International Research Journal of Engineering and Technology (IRJET) e-ISSN: 2395 -0056
Volume: 04 Issue: 05 | May -2017 www.irjet.net p-ISSN: 2395-0072

# Modification of armature tube used for conical expansion under explosive loading for FCG (Helical Flux Compression Generator)

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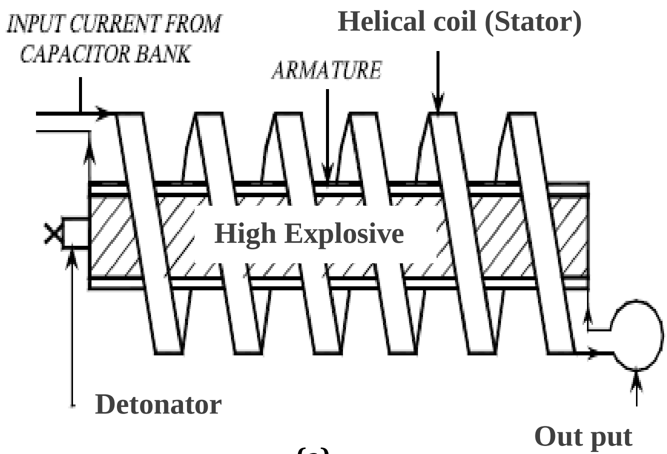
**ABSTRACT**: *In a FCG system, an armature is a crucial part of an electric circuit system, throughout FCG action. In a FCG action process, the electric currents begin rising and flowing on the outer surface of the armature in a circumferential direction due to the magnetic field orientation within FCG system. If current flow direction is altered due to outer surface features irregularity of armature such as initiation of* ***longitudinal cracks*** *due to radial expansion of armature, the developed current flow will be obstructed, retarded and finally an arc can be initiated between helical coil (stator) and armature. These developed arcs are undesirable and make FCG system inefficient. The detail study and numerical simulation with help of AUTODYN for these developed longitudinal cracks on armatures outer surface is the prime focus of this paper. This paper also provides some suggestions to modify an armature so that it can minimise the inefficiency of existing FCG system due to longitudinal cracks on expanded armature surface.*

**Key words: FCG, armature, magnetic flux, inefficiency, high strain rate and longitudinal cracks.**

## 1. INTRODUCTION:

A flux compression generator (FCG) is a device for generating a high amplitude transient current pulse or an ultrahigh magnetic field as an output with help of initial seed current (supplied by a capacitor bank for producing initial magnetic flux inside FCG system) and an explosive energy (for fast expansion of armature surface) as input. The explosive energy in this system has to be used to expand the metal tube (armature) of a FCG system at a high stain rate at the order of $10^5$/sec.

For a FCG action, an initial magnetic field is stabilized between armature and a surrounding helical coil (solenoid), by discharging a charged capacitor bank into solenoid as shown in fig 1(a). Further the high explosive charge mounted inside the armature is ignited from one end with help of detonator.

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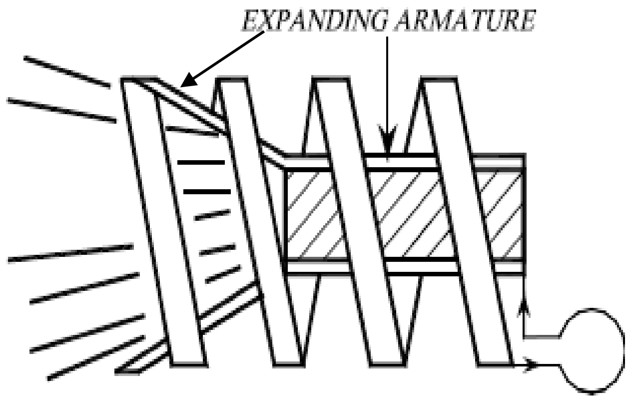



**(b)**

**Fig 1: Helical Flux Compression Generator (a) before explosive initiation and (b) after initiation**

Under the effect of initiated high explosive, the armature tube deforms conically at a high strain rate as shown in fig 1(b). This conically expanded armature makes first contact with a helical conductor. This phenomenon is defined as a crowbarring of FCG system. Now we have to synchronize these two described events (i.e. supply of initial current through capacitor bank and crowbarring) with help of specially designed synchronization unit. Just after this crowbarring phenomenon, total trapped electromagnetic field of FCG system will be compressed by diminishing the number of turns of helical stator. In a process of compressing the magnetic field, FCG system generate an inductive high current as an output.

In an above mentioned conical expansion of armature under high explosive loading, some longitudinal cracks typically developed at the outer surface of armatures at a very smaller expansion ratio than predicted as shown in fig 2. But these typical cracks occurred only within two diameters length from the detonator end of the armature and did not extend further. Such cracks appear to cause magnetic flux cut off and flux losses and makes the FCG system inefficient.

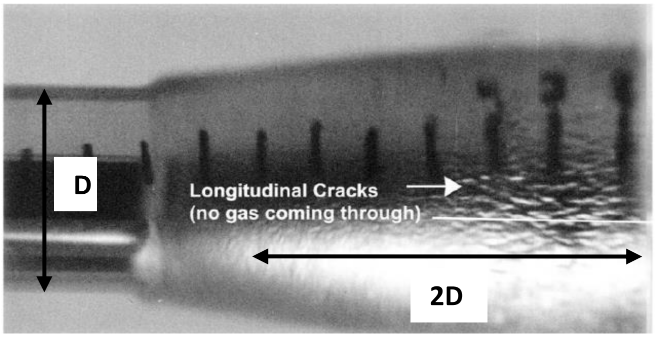



**Fig2: Longitudinal cracks at outer surface of armature**

## 2. REASON OF LONGITUDINAL CRACKS:

As we all know that almost all engineering materials start to break when they stressed beyond their strength limitations. On the bases of experiments, this breaking limit especially for aluminium 6061material armature will be reached when the armature is expanded to more than twice of its original diameter at high strain rate at the order of > $10^5$/sec. For this reason, FCG system has been typically designed in such a way that cracking in armature after expanding double diameter of its original diameter would have no effect on FCG generator performance. But unfortunately in a initial expansion length, within two diametric axial length from detonator end, these cracks are developing on armature's outer surface without expanding double diameter of its original diameter. As a mechanical engineer, we can easily understand that the cracks on armature tube should begin on the inner surface of the armature tube because of maximum circumferential stress at inner surface due to explosive pressurization as compare to outer surface, but the longitudinal cracks began on or near the outer surface as shown in fig 2. Therefore explosive pressurization is not the cause for these cracks. If explosive expansion is not a probable cause of premature fracturing then we have to discuss other factors. Aside from atmospheric pressure, gravity, and explosive expansion, the only other forces acting on the armatures are shock loading from the explosive charge detonation waves. It can be easily considered that atmospheric pressure and gravity are obviously not the cause of armature fracturing; otherwise, the armatures would fracture prior to testing. Therefore, premature cracking in armature are definitely shock-induced if they are not due to explosive expansion, gravity, or atmospheric pressure.

For observing this shock loading phenomena, I have used hydrodynamic code to simulate longitudinal cracks at initial length of armature with help of 2D AUTODYN software.

## 3. MODELLING AND SIMULATION OF FCG ARMATURE:

AUTODYN software offers an alternative approach of actual testing of high explosive blast and explosion phenomena. Their advantage is that they attempt to model the full physics of the phenomena and can be modified as per their use without attempting actual test.

In this paper, two- dimensional explicit hydrodynamic code AUTODYN is adopted to simulate expansion of the armature tube and observe the cracks at initial length. In Autodyn software, a dedicated material model library is available for defining materials as I have used Al6061 and Composition B for simulating armature and high explosive respectively in my armature expansion problem as shown in fig 4.

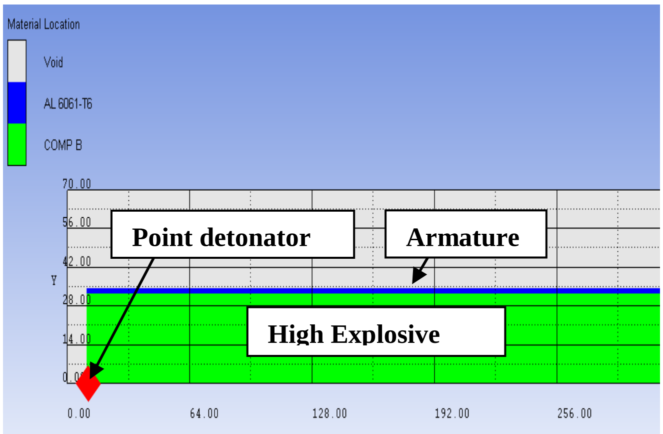
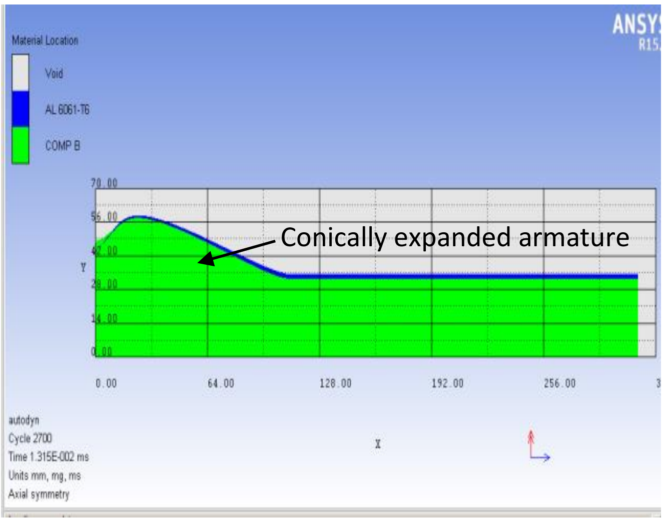



**Fig 3: FEM model of explosive filled armature**

The material models can be broken down into three categories named equation of state (EOS), strength model and failure model. EOS is to be used in providing volumetric stress or pressure information. The strength models, which are the constitutive relations for determining the deviatoric stresses by Hooke's Law and a plastic yield criteria and failure model, which provides a criterion for determining if a material has failed and no longer has strength.

For the FCG armature problem, the large material motions and venting of explosive gases are best modelled using the Euler processor where the numerical mesh is fixed and the "fluid" flows through the mesh. The armature tube is best suited for a Lagrangian framework wherein the numerical mesh moves and distorts with the material motion. AUTODYN-2D allows both of these approaches to be combined in the same analysis.

For validating an AUTODYN simulation result of armature expansion, the material model for armature has been taken without considering failure model and the high explosive has been initiated with point detonator at the centre of cylindrical charge as shown in fig 3. A movable gauge has been applied on armature outer surface at 100mm axial distance from detonator end for recording the rate of expansion of armature surface due to explosive loading. Further these gauge result has been validated through experiments.

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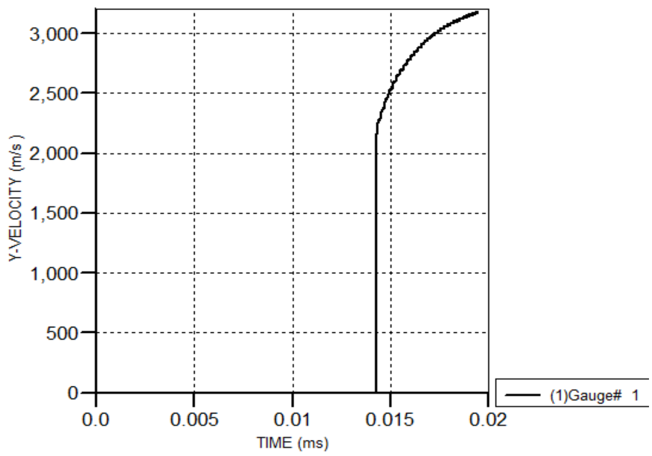



**(b)**

**Fig 4: Simulation result at 100mm distance from detonator end and t= 13.15µs (a) expanded surface of armature (b) rate of expansion of armature**

According to the explosive experiments, the average rate of expansion of armature surface is 3.2km/sec at 100mm axial distance from detonator end. According to the result of AUTODYN simulation the average rate of expansion of armature surface is 3.3km/sec at the same distance of 100mm. The relative error between the AUTODYN and experimental result is less that 5%. Thus, the finite element simulation model can be used for premature longitudinal cracks failure of armature surface and for modification in a system for minimizing the premature failure of armature.

For observing the premature cracks on armature surface, a failure model ‘Grady Spall Failure’ has been assigned to armature material. The Grady Spall model can be used to model dynamic failure of metals under shock loading. With the failure model consideration the expansion of armature has been terminated after 5.53µs due to invasion of explosive into armature surface through developed cracks as shown in fig 5.

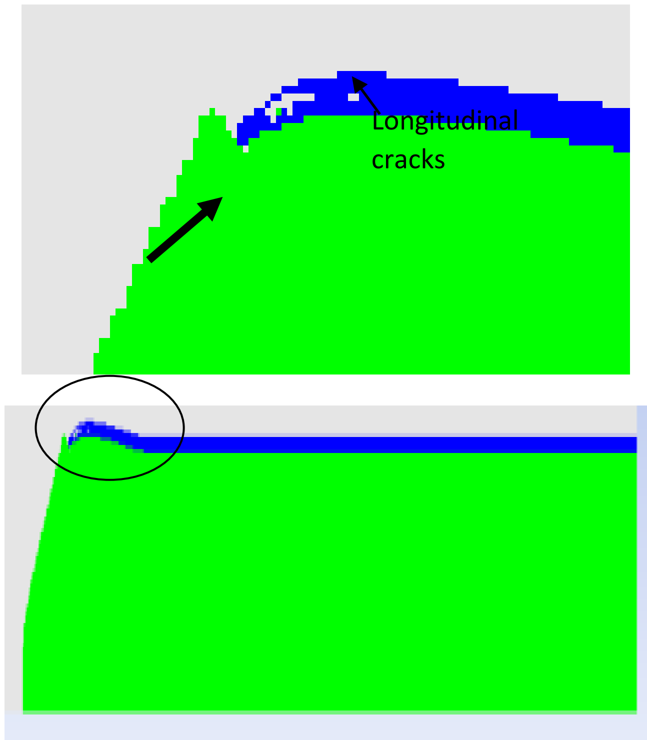
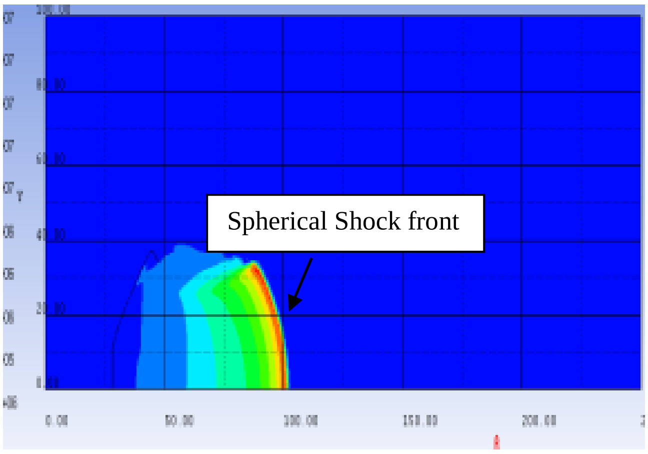



**Fig 5: Armature expansion simulation with considering failure model showing premature cracks in a detail view**

## Various alternatives to minimise the premature crack:

In simulation result shows in fig 6(a), the shape of explosive shock front is spherical within 2D length of armature. After 2D length of armature, it has become planner instead of spherical as shown in fig 6(b).

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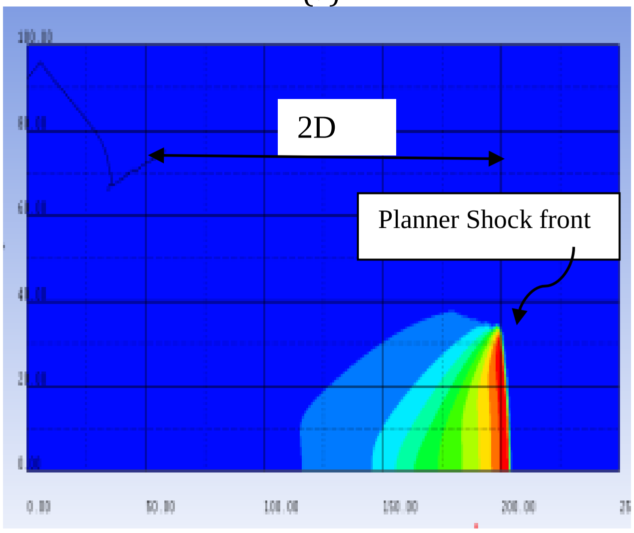



(b)

**Fig 6: Simulation results of high explosive shock front (a) Spherical shock front up to 2D length (b) planner shock front after 2D length**

On the basis of these simulation results of explosive shock front, it can be inferred that premature cracking on armature outer surface is being occurred due to applied compressive and tensile regions in armatures by spherical shock front. This complex stress field causes low-cycle metal fatigue.

## Keep initial 2D length unutilized in FCG system:

The most easy and inexpensive way to minimise premature cracks is to leave initial 2D length of armature unutilized in FCG system. The simulation result shown in fig 7, it is being observed that there are no premature cracks on expanded armature after initial 2D length.

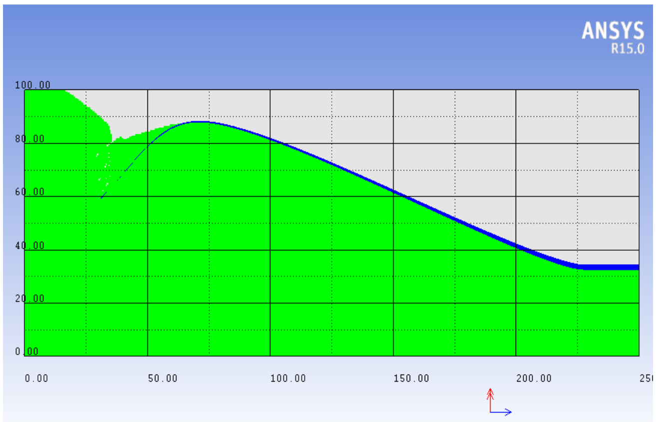
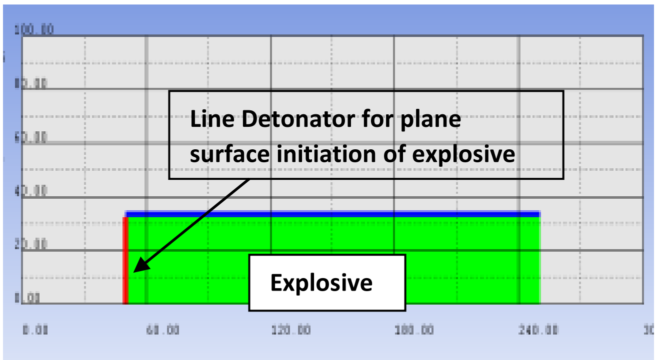



**Fig 7: Armature expansion considering initial 2D length of armature without failure model**

## Use of plane wave shaper:

As we have seen that after planner shock front there was no premature cracking in armature. For stabilizing a planner shock front at the starting phase of high explosive initiation, a specialized plane wave shaper has to be used. The simulation result with line detonator initiation has been shown in fig 8(a). The armature expansion under the effect of plane initiation of high explosive is shown in fig 8(b).

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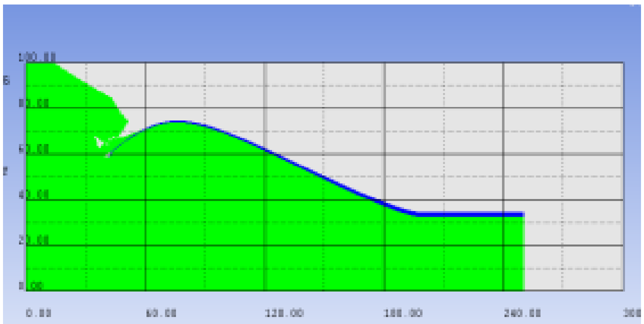
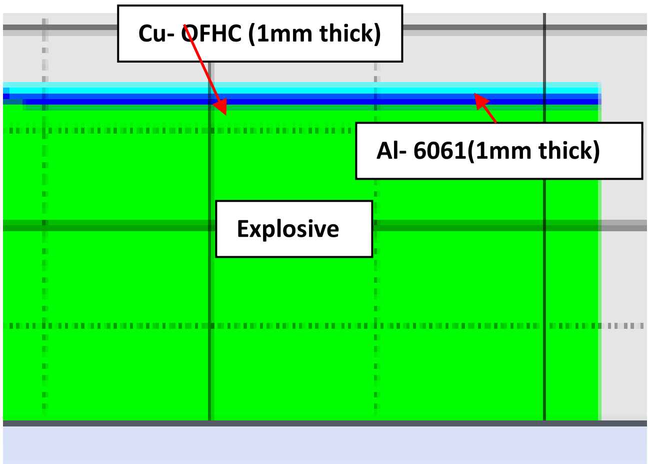


**(b)**

**Fig 8: Simulation by considering plane detonation and failure model (a) model with line detonator (b) expanded armature**

### Use bimetallic armature:

shock loading in an armature due to spherical front of initiated explosive can be minimized through balancing the impedance mismatch across various interface of medium. The impedance mismatch can be balanced by using bimetallic armature. In my AUTODYN simulation, I have modelled armature material with outer 1mm layer of OFHC copper and inner 1mm layer of aluminium 6061 material as shown in fig 9(a). The simulation result of it is shown in fig 9(b). As we can see, the problem terminated around 12µs which is much better option as compared to single material armature.

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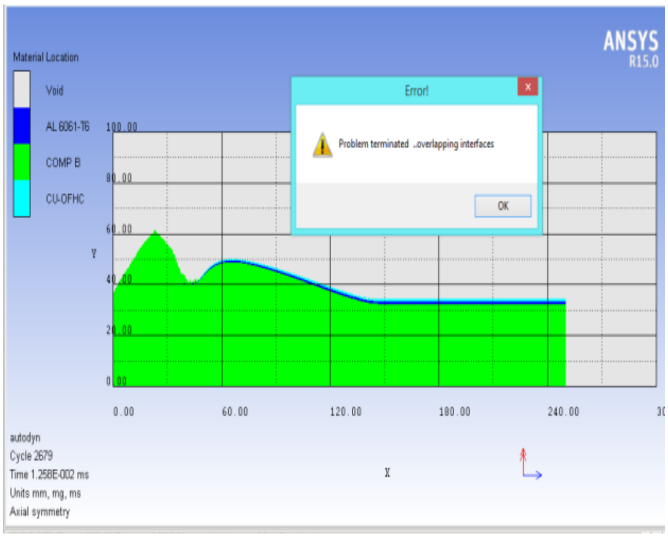


**(b)**

**Fig 9: Bimetallic armature expansion simulation with considering failure model (a) bimetallic armature model (b) expanded armature**

## 4. CONCLUSIONS:

In an AUTODYNE analysis, we show that premature cracks on armature surface have been formed due to presence of spherical shock wave front of initiated high explosive within double diameter length of armature. Further this hydrocode simulation for various alternatives has been used for reduction of premature longitudinal cracks on armature surface at initial length.

On the basis of various simulation results of armature expansion with the same armature wall thickness and outer radius, there are following conclusions:

1) When the expansion behavior of the armatures is of primary concern, aluminum 6061-T6 armature with plane initiation of high explosive is the best among all possible options.

2. When the outer layer of the armature is required or preferred to be of the OFHC copper material for achieving high conductivity requirement of a electrical contact between expanded armature and helical coil, the bimetallic armature consisting of copper outer layer, aluminum inner layer, shows the best expansion behavior.

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