**EPMA European Hard Materials Group**

# Simulation of Fatigue Crack Growth in Hardmetal at a Mesoscopic Scale Project: "Simu-Crack Phase I"

## Consortium Agreement

Issued 16 May 2011

The Project – "*Simu-Crack Phase I*" as defined in Annex 1 Phase I
The Contractors –

- „RWTH Aachen für den Lehrstuhl für Werstoffanwendungen im Maschinenbau, Templergraben 55, 52062 Aachen, vertreten durch den Rektor oder die von ihm beauftragte Person": IWM RWTH Aachen
- Universitat Politècnica de Catalunya (UPC), C./ Jordi Girona 31, 08034 Barcelona, through CIEFMA (Centro de Integridad Estructural y Fiabilidad de Materiales, TECNIO member): CIEFMA UPC

The Coordinator – The European Powder Metallurgy Association EPMA
The Members - **paid up corporate <u>EPMA members*</u>** funding the Project
The Participants – The Contractors and the Members

UV = unanimous vote of Members and Contractors; MV = majority vote of 2/3 members or higher

<u>Heads</u>

1. The Members and Contractors agree to cooperate in order to complete the Project according to Annex 1.

2. All information generated under the Project will remain confidential to the Members during the Project and for 5 years after delivery of the final written report to Members, and may only be disclosed to third parties (e.g. for dissemination purpose in PM Congress) with UV.

   For **IWM RWTH Aachen**: Under the relevant provisions of the Universities Act NRW (Hochschulgesetz NRW), the contractor is obliged to publish in the usual scientific form the results of studies undertaken during performance of the project. The client gives his fundamental consent to such publication. In particular, the client will allow publication in connection with the taking of doctorates. The contractor will inform the client beforehand of any planned publication and will give him the opportunity of commenting upon it within a reasonable period, at latest ten (10) weeks after submission of the text intended for publication. A Member is entitled to refuse his consent to a publication if it is intended to publish company related data or, in connection with the granting of patent rights, if it is intended to publish any anticipatory information likely to constitute a bar to novelty. In such cases, the contracting parties will, without delay, seek to reach a special agreement governing the form and timing of rapid publication and taking due account of the legitimate interests of both parties.

   For **CIEFMA UPC**: The Member is aware of the Contractor status as scientific research establishment, and, consequently, a generous attitude to publication shall be maintained. In order to ensure that no risk to potential patents is taken, however, no publication of any result from the Project shall be made without the Member written consent, which will not be unreasonably withheld. The Contractor shall supply the Member with the manuscript of the intended publication, and, within ten (10) weeks, the Member will respond with permission, or otherwise, to publish the manuscript either as is, or after suggested changes in content have been made. Failure of the Member to respond as specified will be considered as consent by default.

3. The Contractors agree to not carry out a similar project on hardmetals with organisations other than the Members until the completion of the project (delivery of the final report). The

aforementioned obligation shall not apply to other entities of UPC other than its performing entity CIEFMA research group and to other entities of RWTH other than its performing entity IWM.

4. The Members agree **to share equally the cost of the Project** (EUR 87,464) through a Project Fee of maximum **EUR 21,866** per Member according to the Payment Schedule detailed in 6. The required minimum number of Members is **four** unless the Members agree to exceed the maximum Project Fee.

5. The Members also undertake to provide the Contractors with the necessary materials (powders, specimen etc...) for the project. If no agreement on in-kind contribution between the industrial partners can be found, the EPMA will coordinate this task "Work Package 0" and charge equally each Member to cover the cost plus an administrative fee of 10%.

6. **Payment Schedule**:
   For the Work Package 0: Full payment within one month after invoice if necessary.
   For "Simu-Crack Phase I" project:
   - **25% at the start**,
   - **25% at the middle**,
   - **50% after completion** of the Simu-Crack Phase I project and delivery of the final report.

7. New paying members may be admitted during the Project by UV on payment of an additional reasonable premium (10%). The premium will be used to decrease the Project Fee for the Consortium Members.

8. Except for the deliverables of the Annex 1, each Participant will retain the Intellectual Property for any other outcomes of the project.

9. Warranty. The contractor's warranty extends solely to the use of due scientific diligence and to compliance with accepted engineering practice. The contractor does not guarantee that the desired objectives of the research and development project will be achieved.

10. Liability. The contractor is liable solely for wilful actions and gross negligence. Liability for proven damage is limited to the amount of the contractual sum.

Except for the terms 4, 9, 10, all the terms of this agreement may be changed by UV.

Coordination will be by the EPMA, who will have responsibility for invoicing, day to day liaison with the Contractors and keeping Members informed. The EPMA will operate under the same confidentiality agreement as Members and the EPMA President will be arbitrator for unresolved disputes.

Signatures: signed individually by all Members and Contractors

ORGANISATION:

NAME:

(Date signed)

***If you are not an EPMA member please contact Dr Olivier Coube, EPMA Technical Director, oc@epma.com***

**Annex 1**

# Simulation of Fatigue Crack Growth in Hardmetal at a Mesoscopic Scale Project: "Simu-Crack Phase I"

**Project Description**


## Abstract

Fatigue crack growth (FCG) in the microstructure of hardmetal will be numerically simulated at a mesoscopic scale using the finite element method (FEM). The microstructure will be modelled explicitly by a three dimensional arrangement of tungsten carbides in the cobalt binder. Cyclic crack propagation is assumed to occur in the binder phase only. It will be modelled using the well established Paris-law for the crack growth rate. Variations of volume fraction, size and interconnectivity of the carbides will be studied in order to find an optimum microstructure with respect to resistance against fatigue crack growth.

The project should be seen as a feasibility study to demonstrate the capability of the FE-method to predict the mechanical behaviour of hard metal under cyclic loads. The successful proof of the method will encourage further efforts to link the mesoscopical model to the macroscopic scale of components on the one hand side and to strengthen the model by incorporating proper microscopic effects of crack propagation at the other.


## Introduction

Lifetime of hardmetal tools and components is limited by mechanisms like wear, fracture and corrosion. Increasingly, hardmetal parts are applied as structural components where the mechanical strength becomes the limiting factor for the entire life of the part. Fatique is the dominating fracture mechanism. Moreover, in a lot of tooling applications fatigue as a micromechanism contributes to abrasive wear significantly.

Effective improvements in fatigue performance of hardmetal components requires a better understanding and control of microstructural mechanisms and effects that contribute to damage under cyclic loads. A lot of research work has been done and results have been published on the experimental characterisation of fatigue in hardmetals, ranging from the determination of macroscopic S-N-curves over fracture mechanical studies on the crack propagation to metallographic and analytical investigations regarding the damage mechanisms and microstructural changes during fatigue. Microstructural simulations of the crack propagation in hardmetal at a so called mesoscopic scale have been performed using two dimensional (plane strain) models. Nevertheless, these studies still are restricted to crack propagation under monotonic increasing loads.

The finite element method is well established as a simulation tool to predict stresses and strains in mechanically loaded components. FEM is a standard method used in the design and lifetime prediction of engineering components. Powerful program codes have been developed, are commercially available and widely spread throughout industry. Well accepted standards have been set for data exchange between pre-processing programs, FEM-solvers and post-processing routines. Some FEM programs like ABAQUS allow for individual programming of routines describing particular material models including hardening, softening, phase transformation and damage mechanisms. Recently, particular methods have been developed to model realistic crack propagation pathes throughout the structure (e.g. XFEM-method). With special focus on mesoscopic models a pre-processor (DIGIMAT) has been programmed which allows for the synthetic generation of three dimensional two phase microstructures. Summarizing, a set of powerful software tools is commercially available and can be used effectively for material modelling.

## Objectives

The proposed project follows two objectives:

1. **Demonstration that fatigue crack propagation through the microstructure of hardmetall can be numerically simulated with a three dimensional model using the finite element method.**

2. **Finding influences of carbide's volume fraction, size and interconnectivity on the fatigue crack resistance by appropriate numerical studies.**

The first target aims to a feasibility study. The proof that the method works and is applicable to hardmetal might lateron initiate further efforts to link the microscopic model to macroscopic FEM-models in order to estimate the lifetime of entire components. Furthermore a positive result might motivate efforts to look deeper into the physical mechanisms of crack propagation in order to bring the more or less phenomenological model closer to a physical basis. These investigations, of course will be fundamental research activities and might be addressed in a following public supported project in national or European frame programs.

Nevertheless, the results of the second target should directly be usable for the participating companies. The numerical studies will give qualitative hints for the development of hardmetal grades with optimized fatigue resistance. The knowledge of individual influences of the major microstructural features on the fatigue crack propagation will lead to an idea of an optimal microstructure which in a further step might be realized by proper production techniques.

## Work packages

The project is subdivided into two phases and 5 work packages (WP).

### WP1 Implementation of the crack propagation model (IWM)

The FEM-code ABAQUS will be used for the simulation. Carbides are being modelled linear elastically using isotropic elastic material constants. The Co-binder will be modelled elastic-plastically taking into account isotropic and kinematic hardening. The plasticity-parameters of the binder need to be determined experimentally by macroscopic material testing of a model alloy (see WP2 and WP3a). Crack initiation will not be modelled. Thus, a carbide, broken right from the beginning, will be the starting point of the crack propagation. Crack propagation itself will be calculated according to the Paris law

$$\frac{da}{dN} = C\Delta K^m \qquad (1)$$

where da/dN denotes the crack growth da per load cycle dN, ΔK is the local cyclic stress intensity factor and C and m are parameters to be determined in WP3b. The direction of crack propagation will be perpendicular to the direction of maximum principle stress.

In this work package the model of crack propagation will be implemented into ABAQUS. Part of this task will be the application of eq. 1 as crack growth controlling criterion in XFEM. According to the target “feasibility study” in phase 1 only ABAQUS is used in order to proof that the method is applicable. In case of success the procedure can be converted to the software ANSYS. This will be part of phase 2 of the project.

| | | |
|---|---|---|
| **Deliverables WP1:** | phase I: | macros and subroutines for FEM-code ABAQUS |
| | phase II: | macros and subroutines for FEM-code ANSYS |

### WP2 Production of a model alloy for the Co-binder (IWM)

The properties of the cobalt binder in the hardmetal will be experimentally determined by testing an appropriate model alloy. This alloy should have the same solid solution state of carbon and tungsten in the cobalt lattice as the binder in the hardmetal. Therefore, a particular chemical composition of the model alloy needs to be designed and a set of samples has to be manufactured by a PM-route using hot isostatic pressing (HIP). The powder for the samples should be given by the supporting industry, capsule production, capsule filling and HIP can be done by IWM.

| | | |
|---|---|---|
| **Deliverables WP2:** | phase I: | chemical composition of the model-binder-alloy |
| | | raw material for tests in WP3 |

### WP3 Experimental determination of model parameters for the Co-binder

#### WP3a Mechanical properties (IWM)

As mentioned above the Co-binder will be modelled elastic-plastically. This model requires as input data the yield limit, the post yield stress stain curve in order to quantify isotropic hardening behaviour and the development of the backstress for proper description of kinematic hardening. Samples of the model alloy described in WP2 will be uniaxially loaded in a servo hydraulic testing machine.

**Deliverables WP3a:** phase I: yield limit and isotropic and kinematic hardening parameters for model-binder

**WP3b Determination of crack growth parameters (UPC)**

Precracked single edge notched bending specimens (SENB) made of the model alloy will be cyclically loaded with decreasing ΔK-values. Crack propagation is monitored using a high resolution telescope. Crack growth threshold is defined at crack growth rates of $10^{-9}$ m/cycle. The results of these tests are da/dN-ΔK-diagrams. By interpretation of these curves the fatigue threshold $\Delta K_{th}$ and the parameters of the Paris law, C and m (see eq. 1) can be determined. Tests will be performed for two load ratios (R = 0.1 and R = 0.5).

**Deliverables WP3b:** phase I: crack growth parameters (ΔKth, c,m) for model-binder

**<u>WP4 Numerical Studies</u> (IWM)**

The FEM-model will be built up using the software DIGIMAT. An example of a mesoscopic 3-D model is given in figure 1. The representative volume element (RVE) will be embedded into a frame structure of homogenized material. This structure is going to be loaded by uniform forces. An existing precrack is assumed to be present in the RVE prior to the first loading cycle. This precrack is realized by a broken carbide. In order to keep comparability, the length of this precrack will be identical throughout all variations of microstructural parameters.

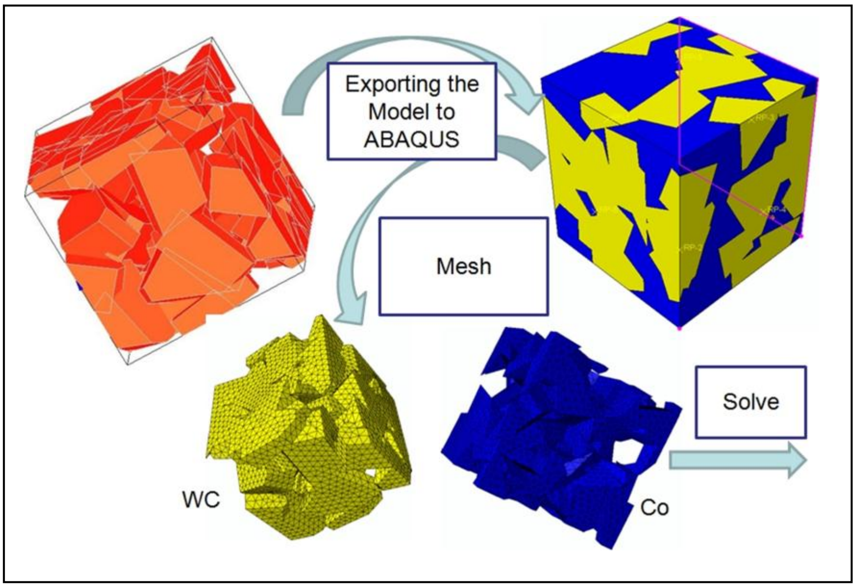


**Figure 1:** Generation of a RVE-Model with the software DIGIMAT

The following features of the microstructure will be varied by producing in total 7 different models. Two of these models will be used in phase I of the project to demonstrate the feasibility of the method. The remaining 5 models will be generated and analysed in phase II in order to identify relationships between microstructure and fatigue behaviour. The conclusions of these studies then can be directly used in material developments.

| | | | |
|---|---|---|---|
| carbide content: | 90 % | 75 % | 60 % |
| carbide size: | 1,0 µm (fine) | 2,0 µm (medium) | 4,0 µm (coarse) |

| | | |
|---|---|---|
| interconnectivity: | two penetrating phases | carbides as dispersion |

Crack propagation will be simulated incrementally. After analysing the first load cycle, the crack velocity will be determined according to eq. 1. Then the crack will propagate for a certain number of cycles with this rate. The crack can run through the binder phase, only. In a next step the crack growth rate will be updated. This procedure is repeated until the crack passed through the whole RVE. The number of cycles necessary to bridge this distance will be used as a measure for the crack growth resistance of the particular microstructure.

**Deliverables WP4:** phase I: proof, that finite element model is working properly
model result: "meso"-da/dN
phase II: diagrams: da/dN=f(carbide content, carbide size)
qualitative: influence of interconnectivity

**<u>WP5 Project management and reporting</u>** **(EPMA+IWM)**

The project management will be supported by EPMA. The final report will be written by IWM and EPMA.

**Deliverables WP5:** phase I+II: 1 report at the end of each phase

**<u>Work package time planning</u>**

Duration of the project: 18 months divided in two phases

Project phase I will be summarized by a report which will be presented at a milestone meeting. Based on the results obtained in phase I the consortium should decide on the continuation of the project.

| Work package | Month | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | phase I | | | | | | | | | | | | phase II | | | | | |
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 |
| WP1: implementation of the model | ■ | ■ | ■ | ■ | ■ | ■ | | | | | | | ■ | ■ | | | | |
| WP2: production of model alloy | ■ | ■ | ■ | | | | | | | | | | | | | | | |
| WP3a: tests: plasticity parameters | | | | ■ | ■ | | | | | | | | | | | | | |
| WP3b: tests: crack growth parameters | | | | ■ | ■ | | | | | | | | | | | | | |
| WP4: numerical studies | | | | | | | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ |
| WP5: project management & report | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ |

**Costs for phase I:**

| | | | |
|---|---|---|---|
| RWTH (IWM) | personnel: | 0.6 full engineer for 12 months: | € 32,760 |
| | | 0.4 technician for 5 months: | € 6,666 |
| | | 1.0 student for 12 months: | € 5,200 |
| | overheads (41%): | | € 18,297 |
| | **total costs:** | | **€ 62,923** |
| UPC | personnel: | 0,5 PM professor: | € 3,085 |
| | | 2 PM technician: | € 7,880 |
| | consumables: | | € 3,500 |
| | overheads (14,7%): | | € 2,125 |
| | **total costs:** | | **€ 16,590** |
| EPMA | administrative costs (10%) | | € 7,950 |

**Total costs of project phase I:** **€ 87,464**

All costs exclusive VAT if applicable

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***Tentative Costs for phase II:***

| | | | |
|---|---|---|---|
| *RWTH (IWM)* | *personnel:* | *0.7 full engineer for 6 months:* | *€ 19,110* |
| | | *1.0 student for 6 months:* | *€ 2,600* |
| | *overheads (41%):* | | *€ 8,901* |
| | ***total costs:*** | | ***€ 30,611*** |
| *EPMA* | *administrative costs (10%)* | | *€ 3,060* |

***Total costs of project phase II:*** ***€ 33,671***

*All costs exclusive VAT if applicable*