Corrosion problems will have to be investigated to some extent. Suitability to long term aircraft use will need to be investigated, with particular focus on the galvanic corrosion problem occurring with some material combinations and the sensitivity to humidity and temperature. Appropriate manufacturing and joining technologies will have to be validated and specified for the advanced laminates.

In every design process, simulation plays a key role. Because of the complex build up of metal and fibre metal laminates, it is difficult to obtain reliable failure properties. The aim of this project is to build a model of a FML/ML which considers all the interactions between the different layers and the adhesives used. Material models and static failure criteria shall be developed to predict the material behaviour of components and structures made of Fibre Metal Laminates and Metal Laminates. This also leads to a cheaper design and development process as extensive testing or material screening is no longer necessary.

Summary of the scientific and technical Objectives:

- Improved static properties (50 %) to receive a better balance between static and fatigue properties providing a higher structural efficiency with increased performance
- Weight reduction (30-50 %) due to the use of materials with reduced density and improved static strength and stiffness values
- Cost reductions (5 %) due to cost efficient laminates or improved manufacturing technologies
- Validation of environmentally friendly surface treatments for the manufacturing of advanced Fibre Metal Laminates or Metal Laminates

- Development of material models and static failure criteria to predict the material behaviour of Fibre Metal Laminates and Metal Laminates
- Design optimisation of structural components with innovative Fibre Metal Laminates and Metal Laminates
- Verification of simulation results with experimental testing of coupons on sub-component and component level

The deliverables being generated by the programme can be summarised as follows:

- development of new FML with higher static strength and stiffness
- development of ML with improved fatigue and damage tolerance behaviour
- development of new material models and static failure criteria for FML
- design optimisation of airframe structures for FML
- specification of improved test standards for FML

The work flow within the DIALFAST project can be visualised and explained in the charts below (fig. 5 and fig. 6).

3. Project description

Covering the whole development chain, the project starts with WP1 "FML" researching basic developments of new improved FML concepts dealing with the improvement and compatibility of the constituents itself and the mechanical properties, environmental behaviour and manufacturing aspects of the final FML. In parallel, WP2 "ML" regards the screening, optimisation, design and testing of the alternative cost-effective variant ML. Information and data on basic materials is exchanged. WP4 "Analysis methods" is providing the basic material models, static failure criteria and their implementation into commercial simulation tools for FML, ML and commonly used joints. WP3, "Structure optimisation", is striving for structural optimisation, testing of larger panels and the realisation of weight reduction within new and tailored, cost-effective structures.

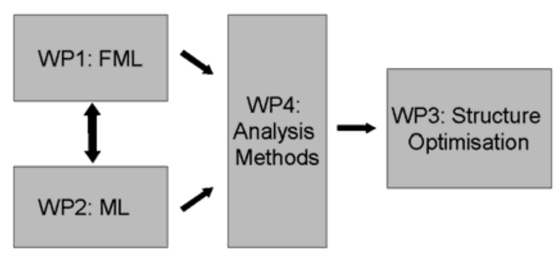

Figure 5: Project flow chart

Intensive co-operation, information and data exchange between the defined work packages is planned especially on the topics below:

- basic material screening, exchange of material data (WP1, WP2, WP4)
- corrosion behaviour (WP1,WP2)
- manufacturing aspects (WP1, WP2)
- joining procedures (WP1, WP2, WP4)
- design solutions (WP2, WP3)
- behaviour of larger panels (WP2, WP3)
- cost/weight analysis (WP1, WP2, WP3)

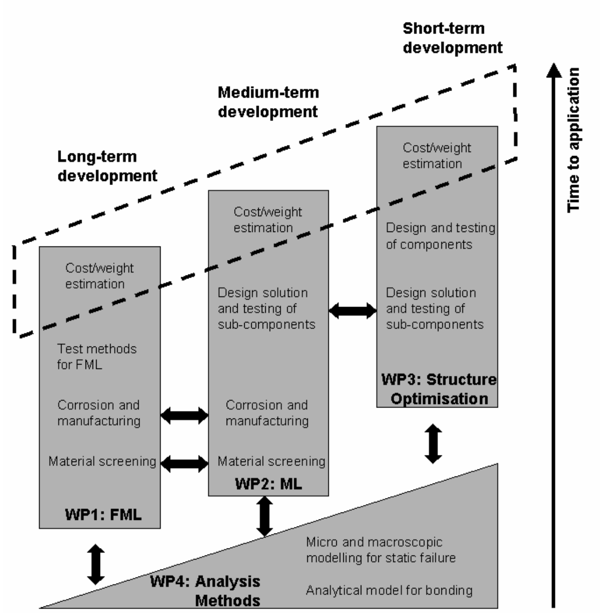

Figure 6: Pert Diagram of DIALFAST

The main competencies in Europe working in the fields of FML/ML are the contractors involved:

- Airbus Germany
- Alenia Aeronautica
- Stork Fokker
- EADS CRC Germany
- EADS CCR France
- FMLC
- NLR
- ISTRAM
- TU Delft
- Pisa University
- Linköping University

4. Work performed

In WP 1 the evaluation of available and suitable fibres and alloys has been made. Investigation of compatibility between selected fibres and adhesive was investigated and discussed with the pre-preg manufacturer. Investigation of metal/metal bonding properties of selected pre-pregs was done and the FML properties with different fibres, based on 2024T3 were determined. Several fibres were compared to fulfill requirements according to goal of WP1. Three fibre types were selected and ordered for pre-preging. Pre-pregs with new fibres have been delivered with different quality levels.

It was possible to organize three different high strength aluminium alloys in 0.4 mm thickness. All are well within the desired property range, which was calculated in advance. Two of them are commercially available and one was produced on a trial mill and only small sheets were available. Additionally it was possible to roll down one Al-Li alloy at a lab rolling mill. Static tensile, fatigue crack initiation and fatigue crack propagation behaviour has been tested.

Advanced fibre metal laminates have been produced with standard pre-preg and new alloys. The standard GLARE® procedures could be used and showed good results. The specimens have mainly been tested. Pre-treatment of the new alloys is still under investigation, because after first pre-treatment trials, the anodizing layer was much too thick. Specimens have been produced without anodizing for the moment, since the reason for anodizing is the improvement of the long time corrosion behaviour.

Laminates have been produced with advanced pre-pregs and standard 2024T3. The evaluation has been finished and most promising fibres have been selected. Now the selected metals and fibres will be combined to new laminates to obtain superior properties resulting in improved metals and pre-pregs.

Initial corrosion tests have started with FML made with carbon fibres. 2 specimen types are under investigation. One had scratches on the surface and one had holes and fasteners. On the edges of the specimen, conductive glue was applied, since a worst case scenario should be represented. The main result was that the decisive point is the conductivity between the layers of the laminate. Basic corrosion tests have been carried out with the new alloys showing sufficient results.

A FEM-Analysis of the effect of several aspects on the shear modulus has been performed. As a result, a new test fixture was ordered and 45 degree tensile tests and Iosipescu tests have been performed on Al-alloys. These results have been analysed in detail. Until now, no major discrepancies could be observed. The shear modulus can be evaluated reasonably well with the standard test method and applying two strain gauges, one on the front side and one of the back side of the specimen.

In WP2 materials have been selected. Three different sheet materials and 4 different adhesive systems have been chosen with different curing properties. Three different lay ups were defined for investigation. Specimens have been prepared and tested for crack growth, fatigue and corrosion behaviour. The aim was to find the optimum material and lay-up configuration with respect to fatigue and damage tolerance. The tests are completed and the results have been used for design purposes of structural tests

The influence of suitable metal constituents have been analysed by numerical modelling. Analysis of influence of suitable bonding technologies and analysis of influence of improved ML structure (combination of different bonding technology and different sheets thickness with asymmetrically lay-ups) has been performed numerically.

The design of 7-stringer test panels has been defined and about 20 specimens are under preparation. Testing of crack growth and residual strength is scheduled. The aim is to decrease the crack growth rate and increase the residual strength.

Selection criteria for the definition of a reference location in the aircraft structure have been identified. Based on these criteria, the reference area has been defined and the static behaviour of this reference has been investigated. For optimization, 4 steps have been defined and investigated. According to these results, a weight reduction of 18 % seems possible for ML. These results will be verified by shear/compression component testing.

In WP3 a test matrix has been defined. Tests have been performed and are still ongoing. Sheets have been partially produced by chemically milling down to 0.2 mm thickness.

Static and fatigue tests have been performed on “L-Pull” specimen. Two types of adhesives and two curing procedures have been used. A high influence of the test frequency has been observed. A thinner bondline showed better results.

The fatigue behaviour of FML riveted joints has also been tested. An additional Al-sheet in the rivet area in each laminate can reduce the number of rivet rows from 3 to 2. Fracture toughness tests have been performed and are still running now.

In WP4 a delamination model has been implemented in FEM code explicit and implicit. Matrix and fibre damage as well as aluminium smeared crack model incl. temperature effects are incorporated in the model. Validation of models against literature data and GLARE fracture toughness tests have been done and show good correlation. Fracture toughness tests for GLARE® 3 are completed in different modes and temperatures. Tests of improved ML and FML are running.

Explicit simulation of rivet fastening with pre-stress analysis has been done. A simplified model for implicit analysis with contact fit option was created. For rivet failure, a smeared crack model for aluminium has been implemented. First results of lap joint testing are available.

GLARE® test specimens were manufactured. Test series on GLARE® is completed. This test series consisted of general tests (three lay-ups, two rivets, two temperatures) and of additional tests (one lay-up, one rivet, additional temperatures).

To quantify the stress and strain in splice joints, a full description of the analytical scheme resulted in systems of differential equations, which have to be solved by numerical methods. A comparison of analytical approach with FEM analysis shows high efficiency of the developed code in terms of computation time.

5. First results

Combining existing GLARE® pre-preg with new high strength metals especially the metal dominated properties like yield, ultimate tensile and blunt notch strength could be improved (table 1).

Combining the standard 2024 T3 material with new pre-preg systems especially the fibre dominated properties such as tensile and compression modulus could be improved (table 2).

The fatigue crack propagation behaviour is still acceptable for the high strength metals and superior for the new fibres (fig. 8) in comparison to GLARE®. Evaluating the obtained test results of the first project phase the most promising constituents and combination of constituents can be selected for further investigations. The still existing mismatch in properties compared to the defined goals might be reached by these new laminates.

6. Summary and outlook

The project DIALFAST is dealing with the development of new fibre metal laminates (FML) and metal laminates (ML) to reach defined material goals for application within new weight reduced aircraft fuselage structures (fig. 7). Finally structural tests of fuselage panels will be carried out. Modelling activities to predict the damage behaviour in FML/ML and its joints are performed as well.

Figure 7: GLARE® fuselage panel

Continuing the described project program new combinations of selected constituents (new fibres together with new metals) will lead to significantly improved properties hopefully matching the defined requirements. For metal laminates the progress is mainly anticipated in the static and fatigue testing of structural coupons with optimized design.

Expected results of the modelling task are new models for calculating fibre metal laminates and metal laminates properties. The proposed intention for use is calculating the properties of the material and the static failure. The main impact will be reduced costs for material tests and therefore reduced development costs for future aircraft programs.

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	GLARE®	Metal A	Metal B	Metal C	Aim of DIALFAST
TUS	100 %	119 %	122 %	120 %	**110 %**
TYS	100 %	161 %	171 %	166 %	**180 %**
Tension modulus	100 %	81 %	88 %	86 %	**120 %**
CYS	100 %	183 %	199 %	193 %	**200 %**
Compression modulus	100 %	98 %	97 %	98 %	**120 %**
Blunt notch (net)	100 %	119 %	134 %	129 %	**115 %**

Table 1: New FMLs with modified metal layers

	GLARE®	Fibre A	Fibre B	Fibre C	Aim of DIALFAST
TUS	100 %	117 %	118 %	106 %	**110 %**
TYS	100 %	129 %	130 %	141 %	**180 %**
Tension modulus	100 %	98 %	109 %	111 %	**120 %**
CYS	100 %	91 %	137 %	143 %	**200 %**
Compression modulus	100 %	86 %	112 %	118 %	**120 %**
Blunt notch (net)	100 %	113 %	116 %	105 %	**115 %**

Table 2: New FMLs with modified pre-preg

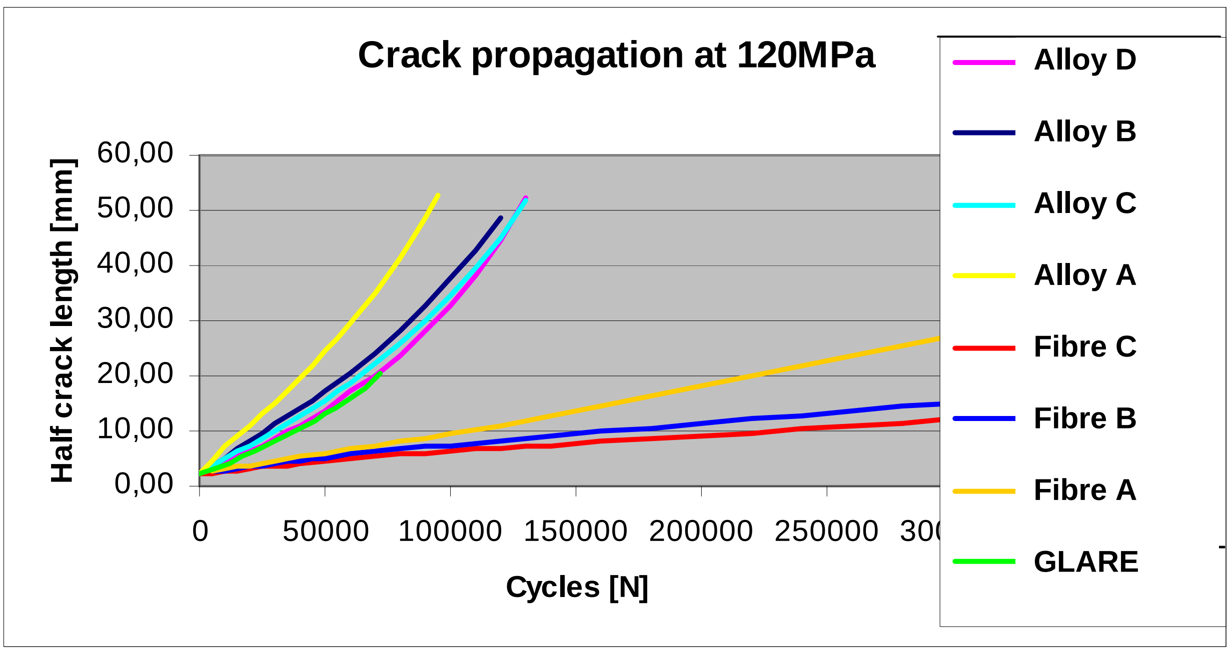

Figure 8: Crack propagation behaviour of new laminates

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