Numerical and Experimental Investigation of Joining Aluminium and Carbon Fiber Reinforced Composites by Electromagnetic Forming Process

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Abstract

Carbon fiber reinforced composites became so popular in automotive, aerospace, marine and military industries in past years, because of their high strength, low weight and subsequently high specific strength. The basic challenges of producing the CFRP components are their forming and joining techniques. In this study, a finite element analysis is carried out by the purpose that the optimum geometries to be selected for manufacturing an electromagnetically assisted joining by forming system of two aluminium and CFRP sheets. Electromagnetic forming is one of the high speed forming technologies that uses the Lorentz force as a forming pressure. High speed and usually one-step forming process are some of its advantages while, the necessity of high electrical conductivity of the work-piece is an important restriction. Aluminium deformed in this study, so that its behaviour is assumed to be dependent on the strain rate. Also, the hardening behaviour of aluminium is described by the Johnson-Cook material model. The joining by forming system is modelled in the finite element code by means of the ABAQUS 6.13 FEM software. The magnetic pressure pulse of the coil is described by the VDLOAD subroutine to apply it to the lower surface of the aluminium field shaper. Under influence of this force, the punch bulges the aluminium sheet into the hole on the CFRP sheet and a cavity on die helps the bulged region to form a mechanical interlock. In the experimental investigations, predrilled CFRP sheets with different diameter holes and locations are used. The effect of geometrical parameters such as metal thickness are studied on the quality of joints. The most important parameter to be considered here, is the tensile strength of the joints. Therefore, the joint samples had been applied under tensile test in order to consider failure modes, experimentally.

Keywords

Joining, Fiber reinforced plastic, Finite element method (FEM)

1 Introduction

Electromagnetic forming is a forming technology that utilizes electromagnetic force as forming force. In this high- speed forming technology, a severe, transient magnetic field is applied to the work-piece and the forming process takes place. EMF is a precise method for forming and joining of the metals and other materials that are able to overcome some technical problems such as spring-back, wrinkling and low formability of materials in other forming methods. Due to the very high speed forming process, strain rate is so high. Therefore, forming limit diagrams can be extended in which the formability of the material is increased significantly (Seth et al., 2005) and spring-back and wrinkling are reduced (Podmanabhan, 1997).

Usually EMF is used for forming of materials of high electrical conductivity, but by using some techniques such as using driver materials it can be used for forming materials of lower electrical conductivity. The magnetic field produced in the coil induces eddy currents in the nearby work-piece that flows in the opposite direction to that of discharge current which causes the mutual repulsion between the work-piece and the forming coil (Walke et al., 2014). This method has now been applied in the automotive, aerospace, military and electronics industries.

Ultra-lightweight materials had been developed in the last 20 years, rapidly, especially in aerospace and automotive industries, because these materials have a great strength to weight ratio and can reduce the energy consumption significantly. One of these lightweight materials is carbon fiber reinforced plastics (CFRP). CFRP has higher specific strength and specific stiffness, higher fatigue strength and higher resistivity in a corrosive environments than metals (Huang et al., 2013). There are two types of CFRP laminates generally: Thermosets and thermoplastics. Thermosetting CFRPs are more applicable than thermoplastic CFRPs for the automotive and aerospace applications as well as the fire-resistant structures. These advantages appear from their non-reversible phase transition polymer matrix and longer fatigue life under a cyclic tension tensile condition (Huang et al., 2013). However thermosetting CFRPs have some disadvantages such as poor formability and no welding capability.

Spot joints are of high importance in industries such as automotive and aerospace, since a car body contains almost 4000 spot joints for example. Since thermosetting CFRPs don’t have welding capability, so heat sources such as laser, ultrasonic and friction can’t be applied for joining them, these techniques are only available for joining of thermoplastic composites. So special methods for joining of CFRPs must be introduced.

In this study a joining by forming system is introduced in order to join metal-CFRP and CFRP-CFRP sheets. Moreover, the system is designed to be able to join any ductile metal sheets to CFRP sheets without respect to their electrical conductivity. In this system a ductile metal sheet is enforced into the hole on a predrilled CFRP sheet. The die cavity helps it to form a mechanical interlock. In order to prevent the trial and error procedure in a manufacturing system, a finite element analysis is carried out by ABAQUS 6.13 FE package. The optimum geometries and sizes for different system parts such as die, blank-holder, field shaper and punch are selected. There are generally three ways to finite element analysis of the EMF process, first is loosely coupled scheme that is used in some works such as (Oliveira et al., 2003). The other method is a fully coupled scheme that is used by (Svendsen et al., 2005) and (Stiemer et al., 2006), and the last method that is simpler in comparison to the former methods used by (Correia et al., 2008), (Imbert et al., 2006) and (Uhlmann et al., 2004). In this method, which is used in the present work, analysis is divided into two different sections: electromagnetic analysis and mechanical analysis, and the pressure resulted by electromagnetic analysis is applied on the work-piece as mechanical force.

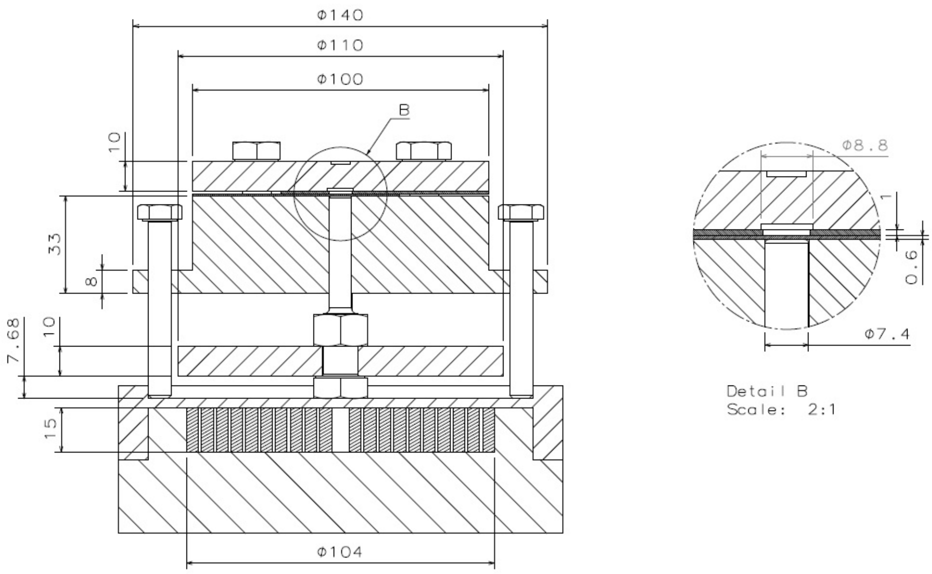


***Figure 1**: The joining by forming system*

After FE analysis and selecting best geometries for system, the parts are manufactured and experimental tests were carried out on the aluminium sheets of 0.6, 1 and 2mm thickness. After joining process, the specimens were applied under tensile test and their tensile strength was obtained.

2 Finite Element Analysis

Finite element analysis is carried out in order to find and select the best geometries and sizes for different system parts. First, it is necessary to define the electromagnetic pressure produced in the coil. The current in the coil is defined by Eq. 1 (Correia et al., 2008):

$$I(t) = I_0 e^{-t/\tau} \sin \omega t \tag{1}$$

where I_0 is maximum intensity of the discharge current, because the field shaper is a disk, a cylindrical coordinate system can be used, thus the magnetic field density **B** possesses a radial component B_r and an axial component B_z which are given as follows:

$$\frac{-1}{\mu_0\sigma_w}\left(\frac{\partial^2}{\partial r^2}+\frac{1}{r}\frac{\partial}{\partial r}+\frac{\partial^2}{\partial z^2}-\frac{1}{r^2}\right)B_r+\frac{\partial B_r}{\partial t}=0 \tag{2.a}$$

$$\frac{-1}{\mu_0\sigma_w}\left(\frac{\partial^2}{\partial r^2}+\frac{1}{r}\frac{\partial}{\partial r}+\frac{\partial^2}{\partial z^2}\right)B_z+\frac{\partial B_z}{\partial t}=0 \tag{2.b}$$

The boundary conditions to solve Eqs.2 are:

$$\boldsymbol{B}=\boldsymbol{B_0}+\boldsymbol{B_1} \qquad at\ z=d_g+u_2(t) \tag{3.a}$$

$$\boldsymbol{B}=0 \qquad at\ z=d_g+u_2(t)+h \tag{3.b}$$

Where $u_2(t)$ is vertical deflection of the field shaper and d_g is the initial gap between coil and the field shaper. For solving these equations the approach used in (Correia et al., 2008) is used in this study too. For more information this approach can be found.

The equations are solved by a VDLOAD subroutine and temporal distribution of electromagnetic pressure is obtained. This pressure is applied to the lower surface of aluminium field shaper as mechanical force in ABAQUS/Explicit. Field shaper is used in order to translate the electromagnetic force produced in coil to the steel punch. Due to the low size of the punch in comparison to the coil size, if not to use the field shaper, most amount of the produced pressure will be wasted and sufficient force to move the punch will not be prepared.

The CFRP sheet modelled, is an 1mm thickness 3ply laminate with epoxy 5052 resin and [0/90] direction fibers.

Aluminum sheet is the part that deforms plastically in this study, so that its behaviour is assumed to be dependent on the strain rate. Also, the hardening behaviour of aluminium is described by the Johnson-Cook material model. Johnson-Cook parameters are listed in **Table 1**.

Parameter	**A (MPa)**	**B (MPa)**	**n**	**T melt (K)**	**T transition (K)**	**m**	**C**	**$\dot{\varepsilon}_0$ (1/s)**
Quantity	324.1	113.8	0.42	925	293.2	1.34	0.002	1.0

Table 1*: Johnson-Cook parameters for aluminium sheet*

Die, blank-holder and the set of punch and field shaper assumed as rigid bodies and the boundary conditions are applied to constrain the die and blank-holder's motion in any direction and the set of punch and field shaper's motion in radial direction.

In the simulation, contact conditions are needed to be considered between the Aluminum sheet and other parts (CFRP, die, blank-holder and punch) as well as the field shaper and blank-holder and CFRP with die. Coulomb friction law has been used with a friction coefficient of 0.2 for aluminum sheet, and the other contacts assumed to be frictionless. The geometrical parameters used for FE simulations are summarized in **Table 2**.

Work-piece material	Thickness (mm)	Electrical conductivity (MS/m)	Density (Kg/m^3)	Young's modulus (GPa)	Poisson ratio
Aluminium 1050	0.6	34.45	2.7e3	80.7	0.33
Epoxy 5052 CFRP	1	1	1.4e3	E_1= 133.86	$v_{12}=v_{13}=0.301$
				$E_2=E_3$= 7.706	$v_{23}=0.396$

***Table 2**: Material properties of aluminium and CFRP sheets in FE analysis*

The aluminum and CFRP sheets are meshed by CPS4R elements which is a four node bilinear plane stress quadrilateral element with reduced integration. A dynamic explicit time integration scheme is employed in ABAQUS/Explicit. The simulation process time is fixed 220 μs.

The aluminum material that is formed into the CFRP hole forms a mechanical interlock by CFRP sheet after the collision with the die cavity. The predicted conditions of the interlock and its strains, stresses and corresponding displacements are shown in **Fig. 2**.

After the finite element analysis, the optimum geometries for manufacturing the system parts were selected and system were manufactured by milling and turning processes.

3 Experimental Procedure

CFRP sheets became so popular in last years because of their special characteristics and great strength to weight ratio. There are two different types of CFRPs: thermosets and thermoplastics. Two basic challenges about thermosetting CFRPs are their no welding capability and brittleness, thus special methods are needed to forming and joining of these materials. Usually adhesive bonds and mechanical fasteners are used to joining process of CFRP sheets.

The system introduced in this study has three main parts: die, blank-holder and set of punch and field shaper. Metal and CFRP sheets lie between die and blank holder. The die is clamped to the blank-holder by four M10 bolts to hold the sheets strongly. Blank-holder is a 33mm height and 120 mm diameter disk made of steel ST37. It has a through all hole in center that is the path for punch motion and has four threaded holes for clamping die. Die is a 10mm height and 120 mm diameter disk made of steel ST37. The die has hollows in both sides with different diameters to be capable to link sheets with two different hole sizes. There are an 1mm depth and 8.8 mm diameter cavity at one side and an 1mm depth and 6.6 mm diameter cavity at the other side. These sizes are determined by the finite element analysis. The other part of the system is the set of punch and field shaper. The field shaper is an aluminum disk by 10 mm height and 110 mm diameter drilled and threaded at center. The punch is an 80mm M12 steel bolt that is clamped to the field shaper by a nut and 50 mm of its end has been turned and surface finished. **Fig. 3** shows the schematic set of joining by forming system by arranged parts and EMF apparatus system which assembled parts is fixed over the coil.

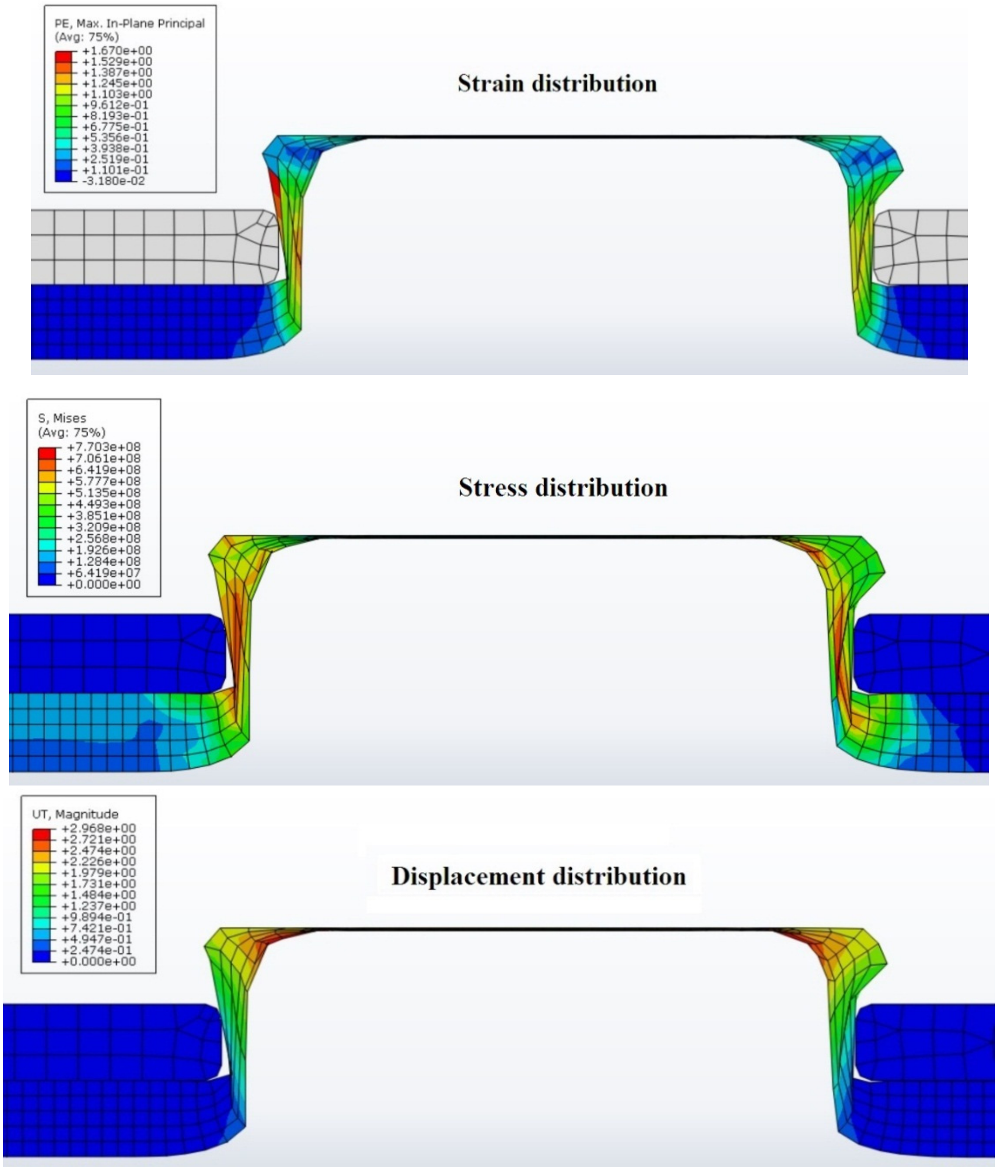
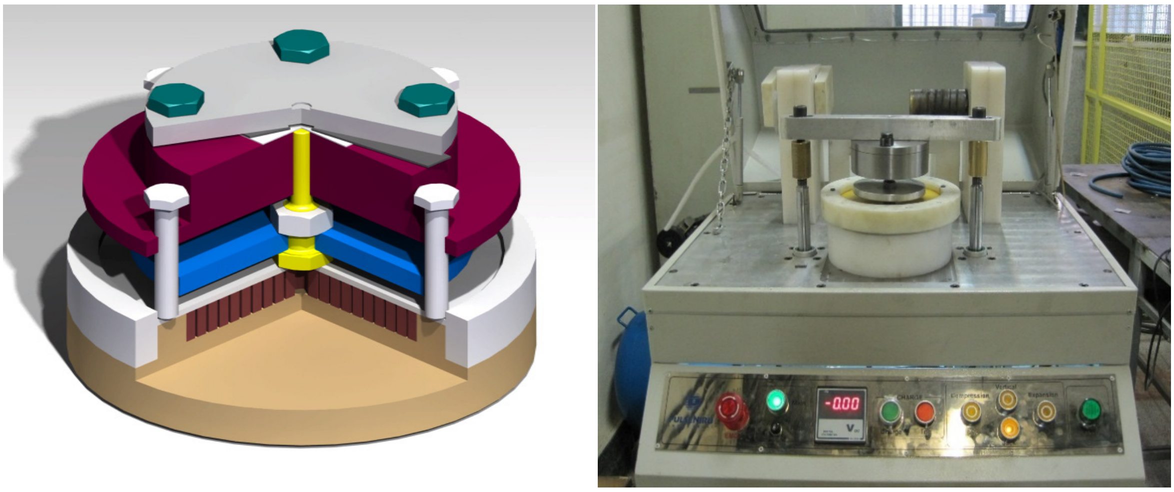


***Figure 2**: FE simulation results*

Fig. 4 illustrates the joined CFRP and Aluminum samples and the universal tensile test machine. First the set of punch and field shaper lies on the coil, then blank-holder and die stand on the set of punch and field shaper in ways that punch enters the hole on the blank-holder. Clearance between the punch and this hole is very low (about 0.05 mm) that constrains the radial motion of punch with high accuracy. In order to adjust the height of the blank-holder from punch, four 100mm M8 bolts are used, by adjusting the height of these bolts, the gap between the blank-holder and punch can be adjusted. By appropriate adjustment of this height the punch can easily move in vertical direction. Initial gap between the coil and field shaper is secured by the M12 bolt (punch) head, this gap is 8 mm.



a) b)

***Figure 3**: The set of EMF system with assembled parts; a). Schematic set. b). Actual set*

For experimental tests aluminum 1050 sheets by 0.6, 1 and 2 mm thickness were used. The CFRP sheets were 1mm thickness 3ply epoxy 5052 resin and [0/90] fibers direction. Since drilling and cutting of CFRPs are so challenging processes that may cause problems such as delamination and local fiber rupture, so selecting an appropriate method for this processes are of high importance. Laser cutting and water jet cutting are some good techniques for cutting and drilling. Laser cutting may cause local temperatures which may cause resin suffering (especially in thermosetting CFRPs), so water jet cutting were used for cutting and drilling processes. The basic characteristics of these sheets were summarized in **Table 2.**

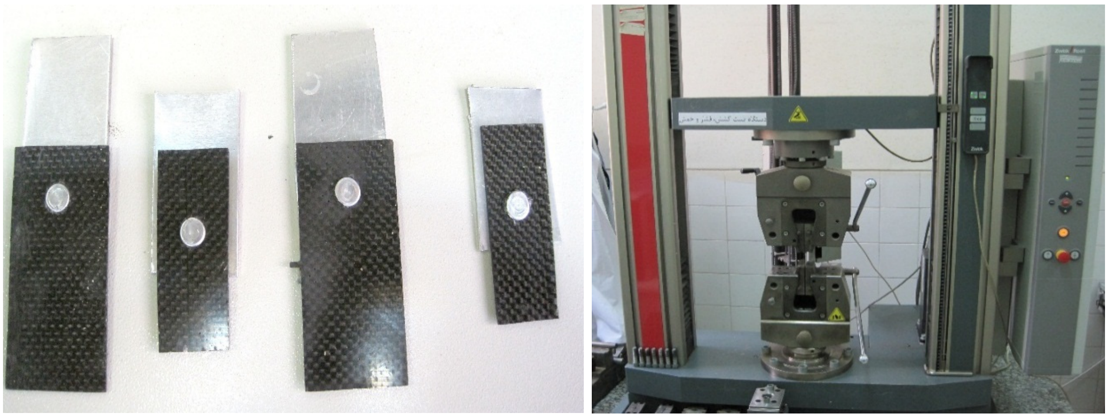


***Figure 4**: a). The joined CFRP and Aluminium samples, b). Tensile testing machine*

The experiments were carried out by voltages between 4 to 5.5 KV voltages, in lower voltages the mechanical interlock were not formed and in higher voltages, the aluminum sheet fails. After tests, the specimens were applied under tensile test, the apparatus for tensile test were Zwick/ Roell Z100 (**Fig. 4b**).

For 0.6 mm sheets, mechanical interlock were created in range of 4 to 4.2 KV voltages, in higher voltages the aluminum sheet fails in the interlock location. The tensile strength of these specimens was only in the range of 200N for different discharge voltages. These joints have no good characteristics because of very low thickness of aluminum at neck zone.

As illustrated in **Fig. 5** the best range of voltage for 1mm sheets were obtained at 4.4 to 4.8KV. The best joint were in case of 4.4 KV, in this case the joint strength was 774.22N and failure mode was aluminum neck fracture, The CFRP sheet was entirely safe and no signs of fracture or delamination had be seen on it, this means that by increasing the thickness of deforming part, a more quality joint can be produced, in other hand the weakest joint was the case of 4.8 KV, the strength of this joint was only 299.73N, failure mode was similar to former specimen, but in this case the neck thickness of aluminum was very low because of the high energy of process, so the failure takes place in very low forces.

In case of 2mm sheets the results were so better than 0.6 and 1mm specimens, so it can be resulted that the thickness of deforming material is a high effective parameter on joint quality, it is evident somehow, since as **Fig. 3** in FE analysis shows, material flow results thinning in joint neck, and when initial thickness is higher, after necking phenomenon, the sheet thickness in neck zone is sufficient to joint be strength enough. In the case of 2 mm aluminum thickness, the joint strength was 1494.38N for 5.2KV and 1742.18N for 5.5KV.

Increasing the velocity of punching process through exposing a high strain rate EMF pressing causes to strike metallic sheet by more plastic flow rate inside die cavity. So, it provides forming by stronger mechanical interlock between the metal sheet and CFRP laminate. Generally, using the conventional methods in low punching velocity such as hydraulic press may perform small size in joining as well as low quality. According to the finite element simulations for a conventional press, in order to obtain similar characteristics with the EMF process, large -amplitude holding forces (about three or four times than EMF process) by heavy apparatus are needed to be used.

One of the most important capabilities of this system is joining two CFRP sheets by means of a small aluminum dummy tape. For this purpose, two predrilled CFRP sheets lie on each other and an aluminum dummy tape lies under them. Other characteristics of the process are as former. **Fig. 6** shows joining two CFRP sheets by this method and the aluminum dummy tape can be seen. Mainly, it is the biggest advantage of this system, whereas the thermosetting CFRP has no welding capability. So, it is necessary to join them by another consumable material. Accordingly, in this method the consumable material is very small in size and is an inexpensive and cost-effective method to join two CFRP sheets.

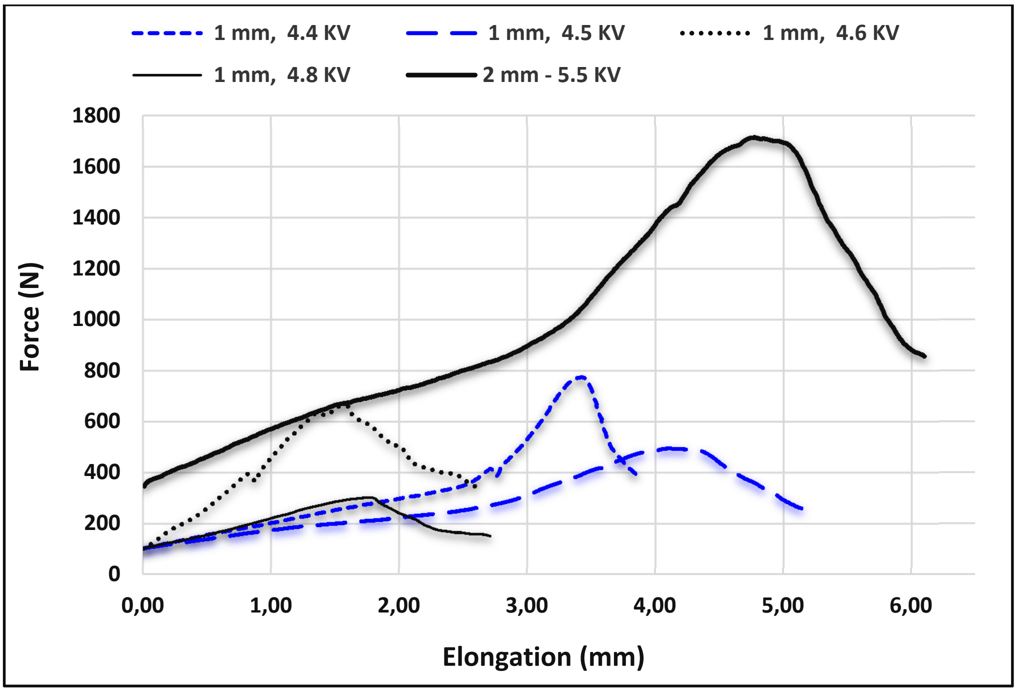


***Figure 5**: Force-Strain (elongation) diagrams for 0.6 mm and 1mm Al sheet*

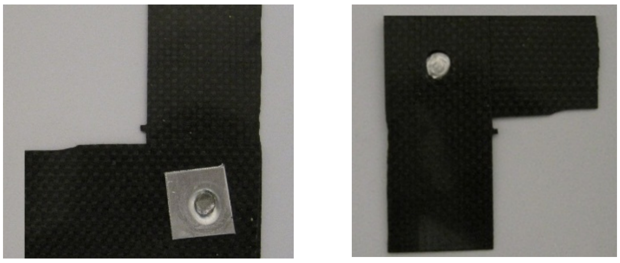


***Figure 6**: Joining two CFRP sheets by an aluminium dummy tape*

4 Conclusions

In this study, a finite element analysis was carried out by the purpose that the optimum geometries to be selected for manufacturing an electromagnetically assisted joining by forming system. Aluminium and CFRP sheets were used for experiments, and after joining process, the specimens were applied under universal tensile test. The joining by forming system were designed in order to overcome the restriction of necessity of high electrical conductivity of work-pieces in EMF process. So, it can be used to join any ductile materials. Another advantage of the system is its capability to link two CFRP sheets by a small dummy tape, whereas the CFRPs have no welding capability. Actually, conventional methods are inexpensive for joining them rather than the high speed joining process, which has no need to any additional equipment. Moreover, by having the advantages along with capability of joining two or more different sheets, it is a convenient method to joining a wide range of dissimilar materials and any geometries.

If the stronger material is substituted for the punch such as annealed steels, it would be more convenient to apply the method for the steel metallic joining parts.

References

Correia, JPM., Siddiqui, MA., Ahzi, s., Belouettar, S., Davies, R., 2008. A simple model to simulate electromagnetic sheet free bulging process. International Journal of Mechanical Sciences 50, pp. 1466-1475.

Huang, Z., Sugiyama, S., Yanagimoto, J., 2013. Hybrid joining process for carbon fiber reinforced thermosetting plastic and metallic thin sheets by chemical bonding and plastic deformation. Journal of Materials Processing Technology 213, pp. 1864-1874.

Imbert, J., Worswick, M., Golovashchenko, S., 2006. Contributing factors to the increased formability observed in electromagnetically formed aluminium alloy sheet. In: Tekkaya, A.E., Daehn, G.S., Kleiner, M. (Eds.), High Speed Forming 2006, Proceedings of the 2nd International Conference, Dortmund, Germany, pp. 3-12.

Oliveira, DA., Worswick, M J., Finn, M., Newman, D., 2003. Electromagnetic forming of aluminium alloy sheet: free-form and cavity fill experiments and model. Journal of Materials Processing Technology 142, pp. 744-754.

Podmanabhan, M., 1997. Wrinkling and spring-back in electromagnetic sheet metal forming and electromagnetic ring compression. MS Thesis, The Ohio state university.

Seth, M., Vohnout, VJ., Daehn, GS., 2005. Formability of steel sheet in high velocity impact. Journal of Materials Processing Technology 168, pp. 390-400.

Stiemer, M., Unger, J., Svensden, B., Blum, H., 2006. Algorithmic formulation and numerical implementation of coupled electromagnetic inelastic continuum models for electromagnetic metal forming. International Journal for Numerical Methods in Engineering, 68, pp. 1301-1328.

Uhlmann, E., Jurgasch, D., 2004. New impulses in the forming of magnesium sheet metals. In: Tekkaya, A.E., Daehn, G.S., Kleiner, M. (Eds.), High Speed Forming 2004, Proceedings of the 1st International Conference, Dortmund, Germany, pp. 229-241.

Walke, GA., Kulkarni, A., Vasudevem, R., 2014. Finite element analysis and parametric study of electromagnetic forming process. International Journal of Engineering Research and Technology.