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# Direct Synthesis Carbon/Metal Oxide Composites for Electrochemical Capacitors Electrode

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## ABSTRACT

*This paper deals with the study of the carbon/metal oxide composites synthesis for electrochemical capacitor electrode material. Transition metal salts, such as FeCl3 and TiCl3 act as activator in the synthesis of activated carbon from gelam wood sawdust (Melaleuca cajuputi Powell) which also have the functions as substrates for the composites. The surface functionalities of activated carbons were modified using oxidative treatments. The changes on crystallography and surface functionalities were analyzed based on XRD and FTIR data. The electrical conductivities and electrochemical properties were determined using kelvin and cyclic voltammetry methods, respectively. FTIR analyses showed that the activation and oxidation treatments affected their surface functionalities. The XRD analyses showed that oxidative treatments also affected carbons crystallite. The electrical conductivities and electrochemical properties were influenced by their crystallite and surface functionalities. The shape of the cyclic voltammograms varied according to the changes on the surface functionalities and on the metals loading. TEM analyses indicated the existence of nanoparticles metal oxides in the carbon samples.*

***Keywords: Gelam wood Carbon Electrode Composite Electrochemical capacitor Cyclic voltammetry***

### 1. Introduction

The chemistry of carbon in the past decade had been dominated by the finding of fullerenes and carbon nanostructures as new carbon allotropes (Harris 2005; Heller et al. 2006; Endo et al. 2008). It is well-known that carbonaceous materials like graphite, soot, coals, and chars have the characteristic in their structural appearances which vary from mostly random or amorphous to a perfectly ordered crystalline structure. Activated carbon materials are characterized by its high specific surface area and porosity. High surface area activated carbon has been extensively applied as electrode material in electrochemical capacitor (EC). Theoretically, activated carbon with higher surface area will have higher specific capacitance. However, in practice, it is more complicated to measure and usually the measured capacitance does not have a linear relationship with the specific area at the electrode material. The main reason for this phenomenon is that the pores may not be accessible by the electrolyte, especially the big organic ions and solvated ions. Ions which are too big to enter the pores will not contribute to the total double layer capacitance of the electrode material.

The use of carbon materials in electrochemistry has been related to their surface functional groups (Lpez-Garzn et al. 2003; Lim et al. 2004; Béguin et al. 2006). Surface chemical functional groups of carbons are derived from the activation process, the various processing routes, the used precursors, the activation conditions, and the post chemical treatment, such as oxidation (Shen et al. 2008; Wang et al. 2008). These factors also affect the crystallographic properties (Andrews et al. 2002; Mochida et al. 2006).

Meanwhile, many researchers have focused on the development of an alternative electrode material for EC. Many transition metal oxides showed to be suitable as electrode materials for ECs, such as ruthenium oxides. Ruthenium oxides are easy to prepare, stable in aqueous electrolytes and have very high capacitance (Wang et al. 2005), whilst the disadvantage of Ru2O is the high cost of the raw material. Therefore, several metal oxides and hydroxides, for example Fe2O3, TiO2, and NiO have been studied in order to obtain low cost materials, which were mixed with carbon electrode as composites. Instead of introducing high capacitance material to fabricated EC, it is also necessary to improve carbon the properties of carbon material. It was reported that the capacitance and electrical conductivity increased with the amount of surface oxygen functional groups (Bleda-Martınez et al. 2005) and the crystalline phase on the carbon.

In this work, gelam wood (paper-bark wood, Melaleuca cajuputi Powell) sawdust was used to prepare activated carbons using chemical activator i.e. transition metal salts which also act as composite precursors. A number of materials with different structures and surface functionalities have been obtained.

Surface functionalities of the activated carbon were modified by heating in concentrate nitric acid under reflux and by aging under hydrothermal condition. All carbons were applied as working electrode in the three electrodes system using acidic and basic aqueous medium, H2SO4 and KOH respectively. The materials were characterized in terms of crystallographic, surface chemistry and electrical conductivity. TEM was used to evaluate the size of carbon particles and metal loading in carbon samples.

## 2. Materials and Methods

The sawdust particles were screened through 100 mesh wire sieved and treated with 20% HCl for 1 day, filtered, washed with demin-water then dried over night at 110oC. Sawdust particles were impregnated with solution of transition metal, i.e TiCl3 or FeCl3 and then were heat-treated under N2 atmosphere at 700oC for 8-10 hours. The obtained carbon samples were considered as the composite of carbon and metal oxide. Carbon/metal composite were oxidized in concentrated nitric acid under reflux or under pressurized water vapor in the hydrothermal reactor. The nitric acid oxidation was carried out at 60°C for 3 hours as described by Mahalakshmy et al. (2009) and the hydrothermal process was conducted at 200°C for 16 hours (Titirici et al. 2007). The products were separated by centrifuge and washed with abundant demin-water.

Structural change was detected chemically with FTIR and XRD patterns. X-ray diffraction (XRD) patterns of the carbons were obtained on a Shimadzu X-ray diffractometer XRD 7000 operating at 40 kV and 30 mA, using Cu-Kα radiation. All XRD spectra were analyzed with X-Powder software (ICDD) to obtained quantitative value for crystallographic parameter (Martin-Islan et al. 2006). Plane spacing (d002) was calculated by applying Bragg's equation to the [002] diffraction peak, while the crystallite sizes along the c-axis, Lc, and a axis, La, were deduced by Scherrer's equation applied to the [002] and the [100], [110] diffraction peaks, respectively (Awitdrus et al. 2010). FTIR spectra were obtained on Shimadzu IR Prestige 21. The dispersion of metal loading in carbon and the size of the carbon particles were evaluated by the TEM micrographs. TEM micrographs were obtained on JEM1200EX.

The EC electrodes were fabricated by mixing the composite powder with PTFE binder (Merck, 99%) in isopropanol (Merck, 99%). 20 drops of triethanolamine (TEA) were added into the mixture. Circular electrodes were obtained from 1.5 g of mixture paste in a 20 mm diameter mold, and pressed under 3 tons load and the molded pastes were heated at 300°C on a hot plate for an hour and removed from mold after being cooled.

Electrochemical test for the electrodes were conducted using cyclic voltammetry technique in three electrodes configuration potentiostat. Ag/AgCl electrode was used as reference electrode and Platinum rod was used as the counter electrode. Considering that the anodic voltammetric charges and cathodic voltammetric charges are not the same in the shape of voltammogram curve, the average specific capacitance of the electrode was calculated using integral area approximation (Kuo et al. 2007)

$$C_{avg} = \frac{\Delta Q}{(w \times \Delta V)} = \frac{\left(\int IdV\right)}{(s \times \Delta V \times w)} \quad [1]$$

Where ΔQ is the total amount of the charge accumulated over a potential window, ΔV , w is the mass of active material in one electrode, I is the current, and s is the potential scan rate. Hence ( ) IdV ∫ is integral area of voltammogram curve.

**3. Results and Discussion**

Sawdust particles impregnated with metallic salt were treated by heating in nitrogen atmosphere, metal salt decomposed into the corresponding metallic oxides, which were subsequently reduced the mass of composites (Encinar et al. 1997; Antal et al. 2003). As the temperature rise, the carbon came close to metal particles.

These particles have diameters in the range of 10-50 nm and built some clusters. This features were revealed by the TEM image obtained for the carbon/Fe2O3 composite (Figure 1A). Carbons with nanoporous were formed around the metal oxide particles through a catalytic mechanism that involved the dissolution of amorphous carbon into the catalyst particles followed by the precipitation of graphitic carbon. Figure 1a shows the metal oxide particles, which were surrounded by graphitic carbon shells. The thickness of the carbon layer for these nanostructures was in the range of 10-17 nm, which was in good agreement with the Lc values estimated from the analysis of the XRD patterns. The distinction between carbons and metal oxide particles were clearly shown. In the background, carbon structures were mixed with cluster of metal oxide particles. During the thermal treatment at 700 °C, only the carbon in contact with the metal oxide particles was converted into carbon nanostructures, the rest of the material remained as amorphous carbon. Consequently, the carbonized material contains organized carbon mixed with non-organized carbon. This is clearly shown in Figure 1B where both structures were displayed.

The XRD diffraction patterns of the carbon/metal oxide composite (figure 2) confirm that the carbon materials contained a few amorphous phase. In fact, the non-composite carbon samples prepared from the same precursor exhibit intense XRD peaks at 2θ = 15°, 28° and 45o which respectively correspond to the [100], [011] and [002] diffractions of the graphitic framework.

The crystallographic parameters of the carbons were deduced from the analysis of the XRD spectra. Thus, the plane spacing (d002) was calculated by applying Bragg's equation to the [002] diffraction peak, while the crystallite sizes along the c-axis, Lc, and a-axis, La, are deduced by Scherrer's equation applied to the [002] and the [100], [110] diffraction peaks, respectively. Values of these parameters are presented in Table 1 and Table 2.

The d-spacing values are presented for [002] reflections indicate the distance between layer planes. Samples synthesized with catalyst have lower values for crystallite size and d spacing. Carbon in Carbon/Fe2O3 composite was smaller (5 Å) than non-composite carbon (5.3 Å). Nevertheless all d-spacing values of carbon samples which were 5-6 Å, indicated the layer planes were not registered but simply parallel without three-dimensional order also known as turbostratic stacking. La and Lc confirmed that carbons and carbon/metal oxide composite were composed of many quasi-graphitic crystallites.

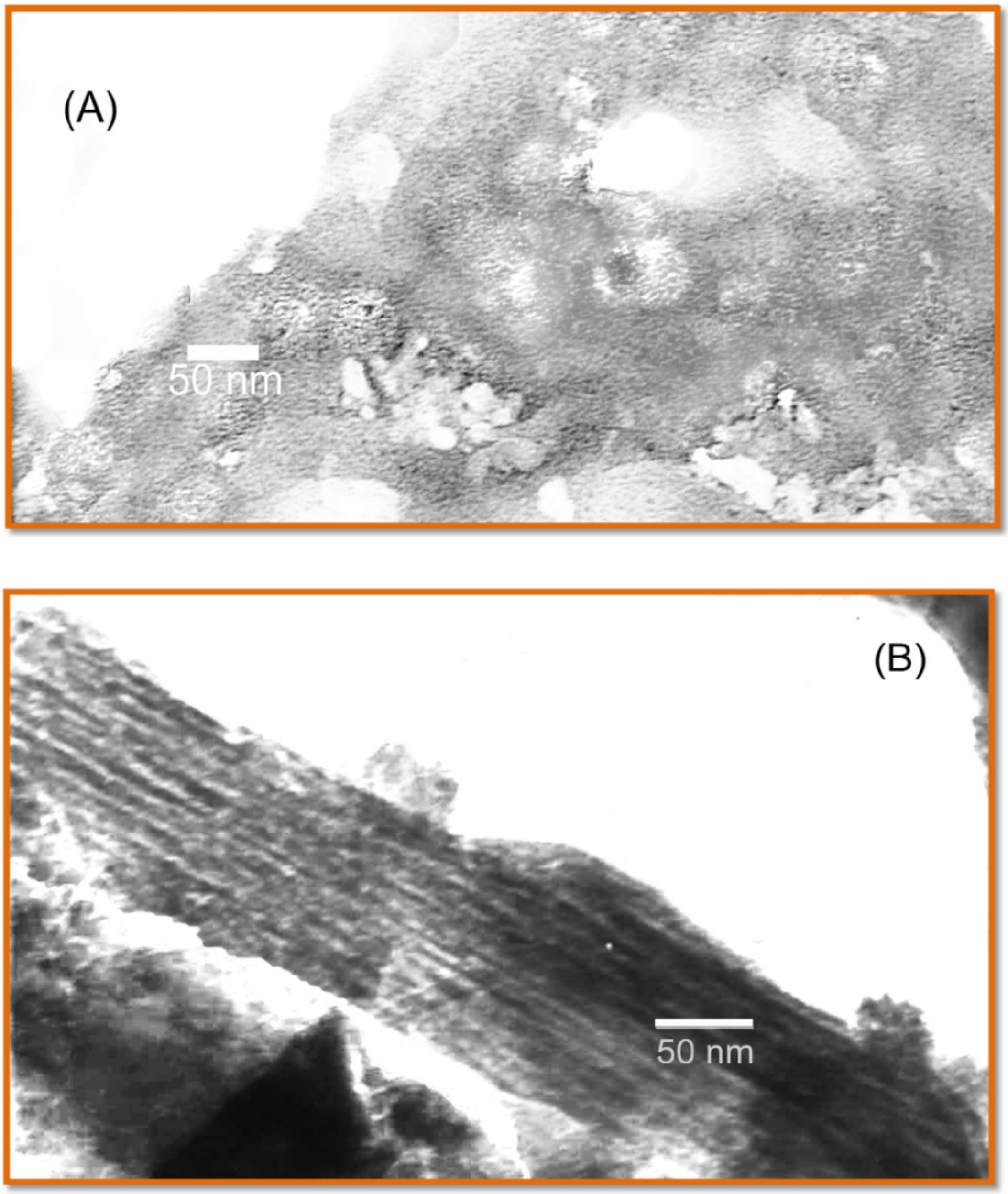


**Figure 1:** TEM images of carbon/Fe2O3 composite, iron oxide cluster exist in carbon matrix (A) and amorphous carbon mixed with crystallite carbon in the activated carbon (B).

The FTIR spectra in Figure 3 and 4 show for the carbon/metal composites, composite carbons and oxidative treated for carbon surface. By means of the FTIR spectroscopy, it is possible to analyze the chemical functionalities of these samples. Generally, the hydrothermal oxidation would result more surface functionalities than the HNO3 oxidation. In Figure 3 surface functionalities of carbon/metal composite changed significantly in the C/TiO2composite.

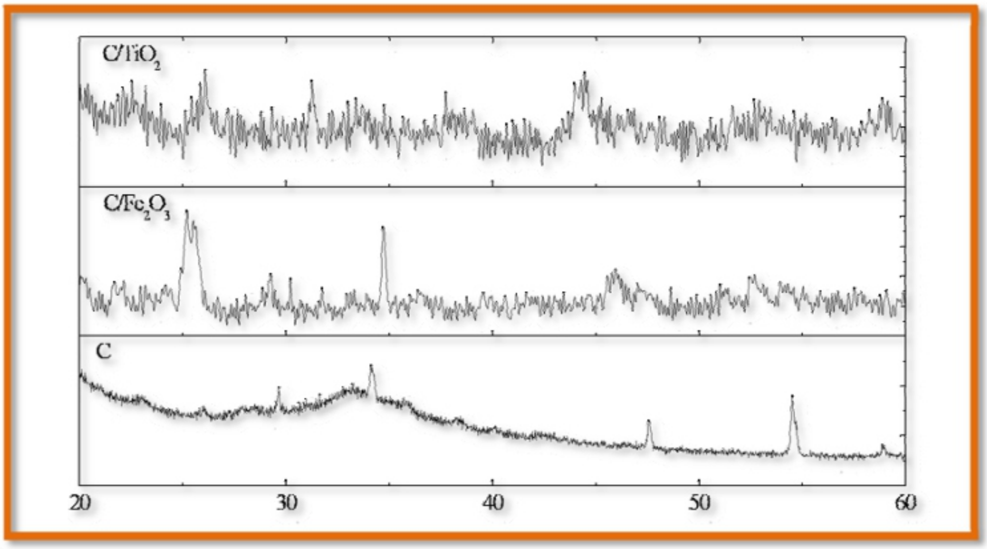


**Figure 2:** XRD patterns of carbon/metal oxide composites and non-composite carbon. The crystallographic parameters of the carbons were deduced from the analysis of these plots.

**Table 1:** Crystallographic parameters values for selected carbon/metal oxide composite

| Sample | $L_a$ (nm) | $L_c$ (nm) | d-sp. (A) |
|---|---|---|---|
| Ref. Carbon | 2 | 4 | 5.6 |
| Non-composite Carbon | 2 | 6 | 5,3 |
| Carbon/$Fe_2O_3$ composite | 2 | 2 | 5,0 |
| Carbon/$TiO_2$ composite | 3 | 4 | 5.0 |

**Table 2:** Calculated carbon atom distribution for selected carbon/metal composite

| Sample | Layer Percentage | | |
|---|---|---|---|
| | Random | Parallel Layer | Single Layer |
| Reference Carbon | 8 | 31 | 61 |
| Non-composite carbon | 0 | 39 | 61 |
| Carbon/$Fe_2O_3$ composite | 1 | 42 | 57 |
| Carbon/$TiO_2$ composite | 3 | 46 | 51 |

It is clearly shown that all carbons spectra have double small peaks in around 2300 – 2400 cm-1 which is the sum of some double bond stretching vibration of C=N, C=O and N=O.

The transmission value at 2300-2400 cm-1, approximately will be in line with the value of transmission in the region 1350-1700 cm-1 which is also appears as double medium peaks.

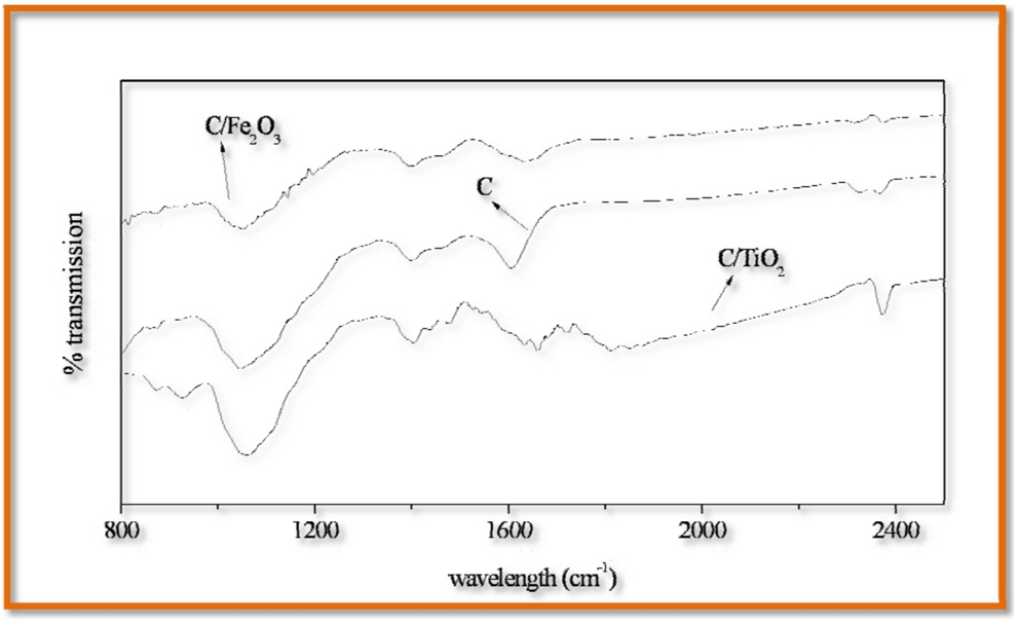


**Figure 3:** FTIR spectra of carbon/metal oxide composite: C/TiO2 C/Fe2O3 and non-composite carbon: C.

The height of peaks indicate the presence of stretching vibrational of C and N single bond for some bonding configurations such as isocyanate (-C-N = O), nitrile and isonitrile (Escobar-Alarcónc et al. 2005). The value of absorption around 2300-2400 cm-1 will be lower than that occurs in the region 1350-1700 cm-1 due to the destruction of symmetry bond C=C.

Single bond vibration band of C and O appears in 1000 - 1100 cm-1 as broad peak. The height of the peaks indicated the presence of bending vibrations for same bonding configurations, such as C-O-C, C-O-O, and C-C-O (Matson et al. 1970). These features are possessed on non-composite carbon and C/TiO2 composite. The absorption intensity increase significantly in below 1000 cm-1 for C/TiO2 composite considered as the opposite effect of increasing absorption intensity in the rest of wave number range. Wave numbers below 1000 cm-1 are referred as C-C single bond.

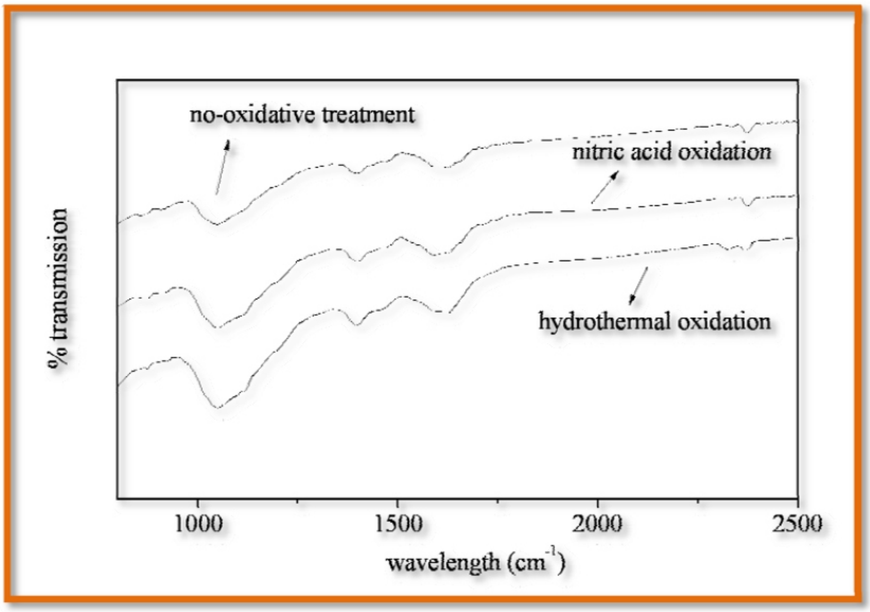


Figure 4: FTIR spectra of carbon/metal composite without oxidation treatment, with hydrothermal oxidation and nitric acid oxidation.

Due to this very broad band it is difficult to determine the transmission bands related to those C-O bending vibrations. Furthermore, in the FTIR spectra of composite C/TiO2 around 1350-1700 cm-1 where the absorption intensity decreased, is accompanied by increased intensity of absorption at wave numbers around 1900-2000 cm-1 shows the changes in functional groups carbon surface. While the surface of the carbon non-composite and C/TiO2composite have much more C = O, C = N, and C = C bond; the majority of the double bonds on the surface of C/Fe2O3 composite change to a triple bond or two adjacent double bonds of C, N and O atoms. These features are formed due to the reactivity of Fe atoms.

Figure 4 showed vibrations around 1350-1700 cm-1 which indicated the defacement of the sp2 bonding symmetry between carbon layers. This feature caused the vibrations of C-C single bond becomes active (Lazar et al. 2005) and could be characterized by the appearance of two absorption bands centered in pairs + 1395 and + 1610 cm-1. The absorption bands in this region will appear synchronous with the absorption band at 1350-1700 cm-1.

The change in crystallography and surface functional groups will affect the electrical resistivity of carbon. Electrical resistivity is proportional to the magnitude of electrical conductivity (Mochidzuki et al. 2003). Therefore, conductivity can be explained by the results of resistivity measurement. Resistivity measurements were carried out to produce some value, namely 0.08, 0.09 and 0:23 respectively to the electrodes of activated carbon without oxidation treatment, oxidation with nitric acid and with water vapour in hydrothermal condition. Electrical conductivity values of carbon are influenced by the presence of sp2carbon in the activated carbon. Their existence in activated carbon is influenced by the temperature applied to produce activated carbon. The information about electrical conductivity is needed to study electrochemical behavior of carbon electrode as well as the presence of surface functional groups in carbons

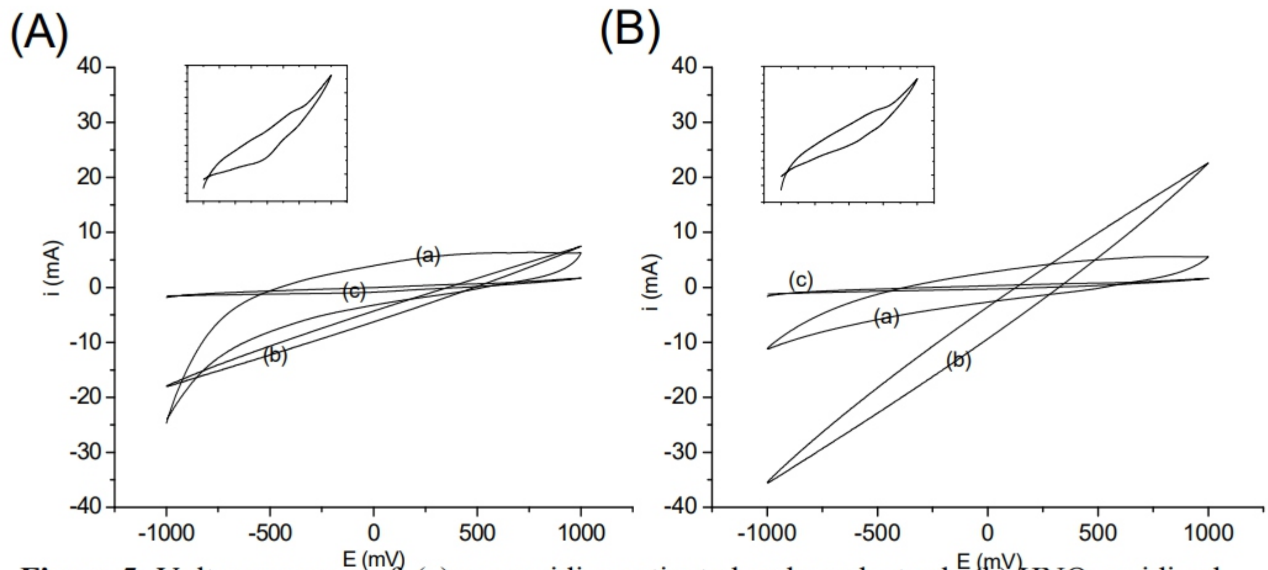


**Figure 5:** Voltammogram of (a) non oxidize activated carbon electrode (b) $HNO_3$ oxidized-activated carbon and (c) vapour oxidized activated carbon in 1M $H_2SO_4$ (A) and 2M $H_2SO_4$ (B) potential scan rate was 20 mV/s. Inset pictures are used to clarify voltammogram (c).

Electrochemical behavior of the carbons depended on the presence of oxygen-containing surface functional groups. Voltammogram in Figure 5A shows that both oxidation treatments and acid concentration give the distinctive features in electrochemical behavior. This feature are arise due to avialibility of charge carrier i.e. ion. Non-faradaic process in carbon electrode was detected in voltammogram. Capacitance value for non treated carbon electrode was 0.35 F/g. Oxidative treatment tends to construct faradaic process in voltammetry system and tends to demonstrate non-faradaic process while acid oxidize with HNO3 tends to reduce the double layer facet in electrode. Capacitance values for treated carbon electrode were 1.258 F/g and 0.053 F/g.

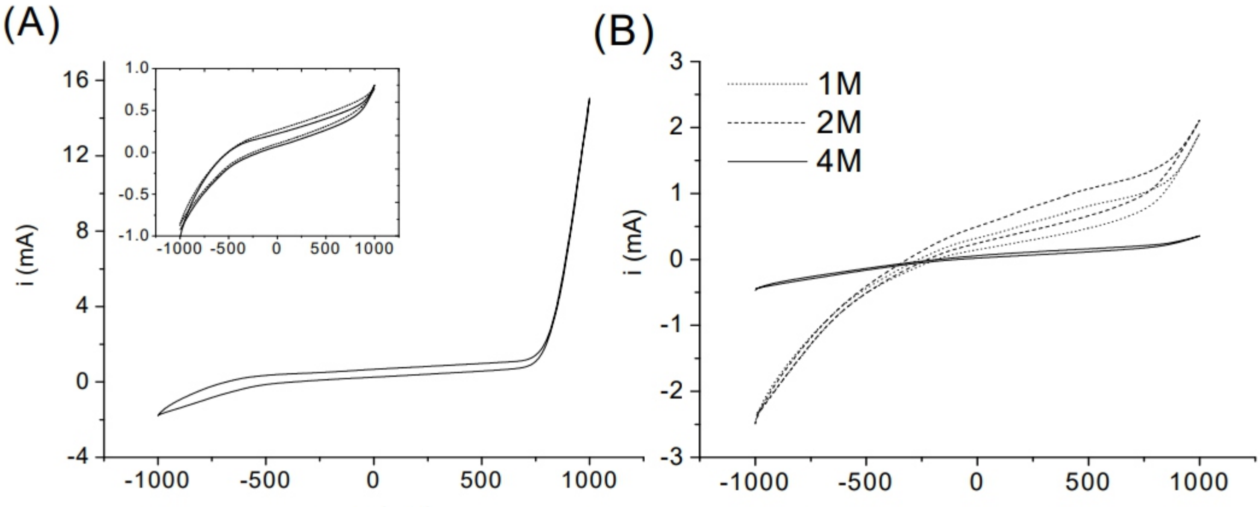


**Figure 6:** Voltammogram of carbon/metal oxide composite electrode (A) Carbon/$TiO_2$ composite in 2M $H_2SO_4$ electrolyte, (B) Carbon/$Fe_2O_3$ composite in KOH electrolyte, scan rate was 20 mV/s.

Both carbon/TiO2 and carbon/Fe2O3 composites exhibited faradaic process in the end of anodic process marked by sharp peak in the both plots. Specific capacitances were calculated and derived from 2M KOH voltammogram were 0,102 F/g and 0.077F/g for C/TiO2 and C/Fe2O3, respectively.

## 4. Conclusion

Direct synthesis metal oxide/carbon composites produced amorphous and crystallite carbon and metal oxide clusters in their structures. XRD patterns and TEM images indicated that some particles of metal loaded on carbon were nanometer-scale. The shapes of cyclic voltammograms varied in relation with the changes in the surface functional groups of the carbon. Non-faradaic process of carbon composite was detected over voltammogram on all samples, which indicated the capability to carry capacitive process. Both carbon/TiO2 and carbon/Fe2O3 composites exhibited faradaic process in the end of anodic process. Owing to this unique characteristic, simple preparation and the abudance availability of material, gelam wood sawdust should become a potential candidate as cheap and environment friendly electrode material for electrochemical capacitor.

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# Aerodynamic and Acoustic Parameters of a Coandã Flow – a Numerical Investigation

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## ABSTRACT

*Coandã flows have been the study of aircraft designers primarily for the prospect of achieving higher lift coefficient wings. Recently the environmental problem of noise pollution attracted further interest on the matter. The approach used is numerical; the computations were made using a large eddy simulation (LES) technique coupled with a Ffowcs-Williams-Hawkings (FWH) acoustic analysis. The spectrum of the flow was measured at three locations in the vicinity of the ramp showing that the low frequency region is dominant. The findings may be used as reference for the development of quiet aircraft that use super-circulation, as it is the case with the Upper Surface Blown (USB) configurations.*

***Keywords: Coanda effect Aerodynamics Acoustics Computational Fluid Dynamics***

## 1. Introduction

Super circulation techniques have been used in the aeronautical industry for many years with good results. However aircraft such as the Antonov An-71 and the Boeing YC 14 do not fully use the benefits of the Coandã lift – in that they only divert the fan flow and do not generate pressure drops on the upper side of the wing.

Reference [9] seeks to prove that a Coandã flow over a curved wall will cause the static pressure to drop hence producing lift. It is therefore important for us to investigate the prospect of using this effect to improve on the state of the art and also to understand the more subtle aspects associated with it. One such aspect is the environmental problem of noise generation, in other words such an aircraft will need to be acoustically certified in order to be allowed to fly. Hence an aero-acoustic study is required in order to estimate the radiated sound pressure levels (SPL) and noise spectrum of such flows.

## 2. Computational Fluid Dynamics Setup

Traditionally simulation of Coandã flows over curved surfaces has proved to be problematic in the case of Reynolds Averaged Navier-Stokes (RANS) methods. This is because of their viscosity modeling. Some of the best results of RANS methods can be obtained through the use of k-omega SST (Menter) described in [5] and Reynolds Stress Model (RSM), according to most authors in [2] and [4]. This is because the Menter SST introduces a limitation in the shears stress in adverse pressure gradients. The RSM does not rely on the turbulent viscosity hypothesis and solves transport equations for the individual Reynolds stresses [3].

The advantages of LES over RANS methods are that the results are generally more accurate due to the sounder modeling of the physical flow phenomena. However, LES methods may prove to be problematic in converging and much more demanding in terms of computational effort. For this reason authors have suggested curvature and rotation additions to RANS viscosity models. Reference [10] describes a rotation and curvature model for the Menter SST and Ref [7] a similar model for the Spalart – Allmaras (S-A) viscosity model.

In [1] a comparative study is made in which both S-A RC and Menter SST RC models are compared to a LES benchmark. The results proved the corrections of rotation and curvature to be in fairly good agreement to the LES simulation whilst being significantly faster.

Detatched Eddy Simulations (DES) were considered however the time advantages of this hybrid RANS-LES method were did not overweigh the accuracy of the LES methodology.

**2.1 Computational Mesh and Boundary Conditions**

The test has been carried out on a ramp with a quarter circular section and the flow was injected through a straight nozzle so that the initial flow was tangential to the ramp. In order to avoid any complications with the compressibility effects associated with higher velocities, the 100 m/sec velocity was chosen. For the temperature of the flow this corresponds to a Mach number of M=0.29. The pressure outlets were moved as far away from the ramp in order to avoid the so-called boundary effect which could have interfered with the attachment over the ramp.

In Figure 1 the computational mesh can be observed, the high order of discretization is necessary in order to meet the low y+ non-dimensional wall distance required for the high precision of the analysis. After successive adaptations, the averaged y+ over the span of the curved ramp was 2.79 for the unsteady k – omega SST simulation and 1.55 for the LES.

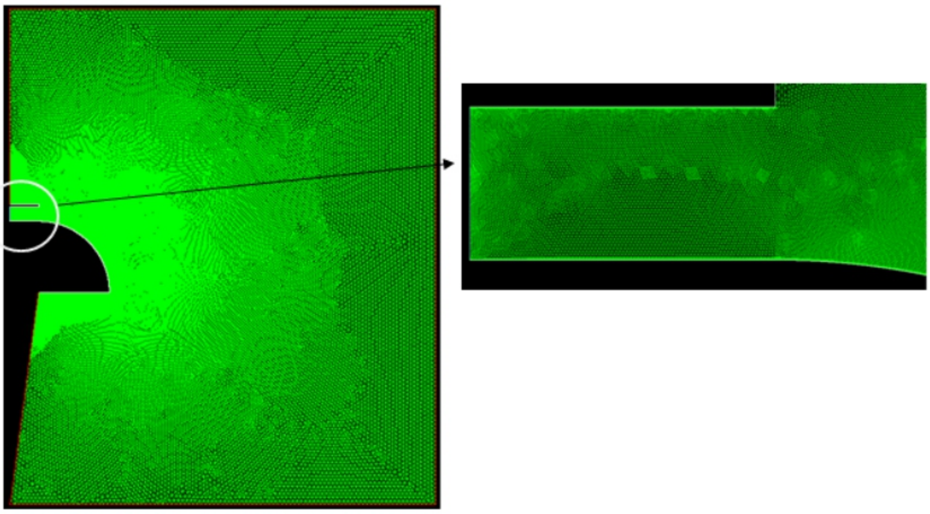

**Figure 1:** The computational mesh after successive adaptations.

The CFD test was performed as follows:

1. Initial computation with Menter k- omega SST, double precision (dp), first order upwind, SIMPLE pressure-velocity coupling.
2. adaptation of the y+ Reiteration of steps 1 and 2
3. Simulation k-omega SST, dp, second order upwind conditions for all parameters monitored, SIMPLE pressure-velocity coupling
4. Simulation LES, PISO pressure coupling, Smagorinsky-Lilly model sub-grid scale turbulence model. Time step 10-4sec
5. k-omega SST, double precision, second order upwind conditions for all parameters monitored, SIMPLE pressure-velocity coupling, unsteady, time step 10-4sec.

The Large Eddy Simulation technique relies on the filtration of the spectrum of turbulent eddies that are smaller than the mesh elements and modeling them through a sub grid scale model, in this case the Smagorinsky-Lilly. All the other eddies are then solved directly numerically from the transient Navier Stokes equations. This is similar, in part, to the direct numerical solving (DNS) which is regarded as the most accurate method for solving Navier-Stokes equations but which requires formidable computation power and time.

Equations 1 through 4 describe the LES technique in its mathematical form from the Navier Stokes Eq.1 through the filtered Navier Stokes in Eq.3 to the SGS turbulent stress, Eq.4:

$$\frac{\partial u_i}{\partial t}+\frac{\partial u_i u_j}{\partial x_j}=-\frac{1}{\rho}\frac{\partial p}{\partial x_i}+\frac{\partial}{\partial x_j}\left(\nu\frac{\partial u_i}{\partial x_j}\right) \tag{1}$$

$$\mathbf{u}(\mathbf{x},t)=\underbrace{\overline{\mathbf{u}}(\mathbf{x},t)}_{\substack{\text{scale of eddies}\\ \text{directlly solved}\\ \text{from Navier Stokes}}}+\underbrace{\mathbf{u}'(\mathbf{x},t)}_{\substack{\text{scale of eddes}\\ \text{modeled trough}\\ \text{Sub Grid Scale}\\ \text{turbulence models}}} \tag{2}$$

$$\frac{\partial \overline{u}_i}{\partial t}+\frac{\partial \overline{u}_i \overline{u}_j}{\partial x_j}=-\frac{1}{\rho}\frac{\partial \overline{p}}{\partial x_i}+\frac{\partial}{\partial x_j}\left(\nu\frac{\partial \overline{u}_i}{\partial x_j}\right)-\frac{\partial \tau_{ij}}{\partial x_j} \tag{3}$$

$$\tau_{ij}\equiv\overline{u_i u_j}-\overline{u}_i\overline{u}_j \tag{4}$$

The PISO pressure-velocity coupling was chosen as the iteration time was already expected to be higher than the previous 3 steps however, due to the addition of a second correction stage, the Pressure Implicit solution by Split Operator method ( Issa 1982 PISO) scheme needs fewer iterations, hence reducing computation time [8].

Figure 2 depicts the correlation between the velocity field and the static pressure field across the ramp for the RANS k-omega SST and the LES simulations respectively. We can draw the preliminary conclusion that, indeed the fluid is accelerated across the curved ramp and-as a consequence of Bernoulli's law- the static pressure drops.

This correlation is useful in showing that in conventional airfoils, the acceleration of the fluid on the upper side is due to the Coandã effect over the curved region rather than the path difference as it is traditionally thought. This remark however is not the object of this investigation and will be discussed in a separate note.

The aero-acoustic processing was done with the FWH formalism and after a Fourier Transform; the acoustic spectrum was obtained for each of the three chosen points in the vicinity of the ramp. Figures 4 through 6 show the spectrum observed for the respective coordinates of the points.

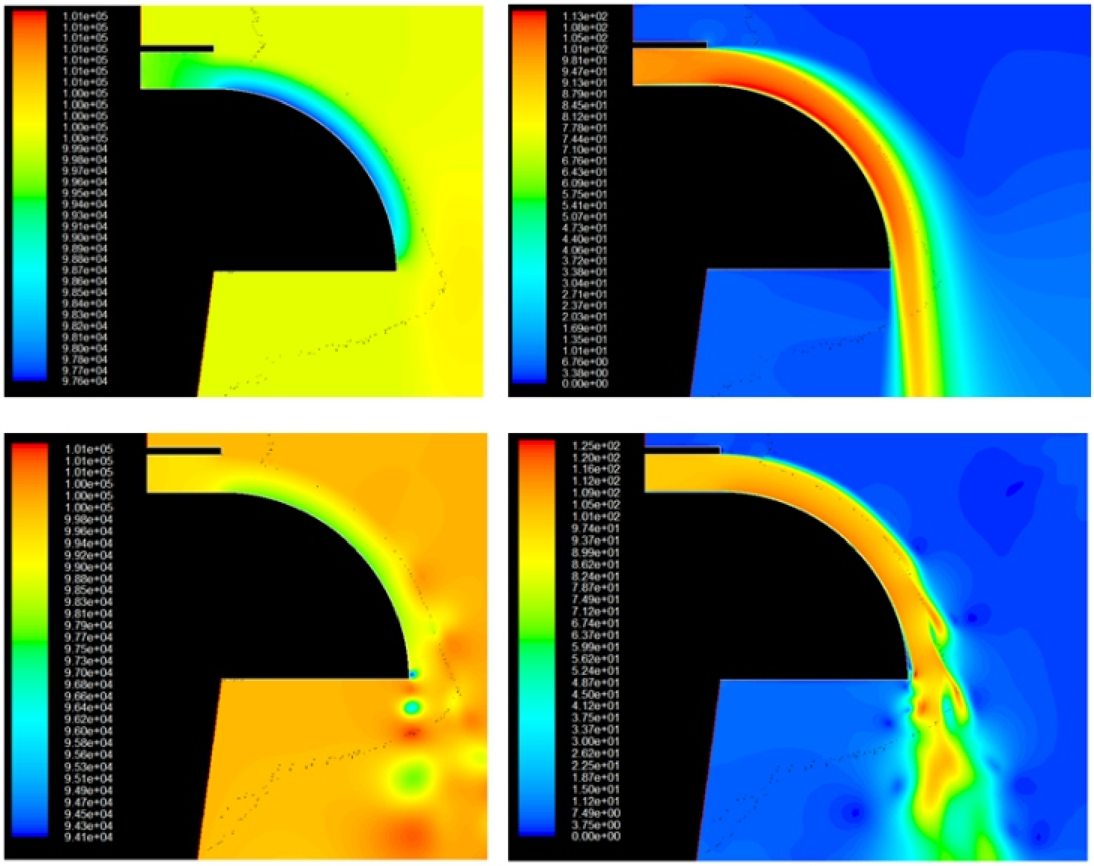

**Figure 2:** Plots correlating velocity and static pressure of k-omega SST (up) and LES (down).

### 3. Results

By integrating the pressure drop over the ramp we can calculate the lift that it would provide in a real airfoil application. Comparing it to the thrust of the bare jet exhausted through the considered nozzle we can verify the claim of Henri Coandã's patent [5]. Equation 5 was used for the assessment and the results were compared with the estimated force resulted from the diversion of the fluid by the observed 87°. The comparison showed that jet diversion alone is not responsible for the total lift generated by the ramp which proves, numerically, Coandã's claims.

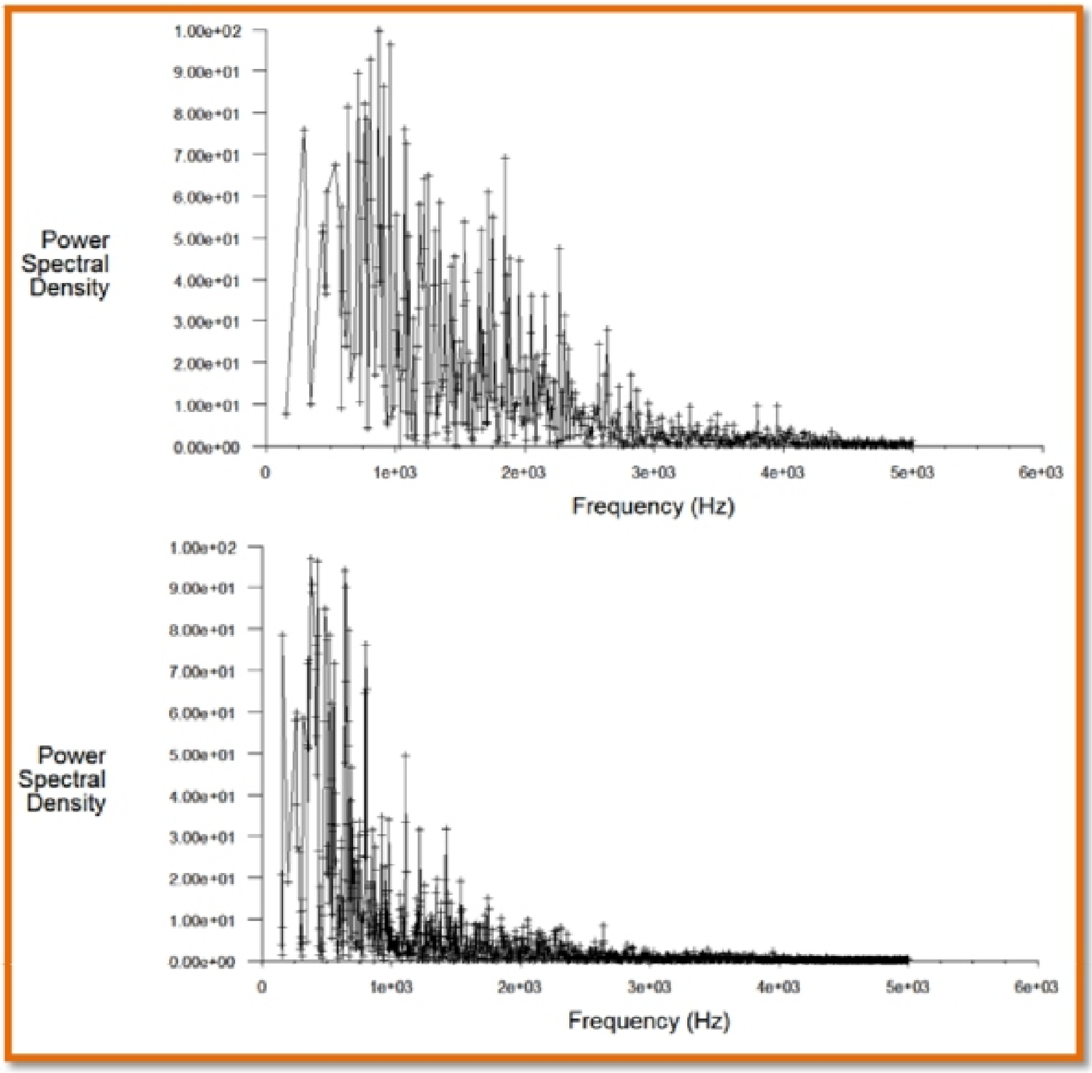


**Figure 3:** First receiver location spectrum, notable differences between 1kHz and 2 kHz LES (up) k-omega SST (down)

**Table 1:** relevant aerodynamic parameters of the three simulations

| Simulation model | y+ | Average static pressure | Karman vortex street | 100*Ramp lift/jet thrust |
|---|---|---|---|---|
| Steady k-ω SST | 5.71 | 98103.56 [Pa] | Not observed | 121.5881 % |
| Large Eddy Simulation | 1.55 | 97870.69 [Pa] | Observed | 136.5185 % |
| Unsteady k-ω SST | 2.79 | 98019.23 [Pa] | Not observed | 126.9948 % |

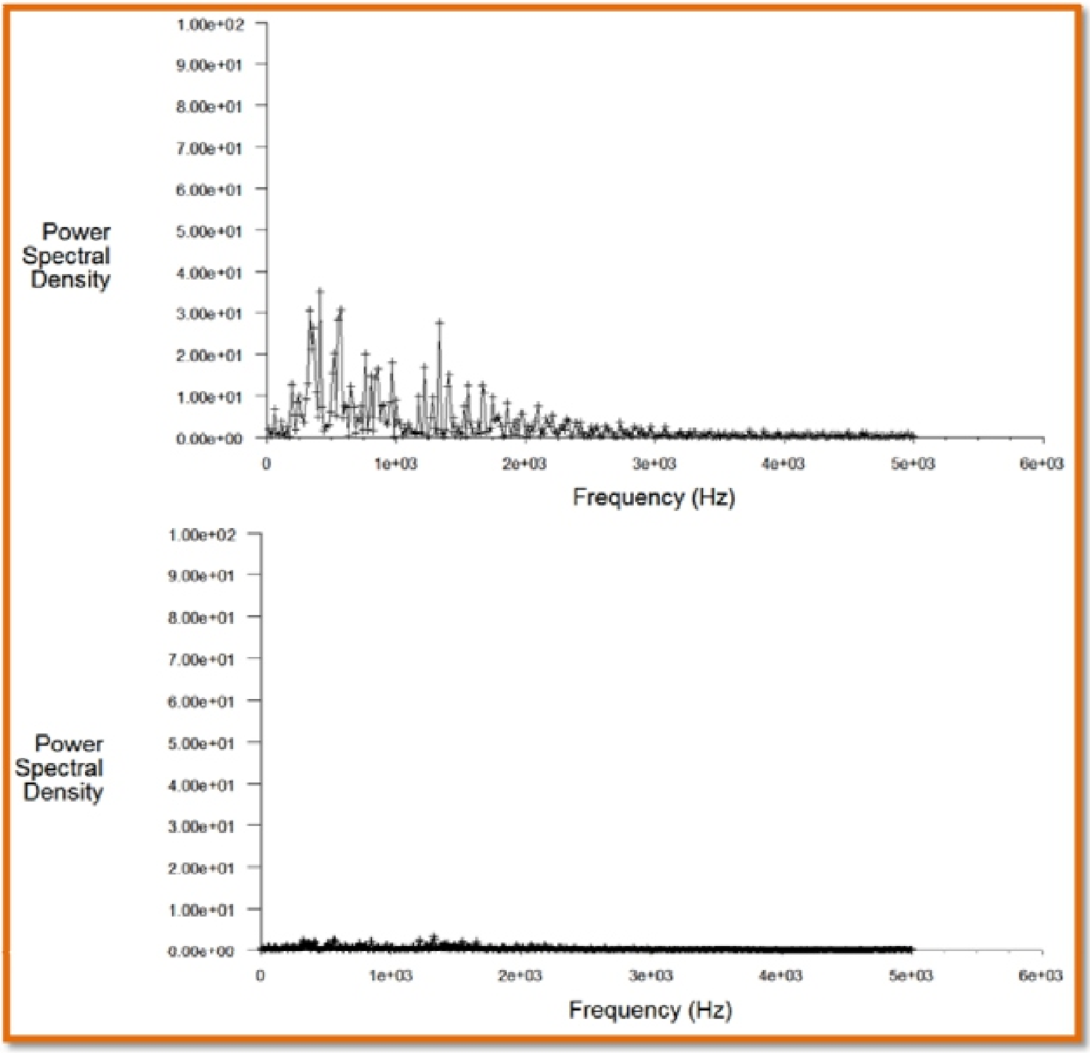


**Figure 4:** Fourth receiver location spectrum, notable differences between entire spectrum is under predicted by the SST; LES (up) k-omega SST (down).

**4. Discussions**

Regarding the aspects of numerical computations we can conclude that the results of a steady k-omega SST RANS simulation give fairly similar results to that of the more time and labor intensive Smagorinsky-Lilly LES method. It needs to be said however that the nature of the thin jet in respect to the ramp size makes it prone to unsteady flows therefore RANS and LES simulations alike should be performed in a time dependent manner.

Detachment of the flow was not accurately predicted by the RANS; however, in this particular case the differences were not large. For thinner jets and higher velocities and curvatures failure to predict flow detachment will be an issue that will give optimistic lift values for super circulation airfoils. Hence it is the recommendation of this paper to use, if possible the LES technique at least in those cases.

Regarding the lift obtained through super circulation; the ramp produced a force equal to 136 % of the thrust of the nozzle. This is confirmation that diversion of the fluid alone is not the cause of the super circulation lift and that pelicular jets indeed may provide a new principle of flight as envisioned by Henri Coandã.

This finding is significant in understanding how conventional airfoils work as there is still a widespread belief amongst aerodynamicists that the acceleration on the upper side of the airfoil is due to the difference in path length. While it is not the object of this study, we can only state the opinion that the acceleration is caused by the curvature of the airfoil which is a distinct physical phenomenon in itself.

The acoustics of the Coandã jet appears to be quite similar in nature to that of a normal jet that is injected in a given volume. However we need to point out that the velocity of the fluid that gets detached from the ramp is lower than that of the initial (fully developed) flow due to turbulence generated while attached to the ramp. This leads in the end to a less steep transition to the still ambient air and hence to less noise generation.

## 5. Applications

The most popular applications for super circulation flows are airfoil surfaces such as airplane wings or turbo machinery blades. Advantages include higher section loadings, higher Angles of Attack (delayed stalling) and higher lift to drag ratios.

Below we present a preliminary comparative study of a super circulated airfoil versus a similar conventional airfoil. Table 2 presents the summary of the aerodynamic performances of the two cases. The super circulated airfoil displayed better aerodynamic performances at both angles of attack tested.

**Table 2:** Aerodynamic parameters of the tested airfoils.

| Airfoil | Section loading N/m$^2$ | Lift to drag ratio |
|---|---|---|
| S. C. 10° AoA | 1266.06 | 20.7042 |
| NACA 10° AoA | 1130.81 | 17.2111 |
| S. C. 15° AoA | 1136.24 | 14.6389 |
| NACA. 15° AoA | 1143.45 | 12.8913 |

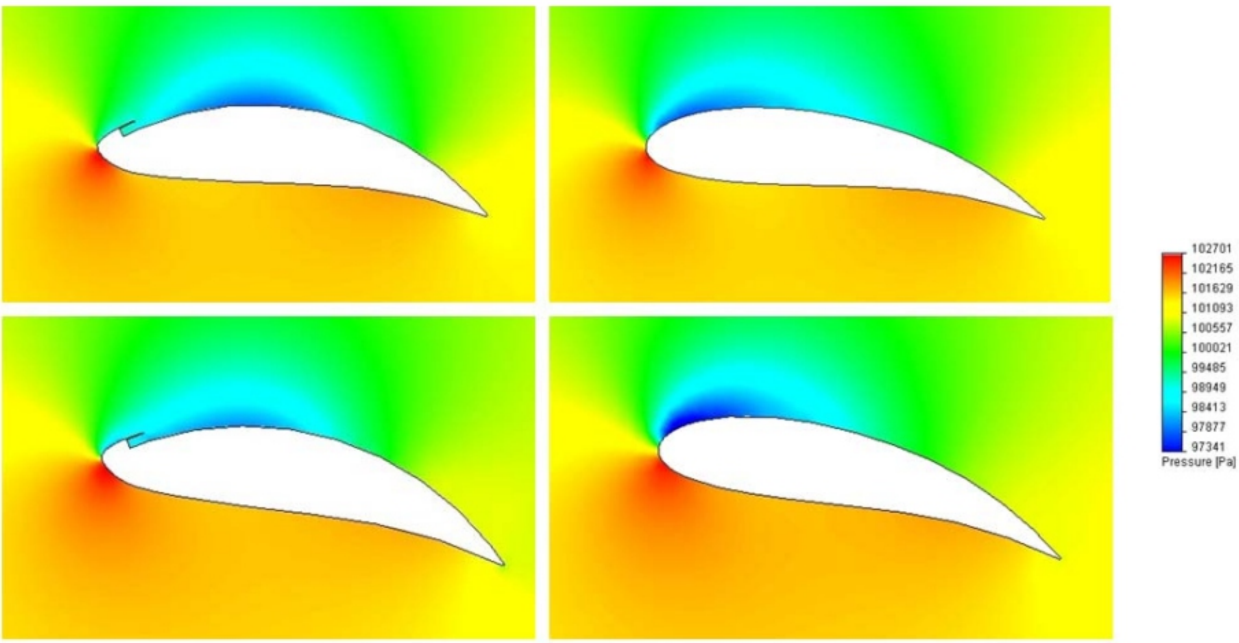


**Figure 5:** Static pressure plots of normal and super circulated airfoils.

## 6. Conclusion

Due to increasing interest in the civilian aviation industry for super circulation aircraft, particularly because of the higher lift capacity and lower noise emissions, we sat out to establish a simple CFD research method in order to derive some quantitative aspects of the super circulation concept.

The paper presents a comparative computational fluid dynamics study between the two major Navier-Stokes methods: RANS and LES. It focuses on the flow characteristics such as boundary layer separation and pressure drop due to the Coandã Effect but also on the aero-acoustic particularities of Coandã flows.

It was found that the curvature of the Coandã surface tends to accelerate the fluid in the immediate vicinity of the wall which causes the static pressure to drop considerably hence generating lift. The pressure drop across the ramp provided a lift equal to 136.5% of the jet thrust. This is evidence that deviation of the fluid alone cannot be the motive of the lift generated on the ramp.

Section 5 depicts a possible application of the super circulation by Coandã effect on a classic NACA airfoil. The results obtained through CFD simulations in these cases show improved lift to drag ratios thus improving overall aircraft efficiency.

Comparing the two CFD methods used, the RANS k-omega and LES we can conclude that the LES predicted the detachment from the ramp whilst the k-omega did not. Also, the k-omega SST under predicted the pressure drop across the ramp. The LES technique captured the unsteady phenomenon of a Karman vortex street generated at the detachment point.

The acoustic spectrum in the LES case predicts a wider range from 500 Hz to 2000 Hz while the SST only predicts a spectrum from 500 Hz to 1000 Hz. This is an important difference since the human ear is more sensitive in the range 1000-2000 Hz. All four receiver locations registered largely the same differences in the noise spectrum.

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# Optimizing Fusion Zone Grain Size and Ultimate Tensile Strength of Pulsed Current Micro Plasma Arc Welded Inconel 625 Alloy Sheets using Hooke & Jeeves Method

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## ABSTRACT

*Pulsed Current Micro Plasma Arc welding (PCMPAW) process is an important joining process widely used in sheet metal fabrication industries. The paper focuses on developing mathematical models to predict grain size and ultimate tensile strength of pulsed current micro plasma arc welded Inconel 625 nickel alloy using Response Surface Method (RSM). The experiments were carried out based on Central Composite Design (CCD) with 31 combinations of experiments. The adequacy of the models is checked by Analysis of Variance (ANOVA) technique. Hooke and Jeeves method is used to minimize grain size and maximize the ultimate tensile strength.*

***Keywords: Pulsed Current Micro Plasma Arc Welding, Inconel625, Grain Size, Ultimate Tensile Strength, Hooke & Jeeves method.***

### 1. Introduction

In welding processes, the input parameters have greater influence on the mechanical properties of the weld joints. By varying the input process parameters, the output could be changed with significant variation in their mechanical properties. Accordingly, welding is usually selected to get a welded joint with excellent mechanical properties. To determine these welding combinations that would lead to excellent mechanical properties, different methods and approaches have been used. Various optimization methods can be applied to define the desired output variables through developing mathematical models to specify the relationship between the input parameters and output variables. One of the most widely used methods to solve this problem is Response Surface Methodology (RSM), in which the unknown mechanism with an appropriate empirical model is approximated, being the function of representing a RSM.

Pulsed current MPAW involves cycling the welding current at selected regular frequency. The maximum current is selected to give adequate penetration and bead contour, while the minimum is set at a level sufficient to maintain a stable arc (Balasubramanian et.al,2006, Madusudhana Reddy G ert.al, 1997). This permits arc energy to be used effectively to fuse a spot of controlled dimensions in a short time producing the weld as a series of overlapping nuggets. By contrast, in constant current welding, the heat required to melt the base material is supplied only during the peak current pulses allowing the heat to dissipate into the base material leading to narrower Heat Affected Zone (HAZ). Advantages include improved bead contours, greater tolerance to heat sink variations, lower heat input requirements, reduced residual stresses and distortion, refinement of fusion zone microstructure and reduced with of HAZ.

Several researchers (Balasubramanian et.al, 2010, Balasubramanian et.al, 2006, Madusudhana et.al, 1997) have studied the importance of using optimum pulse parameters to obtain sound mechanical properties in Gas Tungsten Arc Welding (GTAW) process. Very few works are reported on using current pulsing technique in MPAW process. From the previous works (Kondapalli Siva Prasad et.al, 2011a, 2011b, 2011c, 2011d, 2011e) it is decided that four important parameters, namely peak current, back current, pulse rate and pulse width affect the weld quality to a larger extent. One had to carefully balance various pulse parameters to arrive at an optimum combination. Hence in this investigation, an attempt has been made to optimize the Pulsed Current MPAW parameters to attain minimum grain size and maximum ultimate tensile strength using Hooke & Jeeves method.

## 2. Experimental Procedure

Inconel625 sheets of 100 x 150 x 0.25mm are welded autogenously with square butt joint without edge preparation. The chemical composition of Inconel625 stainless steel sheet is given in Table 1. Experiments were conducted using the pulsed current MPAW process. The welding has been carried out under the welding conditions presented in Table 2. From the literature four important factors of pulsed current MPAW as presented in Table 3 are chosen. A large number of trail experiments are carried out using 0.25mm thick Inconel625 sheets to find out the feasible working limits of pulsed current MPAW process parameters. Due to wide range of factors, it was decided to use four factors, five levels, rotatable central composite design matrix to perform the number of experiments for investigation. Table 4 indicates the 31 set of coded conditions used to form the design matrix. The method of designing such matrix is dealt elsewhere (Montgomery, 1991, Box et.al, 1978).

**Table 1:** Chemical composition of Inconel625 (weight %).

| C | Mn | P | S | | Si | Cr | Ni |
|---|---|---|---|---|---|---|---|
| 0.0300 | 0.0800 | 0.0050 | 0.0004 | | 0.1200 | 20.8900 | 61.6000 |
| Al | Mo | Cb | Ta | Ti | N | Co | Fe |
| 0.1700 | 8.4900 | 3.4400 | 0.0050 | 0.1800 | 0.0100 | 0.1300 | 4.6700 |

**Table 2:** Welding conditions.

| Power source | Secheron Micro Plasma Arc Machine (Model: PLASMAFIX 50E) |
|---|---|
| Polarity | DCEN |
| Mode of operation | Pulse mode |
| Electrode | 2% thoriated tungsten electrode |
| Electrode Diameter | 1mm |
| Plasma gas | Argon & Hydrogen |
| Plasma gas flow rate | 6 Lpm |
| Shielding gas | Argon |
| Shielding gas flow rate | 0.4 Lpm |
| Purging gas | Argon |
| Purging gas flow rate | 0.4 Lpm |
| Copper Nozzle diameter | 1mm |
| Nozzle to plate distance | 1mm |
| Welding speed | 260mm/min |
| Torch Position | Vertical |
| Operation type | Automatic |

**Table 3:** Important factors and their levels.

| Serial No | Input Factor | Units | Levels | | | | |
|---|---|---|---|---|---|---|---|
| | | | -2 | -1 | 0 | +1 | +2 |
| 1 | Peak current | Amperes | 6 | 6.5 | 7 | 7.5 | 8 |
| 2 | Back current | Amperes | 3 | 3.5 | 4 | 4.5 | 5 |
| 3 | Pulse rate | Pulses/Second | 20 | 30 | 40 | 50 | 60 |
| 4 | Pulse width | % | 30 | 40 | 50 | 60 | 70 |

**Table 4:** Design matrix and experimental results.

| Serial No | Peak current (Amperes) | Back current (Amperes) | Pulse (Pulses/Second) | Pulse width (%) | Grain size (Micons) | Ultimate tensile strength (VHN) |
|---|---|---|---|---|---|---|
| 1 | -1 | -1 | -1 | -1 | 40.812 | 833 |
| 2 | 1 | -1 | -1 | -1 | 50.226 | 825 |
| 3 | -1 | 1 | -1 | -1 | 41.508 | 838 |
| 4 | 1 | 1 | -1 | -1 | 47.536 | 826 |
| 5 | -1 | -1 | 1 | -1 | 47.323 | 826 |
| 6 | 1 | -1 | 1 | -1 | 45.206 | 830 |
| 7 | -1 | 1 | 1 | -1 | 45.994 | 825 |
| 8 | 1 | 1 | 1 | -1 | 43.491 | 826 |
| 9 | -1 | -1 | -1 | 1 | 46.290 | 825 |
| 10 | 1 | -1 | -1 | 1 | 49.835 | 820 |
| 11 | -1 | 1 | -1 | 1 | 40.605 | 835 |
| 12 | 1 | 1 | -1 | 1 | 47.764 | 828 |
| 13 | -1 | -1 | 1 | 1 | 50.095 | 818 |
| 14 | 1 | -1 | 1 | 1 | 46.109 | 826 |
| 15 | -1 | 1 | 1 | 1 | 47.385 | 824 |
| 16 | 1 | 1 | 1 | 1 | 45.013 | 830 |
| 17 | -2 | 0 | 0 | 0 | 40.788 | 830 |
| 18 | 2 | 0 | 0 | 0 | 45.830 | 826 |
| 19 | 0 | -2 | 0 | 0 | 51.663 | 821 |
| 20 | 0 | 2 | 0 | 0 | 47.263 | 828 |
| 21 | 0 | 0 | -2 | 0 | 45.270 | 832 |
| 22 | 0 | 0 | 2 | 0 | 46.030 | 825 |
| 23 | 0 | 0 | 0 | -2 | 44.626 | 831 |
| 24 | 0 | 0 | 0 | 2 | 46.626 | 825 |
| 25 | 0 | 0 | 0 | 0 | 44.845 | 830 |
| 26 | 0 | 0 | 0 | 0 | 44.845 | 830 |
| 27 | 0 | 0 | 0 | 0 | 40.145 | 840 |
| 28 | 0 | 0 | 0 | 0 | 44.845 | 830 |
| 29 | 0 | 0 | 0 | 0 | 40.045 | 838 |
| 30 | 0 | 0 | 0 | 0 | 44.845 | 830 |
| 31 | 0 | 0 | 0 | 0 | 40.445 | 832 |

## 3. Recording the responses

### 3.1 Measurement of grain size

Microstructural examinations were carried out using metallurgical microscope (Make: Carl Zeiss, Model: Axiovert 40MAT) at 100X magnification. The specimens for metallographic examination were sectioned to the required size from the weld joint and were polished using different grades of emery papers. Sample preparation and mounting is done as per ASTM E 3-1 standard. The samples are surface grounded using 120 grit size belt with the help of belt grinder, polished using grade 1/0 (245 mesh size), grade 2/0 ( 425 mesh size) and grade 3/0 (515 mesh size) sand paper. The specimens are further polished by using aluminum oxide initially and the by utilizing diamond paste and velvet cloth in a polishing machine. The polished specimens are etched by using Aqua regia solution to reveal the microstructure as per ASTM E407. The micrographs of parent metal zone and weld fusion zone are shown in Figure 1 & 2 (Kondapalli Siva Prasad et.al, 2011e).

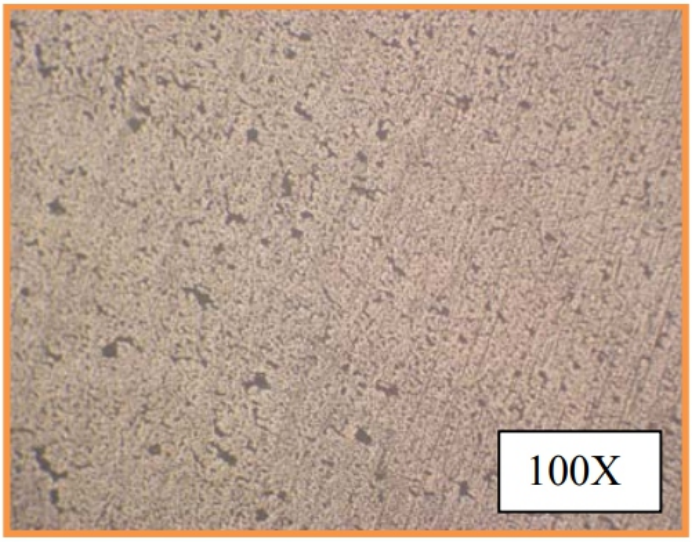


**Figure 1:** Microstructure of parent metal zone.

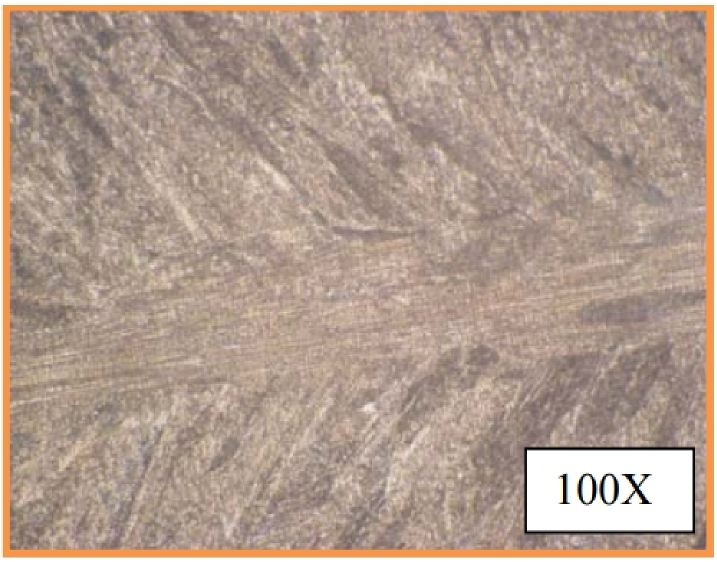


**Figure 2:** Microstructure of weld fusion zone.

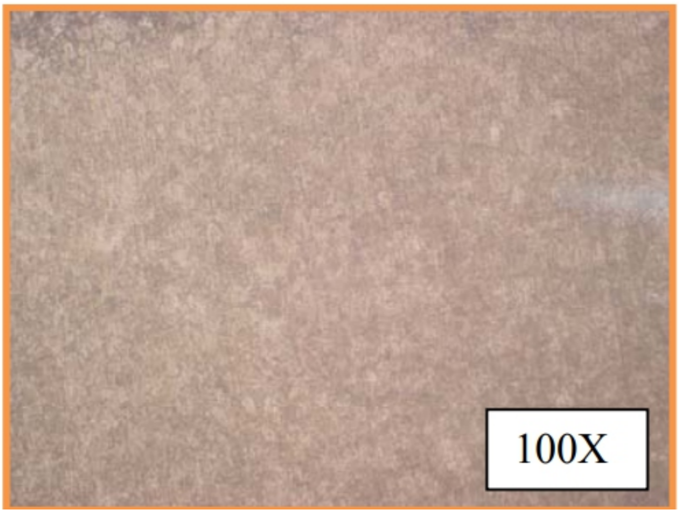


**Figure 3:** Grain size of parent metal at 100X.

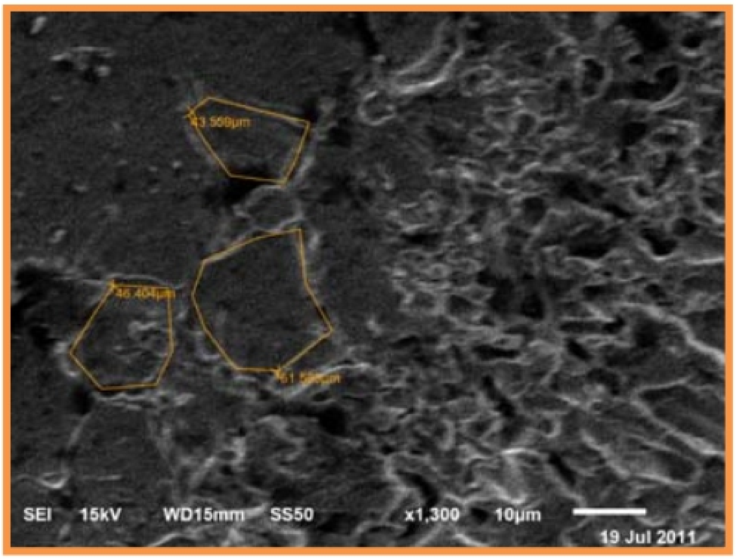


**Figure 4:** Grain size of weld fusion zone (SEM)

Grain size of parent metal and weld joint is measured by using Scanning Electron Microscope (Make: INCA Penta FETx3, Model:7573). Figure 3 & 4 indicates the measurement of grain size for parent metal zone and weld fusion zone. Average values of grain size at the fusion zone are presented in Table 4.
The average grain size at the weld interface is about 45.772 Microns and that of parent metal is about 50 Microns. Smaller grains at interface indicate better strength of weld joint.

**3.2 Measurement of ultimate tensile strength**

Three transverse tensile specimens are prepared as per ASTM E8M-04 guidelines and the specimens after wire cut Electro Discharge Machining are shown in Figure 5. Tensile tests are carried out in 100 KN computer controlled Universal Testing Machine (ZENON, Model No: WDW-100) as shown in Figure 6 (Kondapalli Siva Prasad et.al, 2011d). The specimen is loaded at a rate of 1.5 KN/min as per ASTM specifications, so that the tensile specimens undergo deformation. From the stress strain curve, the ultimate tensile strength of the weld joints is evaluated and the average of three results for each sample is presented in Table 4.

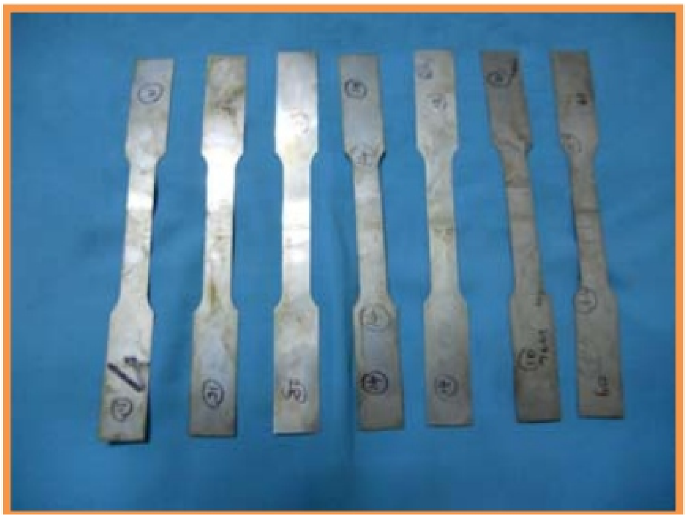

**Figure 5:** Tensile specimens.

**Figure 6:** Universal Testing Machine.

**4. Developing Mathematical Models**

The grain size (G) and ultimate tensile strength(T) of the weld joint is a function of peak current (A), back current (B), pulse rate (C) and pulse width (D). It can be expressed as (Cochran W G & Cox G M, 1957, Barker T B, 1985 , Gardiner W P, Gettinby G, 1998).

Grain size (G),

$$G = f(A, B, C, D) \quad (1)$$

Ultimate tensile strength (T)

$$T = f(A, B, C, D) \quad (2)$$

The second order polynomial equation used to represent the response surface 'Y' is given by (Montgomery D.C, 1991):

$$Y = b_o + \sum b_i x_i + \sum \beta_{ii} x_i^2 + \sum\sum b_{ij} x_i x_j + \in \quad (3)$$

Using MINITAB 14 statistical software package, the significant coefficients were determined and final models are developed using significant coefficients to estimate grain size and ultimate tensile strength values of weld joint.

The final mathematical models are given by

Grain Size (G)

$$G = 42.859 + 1.052X_1 - 1.058X_2 + 0.3150X_3 + 0.625X_4 + 1.640X_2^2 - 2.320X_1X_3 \quad (4)$$

Ultimate tensile strength (T)

$$T = 833.143 - 0.875X_1 + 1.792X_2 - 1.625X_3 - 1.458X_4 - 1.296X_1^2 - 2.171X_2^2 - 1.296X_4^2 + 3.187X_1X_3 \quad (5)$$

Where X1, X2, X3 and X4 are the coded values of peak current, back current, pulse rate and pulse width respectively.

**5. Checking the adequacy of the developed models**

The adequacy of the developed models was tested using the analysis of variance technique (ANOVA). As per this technique, if the calculated value of the Fratio of the developed model is less than the standard Fratio (from F-table) value at a desired level of confidence (say 99%), then the model is said to be adequate within the confidence limit. ANOVA test results are presented in Table 5 & 6 for all the models. From the table it is understood that the developed mathematical models are found to be adequate at 99% confidence level. The value of co-efficient of determination ' R2 ' for the above developed models is found to be about 0.86 .

Figures 7 and 8 indicate the scatter plots for grain size and ultimate tensile strength of the weld joint and reveal that the actual and predicted values are close to each other with in the specified limits.

**Table 5:** ANOVA test results for grain size.

| Grain Size | | | | | | |
|---|---|---|---|---|---|---|
| Source | DF | Seq SS | Adj SS | Adj MS | F | P |
| Regression | 14 | 249.023 | 249.023 | 17.7873 | 6.10 | 0.000 |
| Linear | 4 | 65.207 | 65.207 | 16.3018 | 5.59 | 0.005 |
| Square | 4 | 91.443 | 91.443 | 22.8608 | 7.84 | 0.001 |
| Interaction | 6 | 92.372 | 92.372 | 15.3954 | 5.28 | 0.004 |
| Residual Error | 16 | 46.639 | 46.639 | 2.9149 | | |
| Lack-of-Fit | 10 | 9.750 | 9.750 | 0.9750 | 0.16 | 0.994 |
| Pure Error | 6 | 36.889 | 36.889 | 6.1481 | | |
| Total | 30 | 295.661 | | | | |

**Table 6:** ANOVA test results for ultimate tensile strength.

| Ultimate tensile strength | | | | | | |
|---|---|---|---|---|---|---|
| Source | DF | Seq SS | Adj SS | Adj MS | F | P |
| Regression | 14 | 679.070 | 679.070 | 48.5050 | 6.89 | 0.000 |
| Linear | 4 | 209.833 | 209.833 | 52.4583 | 7.45 | 0.001 |
| Square | 4 | 211.362 | 211.362 | 52.8405 | 7.51 | 0.001 |
| Interaction | 6 | 257.875 | 257.875 | 42.9792 | 6.11 | 0.002 |
| Residual Error | 16 | 112.607 | 112.607 | 7.0379 | | |
| Lack-of-Fit | 10 | 1.750 | 1.750 | 0.1750 | | |
| Pure Error | 6 | 110.857 | 110.857 | 18.4762 | 0.01 | 1.000 |
| Total | 30 | 791.677 | | | | |

Where SS=Sum of Squares, MS=Mean Squares, DF =Degree of Freedom, F= Fisher's ratio

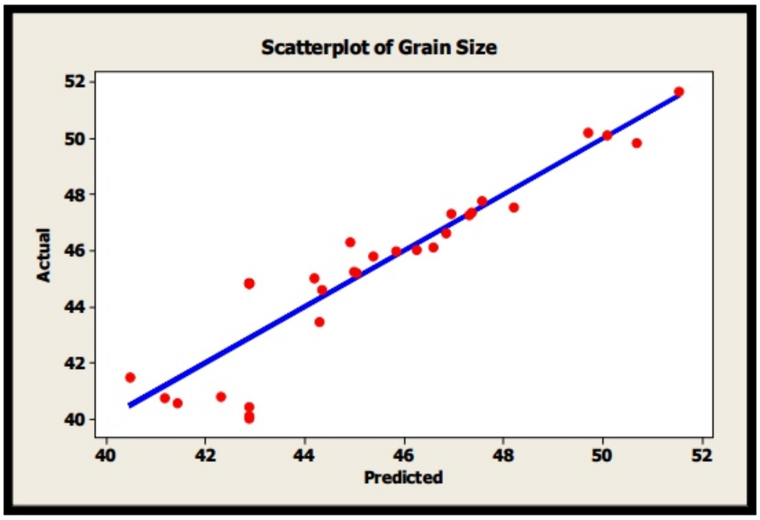


**Figure 7:** Scatter plot of Grain size.

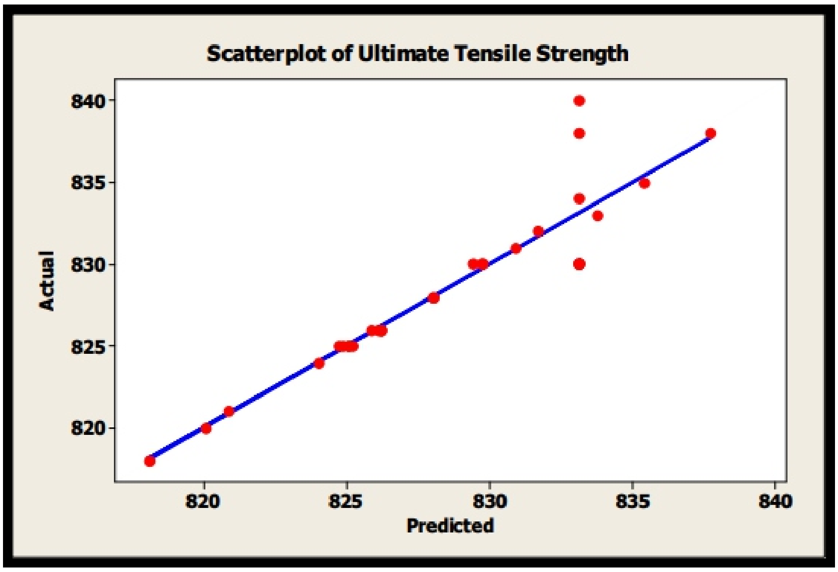


**Figure 8:** Scatter plot of Ultimate tensile strength.

**6. Optimizing Using Hooke & Jeeves algorithm**

Hooke and Jeeves method (Kalyanmoy.D, 1988) is used to search the optimum values of the process variables. In this paper the algorithm is developed to optimize the pulsed current MPAW process variables. The objective is to minimize grain size & maximize ultimate tensile strength. The coding for the Hooke Jeeves method is written in MATLAB software.

The Hooke & Jeeves method incorporates the past history of a sequence of iterations into the generation of a new search direction. It combines exploratory moves with pattern moves. The exploratory moves examine the local behavior of the function & seek to locate the direction of any stepping valleys that might be present. The pattern moves utilize the information generated in the exploration to step rapidly along the valleys.

**Exploratory Move:**

Given a specified step size which may be different for each co - ordinate direction and change during search. The exploration proceeds from an initial point by the specified step size in each coordinate direction. If the function value does not increased the step is considered successful. Otherwise the step is retracted and replaced by a step in the opposite direction which in turn is retained in depending upon whether it success or fails. When all N coordinates have been investigated, the exploration move is completed. The resulting point is termed a base point.

**Pattern Move:**

A pattern move consists of a single step from the present base point along the line from the previous to the current base point.

A new pattern point is calculated as:

$$x_p^{(k+1)} = x^{(k)} + (x^{(k)} - x^{(k-1)})$$

where, xp*(k+1)* is temporary base point for a new exploratory move.

If the result of this exploration move is a better point then the previous base point (xk) then this is accepted as the new base point *x(k+1)*. If the exploratory move does not produce improvement, the pattern move is discarded and the search returns to *x(k),* where an exploratory search is undertaken to find a new pattern.

Various steps involved in Hooke & Jeeves method is discussed below.

Step 1: Starting point x(0)

The increments $\Delta i$ for i=1,2,3, …, N
Step reduction factor $\alpha > 1$
A termination parameter $\varepsilon > 0$

Step 2: Perform exploratory search

Step 3: Was exploratory search successful (i.e. was a lower point found)
If Yes go to step (5 )

Else continue

Step 4: check for the termination $||\Delta|| < \varepsilon$ current pint approximation x0
$\Delta i = \Delta i / \alpha$ for i = 1,2,3, … , N

Go to step 2
Step 5: Perform pattern move
$xp(k+1) = x(k) + (x(k) - x(k-1))$

Step 6: Perform exploratory research using *xp(k+1)* as the base point; let the result be *x(k+1)*.

Step 7: This step decides whether you are doing this operation for minimization or maximization.

If you applied the condition *"Is f(x(k+1)) < f(x(k)) ?"* then it is to find the maximum ultimate tensile strength.
If *"Is f(x(k+1)) < f(x(k)) ?"* then it is to find minimum grain size.

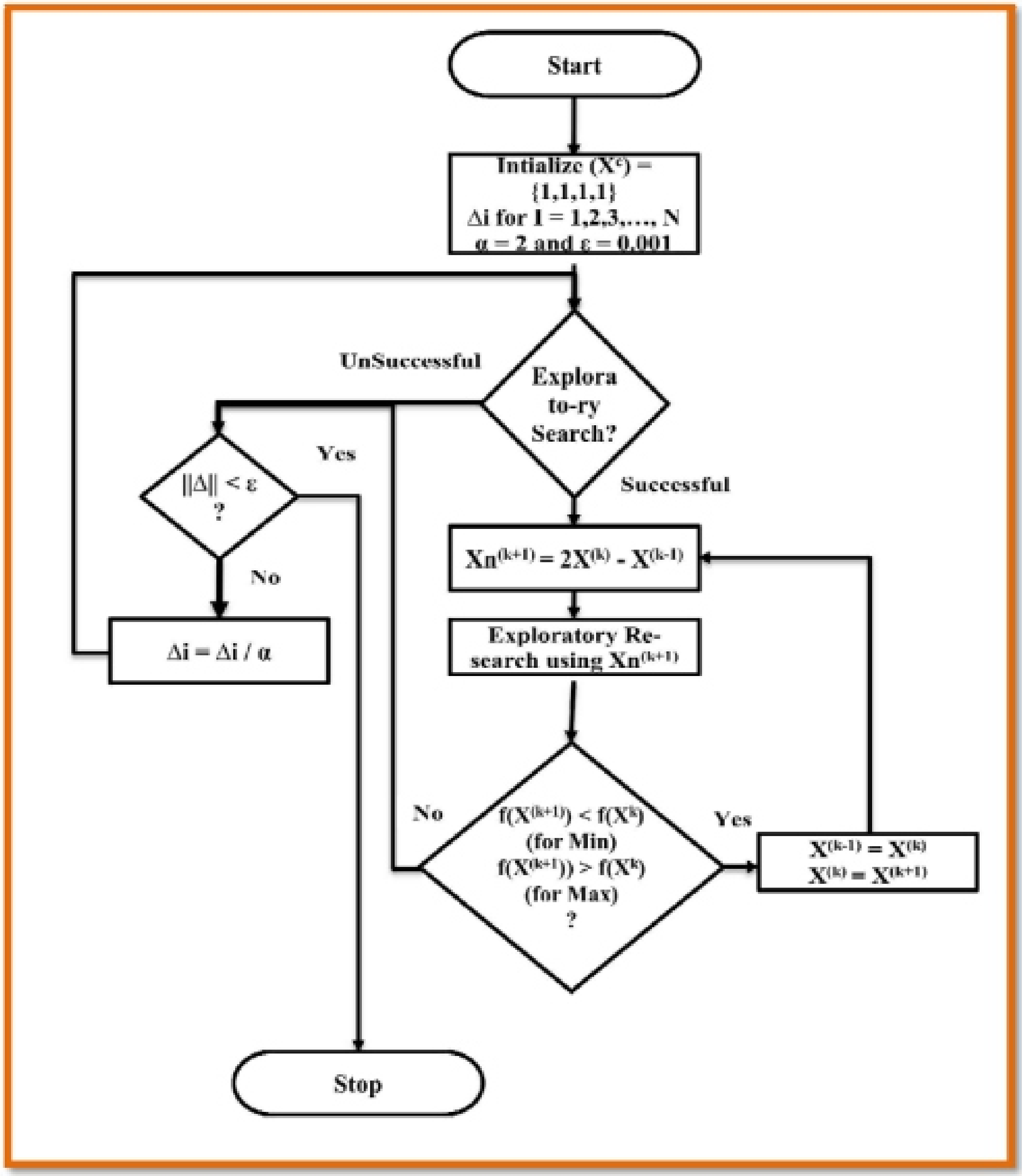


**Figure 9:** Flow chart of Hooke & Jeeves method.

Step (i) & (ii) results either Yes or No basing on the requirement of minimum grain size or maximum tensile strength. After getting the result continue with the following process.

If Yes Set $x^{(k-1)} = x^{(k)}$

$x^{(k)} = x^{(k+1)}$ go to step (5).

Else go to step (4)

Detailed flow chart of Hooke & Jeeves method is presented in Figure 9.

**Table 7:** Optimized pulsed current MPAW parameters for grain size.

| | Hooke & Jeeves | Experimental |
|---|---|---|
| Peak current(Amperes) | 7.1196 | 7 |
| Back current(Amperes) | 4.1196 | 4 |
| Pulse rate (Pulses/econd) | 42.3911 | 40 |
| Pulse width (%) | 52.3911 | 50 |
| Ultimate Tensile Strength(Mpa) | 41.1640 | 40.045 |

**Table 8:** Optimized pulsed current MPAW parameters for ultimate tensile strength.

| | Hooke & Jeeves | Experimental |
|---|---|---|
| Peak current(Amperes) | 7.2177 | 7 |
| Back current(Amperes) | 4.2177 | 4 |
| Pulse rate(Pulses/Second) | 44.3545 | 40 |
| Pulse width (%) | 54.3545 | 50 |
| Ultimate Tensile Strength(Mpa) | 844.3545 | 840 |

From Tables 7 and 8, it is understood that the values predicted by Hooke and Jeeves method and experimental values are very close to each other.

## 7. Conclusions

The developed empirical models can be effectively used to predict grain size and ultimate tensile strength of Pulsed Current Micro Plasma Arc Welded Inconel 625 joints. The developed models are valid within the range of selected weld input parameters. A minimum grain size of 40.045 microns and maximum ultimate tensile strength of 840 Mpa is obtained for the input parameter combination of peak current of 7 Amperes, back current of 4 Amperes, pulse rate of 40 Pulses /Second and pulse width of 50% experimentally. From Hooke and Jeeves method, the minimum grain size obtained is 41.1640 microns for the input parameter combination of peak current of 7.1196 Amperes ,back current of 4.1196 Amperes, pulse rate of 42.3911 Pulses /Second and pulse width of 52.3911%. The maximum ultimate tensile strength obtained is 844.3545 MPa for the input parameter combination of peak current of 7.2177Amperes, back current of 4.2177 Amperes, pulse rate of 44.3545 Pulses /Second and pulse width of 54.3545%. The values of grain size and ultimate tensile strength obtained experimentally closely matches with the values obtained using Hooke & Jeeves method.

## 8. Acknowledgment

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# Effects of NAA BA and Sucrose On Shoot Induction and Rapid Micropropagation by Trimming Shoot Of Curcuma Longa L.

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## ABSTRACT

*Shoot tip of Curcuma longa L. were used as explants. These explants were cultured on MS medium supplemented with various concentration of (0, 1, 2, 3 and 4 mg/l ) BA and (0,0.5, and 1 mg/l) NAA. They were significant difference (p≤0.05) in each parameter. Explants which cultured on MS medium supplemented with 1 mg/l NAA and 2 or 3 mg/l BA gave the highest average number of new shoots ( 2.4, 2.6 shoots, respectively) and number of leaf (5.4 leaves), optimum number of roots ( 2.6 roots per shoot) and plant height (4.5 cm). In MS medium supplemented with only 2 mg/l BA produced the highest average number of shoot (2.6 shoots) and 5.4 leaves per shoot. When trimmed explants in longitudinal section (LS) to 2 and 3 sections. At 2 sections gave the highest number of new shoots (4.3 shoots per section). Explants which cultured on MS medium with 60 gm/l gave the highest average shoots and leaves per bunch, longest and biggest size of root.*

***Keywords: Curcuma longa L.; BA; NAA; sucrose; trimming***

### 1. Introduction

Curcuma longa L. is belong to Family Zingiberaceae , produces edible rhizome which use as a medicine and food additive. Rhizome was used for peptic ulcer (Prucksunand et al,.2001), gastic ulcer (Kositchaiwat et al., 1993) and dyspepsia (Thamlikitkul et al., 1989). Micropropagation gave many plantlets which true to type and provided uniform plants. (George, 1993). High quality of Curcuma longa with high and constant level of curcuminoids and volatile oil were wanted to get multiple their plants. In vitro propagations of Curcuma longa have been done (Yasuda et al,. 1988, Salvi et al., 2000, 2001, 2002 and Prathanturarug et al., 2003, 2005).

This work involved investigations about size of shoot tip which trimmed in small pieces and studied the effect of BA, NAA and sucrose concentration which effected on number of new shoots and new roots for large scale propagation.

### 2. Materials and Method

MS medium was used as culturing medium, sprout of young shoots tip about 1.5 cm long were used as explants. All explants were washed many times with running tap water, then soaked in 70% alcohol for 3 min and transferred to 10% clorox for 20 min and followed by 5% Clorox for 10 min. then rinsed 3 times with sterile distilled water for 3 min. each. All shoot bud explants were cultured on MS medium supplemented with vary concentration of (0, 1, 2, 3, 4 mg/l) BA and (0, 0.5, 1 mg/l) NAA for initiation, elongation, regeneration and shoot bud formation. The second experiment: Shoot tip about 0.5 cm long were used for trimming in longitudinal section with half (2 sections) and 3 sections per shoot tip. The third experiment: Shoot tip about 0.5 cm long were cultured on MS medium supplemented with 20, 30, 40, 50, 60 gm/l of sucrose. All cultures were placed at 25±2ºC under cool white florescent light (37µmolm-2 S-1) for 16/8 h. photoperiod.

### 3. Statistical analysis

The data were subjected to one way analysis of variance (ANOVA) to assess treatment differences and interaction using the SPSS version 11.0 significance between means was tested by DMRT's Test ($p \leq 0.05$).This experiment with 25 replications per treatments.

## 4. Result and Discussion

After cultured explants on MS medium with vary concentration of (1, 2, 3 and 4 mg/l) BA and (0, 0.5 and 1 mg/l) NAA for initial studied. Clean cultured of explants were subcultured every 3 weeks in the same culture medium for 4 times. Explants grew up and the parameters of growth were studied as:

### 4.1 Effect of NAA and BA on growth of plantlet

Shoot tip about 0.5 cm were used as explants and cultured on MS medium consisted of vary concentration of (0, 1, 2, 3 and 4 mg/l) BA and (0, 0.5 and 1 mg/l) NAA. All parameters which are number of new shoots, leaf, roots, and plants height were recorded after cultured for 12 weeks. It was found that all parameters were significant difference ($p \leq 0.05$) among their treatments as shown in Table 1.

**Table 1:** Average number of new shoot, root, leaf and plant height of Curcuma longa L. on MS medium supplemented with combination of BA and NAA after cultured for 12 weeks.

| MS supplemented with | | number of new shoot* | number of leaf* | number of root* | plant height (cm)* |
|---|---|---|---|---|---|
| NAA (mg/l) | BA (mg/l) | | | | |
| 0 | 0 | 1.8bc | 0.6f | 0.6fg | 2.34gh |
| 0 | 1 | 1.2d | 1.0ef | 1.2def | 3.04ef |
| 0 | 2 | 2.6a | 5.4a | 2.6bc | 4.5b |
| 0 | 3 | 1.6cd | 0.6f | 1.6de | 3.34def |
| 0 | 4 | 1.8bc | 3.2b | 1.8de | 4.78a |
| 0.5 | 0 | 1.0d | 2.2c | 2.2cd | 4.86a |
| 0.5 | 1 | 1.6cd | 1.2ef | 0.6gh | 3.46cde |
| 0.5 | 2 | 1.2d | 0.0 | 0.2h | 2.28gh |
| 0.5 | 3 | 1.0d | 1.8d | 0.6gh | 3.56bcd |
| 0.5 | 4 | 1.6cd | 2.0c | 1.6de | 3.14def |
| 1.0 | 0 | 1.0d | 0.6f | 0.8fg | 3.00ef |
| 1.0 | 1 | 1.4cd | 2.2c | 2.8b | 3.12def |
| 1.0 | 2 | 2.4ab | 1.6de | 3.0ab | 3.6bcd |
| 1.0 | 3 | 2.6a | 1.6de | 2.6bc | 3.44cde |
| 1.0 | 4 | 1.8bc | 4.0ab | 3.2a | 3.36def |

* significant difference ($p \leq 0.05$),

a b c- Average compared mean within column by Duncan's multiple range test ($p \leq 0.05$)

It is evident from Table 1 that among all treatments, the average number of 2.6 and 2.4 new shoots were the highest. These new shoots were cultured on MS medium supplemented with 1 mg/l NAA and 2 or 3 mg/l BA, ( respectively) . MS medium supplemented with only 2 mg/l BA also produced the highest average number of new shoots (2.6 shoots), number of leaves (5.4 leaves) and optimum number of roots (2.6 roots per shoot) and plant height (4.5 cm). As Shukla et al.(2007) had done with Curcuma angustifolia Rozbi which used 3 mg/l BAP could produced 6.9 shoots per explants within 6 weeks . Nasirujjaman et al.(2005) had done with Curcuma longa and cultured young shoot on WPM medium supplemented with 4 mg/l BAP which was the best medium to regenerated new shoot (6.25 shoots per plant) within 2 weeks. In Zingiber officinale Rosc. which related family to turmeric, was reported by Balachandran et al (1990). Malamug et al. (1991) and Sunitibala et al. (2001) reported that MS medium containing 2.0 mg/l BAP and 1 mg/l NAA was able to regenerate the optimum clonal propagation of turmeric by rhizome bud culture.

**Table 2:** Average of new shoots per section of Curcuma longa which cultured on MS medium supplement with 3 mg/l BA for 4 weeks.

| trimming in longitudinal section | Average of new shoot (shoot)* |
|---|---|
| Not trimmed (controlled) | 2.20 c |
| 2 sections | 4.30 a |
| 3 sections | 3.50 b |

* Significant difference ($P \leq 0.05$)

abc - Average compared mean within column by Duncan's multiple range test at ($p \leq 0.05$).

**4.2 Induced new shoots from trimming shoot tip**

After trimming shoot tip in longitudinal section to 2 and 3 sections, all of sections were cultured on MS medium supplemented with 3 mg/l BA. After cultured the section of shoot tip for 4 weeks, many new shoots were regenerated at the base of section which contract to the medium in each sections and the result were recorded in Table 2. When compared the average number of new shoots which regenerated from each sections. It was significant difference ( $p \leq 0.05$) from each other. Shoot tip which trimmed in half (2 sections) gave the highest number of new shoots (4.3 shoots) when compared to the control (2.2 shoots) and trimmed in 3 sections (3.5 shoots) was the second.

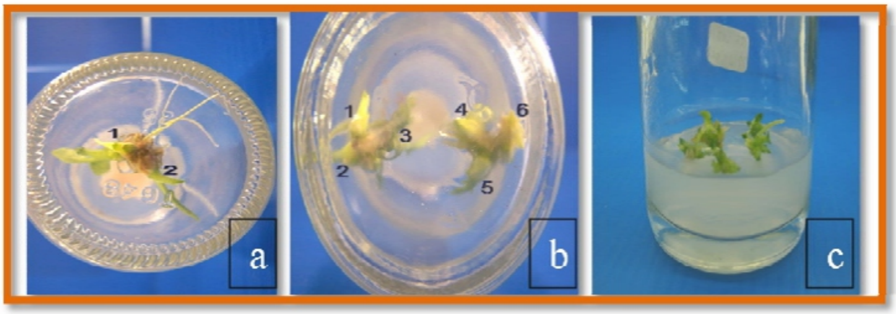


**Figure 1:** New shoots regenerated from section which cultured on MS medium supplemented with 3 mg/l BA for 4 weeks a) no trimmed b) 2 section c) 3 sections.

As Balachandran et al. (1990) reported a proliferation rate of 3.43 shoot/bud from Curcuma sp. after growing the terminal bud on MS medium supplemented with 13.32 µMBA for 4 weeks. Salvi et al. (2002) also reported that shoot multiplication rates of 4.2, 3.5 and 6.6 shoots/explants for 8 weeks in liquid medium supplemented with 1µM NAA and BA, kinetin or 2iP (10µM each), respectively. Prathanturarug et al. (2003, 2005) also reported a high frequency shoot multiplication (18.22 shoots/explants) after culturing terminal bud explants on MS medium supplemented with 18.17 µM thidiazuron for 12 weeks. Ora-Ubon (1991) reported that trimmed shoot tip of Curcuma sparnifolia Gagnep were increased new shoot tip more than no trimming. Phaephun et al. (2006, 2007) had trimmed

Curcuma paviflora hybrid to 2, 3 and 4 section. The result showed that 2 sections gave the highest new shoots and 3 sections was the second.

**4.3 Effect of sucrose concentration for shoot induction**

When cultured young shoot tip about 1 cm. long on MS medium supplemented with vary concentration of (3, 4, 5, 6 and 7%) sugar for 12 weeks. The result showed that plant grew up and their were significant different ($p \leq 0.05$) between their parameter except number of root was not significant difference (Table 3). However, a significant difference increases in shoot length, number of leaf, leaf width and size of root were observed. In MS medium supplemented with 6% sugar gave the highest average new shoots per bunch also number of leaves per bunch, leaf width and size of root where as 13.4 shoots, 56.8 leaves, 2.25cm, and 2.1cm, respectively. Numbers of roots in each treatment were 1.7 – 2.1. In MS medium supplemented with 4 % gave the highest average number of root length where as 14.15 cm. Sucrose is widely used as a standard carbon source for plant tissue culture, and different concentrations and different osmotic environments have been used. Barthakur and Bordoloi (1992), Sanghamitra and Nayak (2000) Sunitibala et al. (2001) and Adelberg and Cousins(2007) reported that MS medium supplemented with 6% sucrose led to increased turmeric plant size, leaf and root. (As Das et al. (2010) reported that 2% sugar that low concentration of sugar could be best for in vitro multiplication of Curcuma sp. However high concentration of sugar source has been found to be ideal for in vitro microrhizome production in Zingiber officinale ( Zheng et al., 2008), but Raghu (1997) produced microrhizomes turmeric on MS medium supplemented with 10%sucrose.

**Table 3:** Effect of concentration of sugar in MS medium on number of shoot per bunch, number of leaf per bunch, leaf width, leaf petiole length, leaf length, number of root, root length, and size of root of Curcuma longa L. after cultured for 12 weeks.

| Sucrose Conc. | No. of shoot/bunch * | No. of leaves/bunch* | Leaf width* | Leaf Petiole Length* | Leaf length* | No. of root ns | Root length* | Size of root* |
|---|---|---|---|---|---|---|---|---|
| 0 | 3.2f ±0.971 | 12.6f ±4.540 | 2.5b ±00.098 | 9.7ab ±0.405 | 7.6 a ±0.366 | 0.2 ±0.152 | 0.51f ±1.943 | 1b ±0.006 |
| 3% | 6.9e ±2.377 | 39.8e ±9.070 | 2.71a ±0.228 | 10.81ab ±0.977 | 8.7 b ±0.777 | 1.7 ±0.163 | 1.53 e ±1.955 | 1 b ±0.133 |
| 4% | 8.9d ±2.280 | 46.5c ±4.230 | 1.89b ±0.102 | 10.42ab ± 0.453 | 9.09b ±0.679 | 1.6 ±0.314 | 14.15 a ±1.824 | 1.2 b ±0.166 |
| 5% | 11.9b ±3.528 | 44.9d ±11.27 | 2.07b ±0.351 | 11.0 a ±1.115 | 8.9b ±0.619 | 1.9 ±0.20 | 11.75b ±1.608 | 1.5ab ±0.276 |
| 6% | 13.4a ±1.653 | 56.8a ±6.130 | 2.25b ±1.097 | 8.65 ab ±0.922 | 7.175a ±0.28 | 1.8 ±0.29 | 8.9d ±1.654 | 2.1 a ±0.314 |
| 7% | 10.7c ±1.046 | 50.5b ±3.339 | 2.2b ±0.453 | 7.25c ±0.047 | 9.1b ±0.471 | 2.1 ±1.044 | 10.6c ±0.843 | 2.1a ±0.110 |

* Significant difference ($P \leq 0.05$)

abc - Average compared mean within column by Duncan's multiple range test at ($p \leq 0.05$)

Size of root: Small and thin, diameter about 0.5- 1mm = 1,

Medium: diameter about 1-1.5 mm = 2,

Large: diameter more than 1.5 mm = 3,

Number of root: 1 - 5 roots = 1, 6 -10 roots = 2, More than 11 roots = 3.

## 5. Conclusion

Shoots tip of Curcuma longa L. about 0.5–1cm long were used as explants. These explants were cultured on MS medium supplemented with vary concentration of (1, 2, 3 and 4 mg/l) BA and (0 0.5 and 1 mg/l) NAA for initial studied. Clean cultured of explants were subcultured every 3 weeks in the same culture for 4 times. Explants grew up and all parameters were significant difference among treatments. The highest average number of new shoots (2.6 and 2.4 new shoot) were came from explants which cultured on MS medium supplemented with 1mg/l NAA and 2, 3mg/l BA, (respectively) and MS medium supplemented with only 2mg/l BA also produced the highest average number of new shoots (2.6 shoots), number of leaves (5.4 leaves) and optimum number of roots (2.6 roots per shoot) and plant height (4.5 cm).

After trimming shoot tip in longitudinal section to 2 and 3 sections, and cultured on MS medium supplemented with 3 mg/l BA. Many new shoots were regenerated at the base of sections. It was significant different ($p \leq 0.05$) between their treatments. Shoot tip which trimmed in half (2 sections) gave the highest number of new shoots (4.3 shoots) when compared to the control (2.2 shoots) and trimmed in 3 sections (3.5 shoots) was the second. MS medium supplemented with 6 % sugar was significant different ($p \leq 0.05$) and gave the highest average on number of shoot and leaf per bunch, leaf width, leaf petiole length, leaf length, number of root, root length, and size of root.

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# An International Delphi Study to Build a Foundation for an Undergraduate Level Lean Manufacturing Curriculum

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## ABSTRACT

*This paper is based on research that was conducted to identify and validate the competency areas included in the body of knowledge developed by a consortium of the Society of Manufacturing Engineers (SME), the Association for Manufacturing Excellence (AME), and the Shingo Prize for three levels of certification examinations in lean manufacturing, namely Bronze, Silver, and Gold. The focus of the paper is to delineate the results obtained from the Bronze level certification exam that can be applied to lay a foundation for developing an undergraduate-level curriculum in lean manufacturing. A modified Delphi technique that included a pre-Delphi round followed with three rounds of Delphi questionnaire iterations was used in the study. Seventy-six experts, from six different countries, selected to serve on the Delphi panel rated the importance of competency areas for testing at each level of lean certification using a 5-point Likert scale and provided additional comments. A convergence of opinion on the competency areas provided a basis for validating the body of knowledge. Forty-two prioritized competency areas that emerged from the study were grouped into five major domains: (a) Enablers for Lean, (b) Lean Core Operations, (c) Business Core Operations – Support Functions, (d) Quality, Cost and Delivery Measures, and (e) Business Results.*

***Keywords: Body of Knowledge; Curriculum; Certification; Delphi Technique; Lean Manufacturing; Validation.***

## 1. Introduction

The focus of lean manufacturing is to obtain highest quality, lowest cost, and shortest lead time by continuous elimination of waste (Dennis, 2002). There are various literatures available on lean manufacturing, but none of them unify its body of knowledge. The Association for Manufacturing Excellence (AME) conducted a survey on North American manufacturing companies to explore the degree of awareness about lean techniques among the senior leaders (Dennis, 2002). The results of the study indicated that 41% of the respondents did not really know about lean; 34% were familiar with the idea of lean, but did not know how to go about achieving it; 22% indicated that their firm was on the lean path but they were not obtaining desired results; and 3% indicated that they were on the lean enterprise transformation journey and were obtaining great results (Koenigsaecker, 2005). These results reflect a lack of knowledge about lean principles among a majority of senior leaders in manufacturing firms, as well as their inability to apply the right tools to obtain desired outcomes.

With recent advances and intense competition in the field of manufacturing, there is a great need to educate and employ qualified professionals. The need for a certification exam in lean manufacturing was revealed in a survey conducted on more than 1100 manufacturing industry respondents by the Society of Manufacturing Engineers (SME) (Hogan, 2005). Eighty-three percent of the participants in the survey mentioned that it was either critical or very important to develop an industry standard for lean certification. Moreover, a well-constructed job analysis study would be an essential foundation for a valid, reliable, and legally defensible professional certification program (Wehrle, 2005).

A role delineation study was conducted for the three levels of the SME/AME/Shingo's lean manufacturing certification exam (Shah, 2007). The purpose of this paper is to apply the results obtained from the study toward laying a foundation for developing an undergraduate-level curriculum in lean manufacturing.

## 2. Review of Literature

The Society of Manufacturing Engineers (SME), the Association for Manufacturing Excellence (AME), and The Shingo Prize for Excellence in Manufacturing (Shingo) collaborated to develop a highly desired lean credential of competence. A description of each of the three levels is as follows:

Level 1: Bronze Certification – measures the knowledge of basic principles, concepts, and tools of lean as applied to factory, office and service, team facilitation, and appropriate measurement of results.

Level 2: Silver Certification – measures the capability of lean practitioners in applying lean principles and tools to drive improvements and show measurable results plus orchestrate the transformation of a complete value stream.

Level 3: Gold Certification – focuses on evaluating the practitioner's strategically focused knowledge and solid understanding of all aspects of lean transformation across the entire enterprise.

The level of difficulty increases from level 1 to level 3, and eligibility criteria also differ on each of these levels. The candidates are to pass a written examination consisting of approximately 150 questions within a three-hour time limit at each level.

### 2.1 Delphi Study

Delphi Technique is a procedure used to obtain consensus on a particular topic through a set of carefully designed sequential survey questionnaires interspersed with feedback from the participants (Delbecq et al., 1975). It is structured to capitalize on the merits of group problem-solving and minimize the liabilities of group problem-solving (Dunham, 1996). Delbecq, Van de Ven, and Gustafson (cited in Jones, 2004) identified five recognized areas of research which have effectively utilized Delphi methodology: (a) determining or developing a range of possible program alternatives; (b) exploring or exposing underlying assumptions or information leading to different judgments; (c) seeking out information which may generate a consensus on the part of the respondent group; (d) correlating informed judgments on a topic spanning a wide range of disciplines; and (e) educating the respondent group as to the diverse interrelated aspects of the topic (pp. 10-11). The Delphi methodology makes the collection of opinions from geographically dispersed experts possible (Delbecq et al., 1975). Moreover, accurate and thoughtful consensus obtained from a group of geographically dispersed experts outweighs the time required to complete the Delphi study. Hence, the Delphi study was used to identify and validate the competency areas needed for developing the three levels of the certification exam.

## 3. Research Methodology

A modified Delphi technique with qualitative and quantitative components was used to survey the participants. The data collection process consisted of a Web-based pre-Delphi study and three rounds of email- and paper-based questionnaires.

An initial list of competency areas was developed based on the review of literature and competency areas included in the existing lean manufacturing certification examination. Responses to a set of demographic questions in the pre-Delphi survey were used to select Delphi panel experts for subsequent Delphi rounds. In Round One, the panel members were asked to provide both quantitative and qualitative feedback on the competency areas. During the second questionnaire round, an analysis made of the first round's results was provided for reference. Qualitative feedback obtained from the open-ended questions for each response was provided verbatim along with possible additions or modifications recommended from Round One. Similarly, in Round Three, an analysis made from Round Two was provided to the panel of members and final modifications recommended by them were incorporated.

### 3.1 Data Collection

The sample for this study was obtained by contacting members from the Society of Manufacturing Engineering (SME) and the Institute of Industrial Engineers (IIE) via email who were interested in lean. The questionnaire in the pre-Delphi round was quantitative in nature with additional spaces provided to the participants to include any additional competency areas that they believed to be important to include in the lean body of knowledge.

The pre-Delphi study obtained responses from 138 subjects, out of which 102 Delphi panel members were selected for the first Delphi round based upon the following reported information, which is listed in order of importance: (a) commitment to serve on the Delphi panel, (b) self-rating of their expertise in lean (greater than or equal to 3 on the Likert scale), and (c) years of experience in lean. During Round One, the Delphi panel members who were selected to participate in the study but did not respond to the Round One questionnaire were contacted to verify whether they were interested in being a part of the study. Based on their responses the Delphi panel was reduced from 102 preliminary members to 76 final members.

The participants were asked to judge importance of a particular competency area for the lean manufacturing exam using a 5- point Likert scale. The following criterion of importance was assigned to the responses provided on the questionnaire, along with an example of how to respond: 4= Extremely important, 3 = Very important, 2 = Important, 1 = Of little importance, 0 = Not important. A "yes" or "no" question was asked to identify the necessity for each specific competency area to be included at each lean certification exam level.

## 4. Data Analysis

After searching the literature and examining the data analysis methods used in different fields of study, the methodology utilized by Tillman (1989) and Shah (2004) seemed to be most applicable to this study. The additional competency areas suggested by participants in the pre-Delphi survey were analyzed and added to the Round One questionnaire under each domain based on researcher judgment and analysis. In Round One, each of the competency areas was given modal and percent of concurrence scores from the pre-Delphi survey results. Data analysis was conducted once all Round One feedback was returned. Each of the competency areas rated in Round One of the Delphi study was given modal and percent of concurrence scores, which were then reflected in the Round Two Delphi questionnaire. Additional comments from Round One that addressed more general concerns about the study were provided in the "Round One Results" document. Data analysis of Round Two was conducted in the same manner as in Round One. Similarly, Round Two results were reported in the Round Three questionnaire. Data analysis of Round Three was performed in the same manner as for Rounds One and Two.

To obtain convergence of opinion, the mean of the standard deviation for each round was calculated. A decrease in the mean standard deviation value indicated a greater convergence of opinion among the panelists. On the basis of the standard deviation scores, the following four categories of the prioritized list were formed (see Table 1): (a) higher mean score, lower standard deviation; (b) higher mean score, higher standard deviation; (c) lower mean score, higher standard deviation; (d) lower mean score, lower standard deviation. A decision of high and low mean and standard deviation was based on the range of results obtained in each category of analysis. An approach followed by Shah (2004) and Tillman (1989) was followed to determine a cut-off point for defining both high and low mean and high and low standard deviation. Higher and lower values of standard deviations were determined based on the median value of standard deviation under each domain.

Competency areas grouped in Category I were considered to be important for candidates to know for the lean certification exam, and there was relative agreement among panel members on their importance. Competency areas in Category II were also considered to be important for the certification but there was less relative agreement among panel members on their importance.

**Table 1:** Matrix to Portray Categories for Prioritization.

| | Standard Deviation in Scoring: Low | Standard Deviation in Scoring: High |
|---|---|---|
| Mean Score: High | I<br>Higher Agreement of Greater Importance | II<br>Lesser Agreement of Higher Importance |
| Mean Score: Low | IV<br>Higher Agreement of Lower Importance | III<br>Lesser Agreement of Lower Importance |

Competency areas in Category III were less important for a lean certification exam than competency areas in Categories I and II, but there was less relative agreement among panel members concerning the competency areas' levels of importance. Competency areas in Category IV were also considered less important for lean certification than competency areas in Categories I and II, and there was relative agreement among panel members on their lower levels of importance.

## 5. Results

The demographic information collected in the pre-Delphi round indicated that the majority of the experts were in the age range of 35-54 with most having a Master's degree. About 44% of the respondents possessed at least one professional certification or license. The majority of them were either at a senior management or mid-management level, while only 5% were college or university faculty. Almost 17% of the panel members were located outside the United States. Their self-rating of the level of expertise in the field of lean manufacturing ranged from medium to very high, with the majority rating themselves as having a high level of expertise. Moreover, a large number of experts had a minimum of 6 to 10 years of experience related to lean.

The panel of experts participated through three iterations of Delphi questionnaires in both hard copy and electronic format, rated competency areas, and offered many valuable comments. Additional competency areas suggested from the pre-Delphi study were added to the Round One questionnaire. The three rounds of the study had response rates of approximately 73%, 79%, and 75%.

Table 2 contains results based on the additional questions asked regarding the importance and overall quality of the study in the Round Three questionnaire. The majority of the Delphi panel experts indicated that the results of this study were either of very high or high importance to the field of lean manufacturing. Moreover, most responses rating the overall quality of the study ranged from very high to high.

**Table 2:** Results on Importance and Overall Quality of the Study from Round Three.

| | Very High | High | Medium | Low | Very Low | TOTAL |
|---|---|---|---|---|---|---|
| | *5* | *4* | *3* | *2* | *1* | |
| Importance of the results of this study to the field of lean manufacturing | 36% | *57%* | 2% | 3% | 2% | 53 |
| Overall quality of study | 32% | *51%* | 15% | 2% | 0% | 53 |

Sample of qualitative responses obtained on the importance and/or quality of the study are listed below:

- "As a lean practitioner over the past 6 years, not having a valid certificate demonstrating proficiency in lean is a drawback. The industry needs an effective method to document and certify individuals, and this study will enable a robust standard to be set."
- "This study was well-developed and was very comprehensive. This is a good model for overall business planning and execution."
- "This study is an important step in validating BOK. "
- "My interest in this survey/study has greatly increased since my professional developmental goal for this year is to obtain a lean certification!"
- "I feel the study was prepared very well and complete."
- "The study is the most comprehensive that I have ever seen in my career. I hope that it will serve to standardize and further lean principles beyond the current narrow-minded focus of cost cutting..."

A list of prioritized competency areas for lean Bronze level examination based on mean and standard deviation scores is given in Table 3. The competency areas have been grouped under each domain and are categorized by low and high standard deviations. The competency areas in bold with asterisks (*) represent a high mean and low standard deviation (higher degree of consensus among panel members), and those not in bold represent a lower degree of agreement among panel members with either high or low mean values. Y% represents the "Yes" percentage of responses obtained from the "Necessary for Certification Exam?" question.

The prioritized list of competency areas obtained for the Bronze level examination indicate the important areas to be included on the body of knowledge of the lean manufacturing certification exam. A curriculum model can be designed based on these competency areas for an undergraduate level program in lean manufacturing.

**Table 3:** Prioritized list of Competency Areas from the Lean Bronze Certification Level.

| Competency Areas | Mean | SD | Y% |
|---|---|---|---|
| I. ENABLERS FOR LEAN | | | |
| ***1.1.4. Principles of lean leadership** | **3.96** | **0.187** | **100** |
| ***1.2.6. Ergonomic, clean and safe work environment, and results** | **3.79** | **0.453** | **98.2** |
| ***1.1.5. Lean corporate culture** | **3.09** | **0.405** | **96.2** |
| 1.2.3. Teamwork | 2.39 | 0.685 | 92.3 |
| ***1.2.2. Employee training and development** | **2.21** | **0.559** | **81.8** |
| 1.2.1. Principles of empowerment | 2.21 | 0.674 | 82.1 |
| ***1.2.4. Suggestion/Feedback/Appraisal System** | **2.05** | **0.553** | **81.8** |
| ***1.1.3. Long and Short-term Planning** | **2.04** | **0.499** | **81.5** |
| 1.1.1 Business vision, mission, values, strategies and goals, including resource allocation | 1.95 | 0.61 | 15.8 |
| Motivation Theory | 1.75 | 0.714 | 10.7 |
| 1.1.2. Respect for Humanity and Social Responsibility | 1.29 | 0.731 | 9.1 |
| Socio-technical Systems | 1.18 | 0.601 | 5.5 |
| 1.2.5. Employee Turnover, Absenteeism and Compensation | 1.14 | 0.718 | 1.8 |
| II. LEAN CORE OPERATIONS | | | |
| ***2.4.3. Cellular and Continuous Flow** | **3.93** | **0.26** | **100** |
| ***2.4.2. Just-in-Time Operations** | **3.91** | **0.29** | **100** |
| ***2.4.1. Systematic identification and elimination of waste** | **3.91** | **0.348** | **98.1** |
| ***2.4.4. Lean Tools for Continuous Improvement** | **3.86** | **0.398** | **100** |
| 2.3.1. Suppliers | 2.23 | 0.708 | 23.2 |
| ***2.1.1. Operational Vision and Strategy** | **2.04** | **0.533** | **10.7** |
| 2.2.1 Product Design and Development | 2.04 | 0.731 | 27.3 |
| Facilities Design and Layout | 1.91 | 0.606 | 25 |
| Six Sigma/Problem-solving Techniques | 1.84 | 0.682 | 14.5 |
| Quantitative Decision-making Techniques | 1.78 | 0.686 | 15.1 |
| 2.3.3. Distribution and Transport Alliances | 1.77 | 0.572 | 7.3 |
| 2.3.2 Customers | 1.4 | 0.776 | 14.3 |
| 2.2.2. Product Market Service | 1.21 | 0.647 | 7.1 |
| Optimization Techniques | 1.18 | 0.71 | 5.4 |
| Simulation Technique | 1.14 | 0.743 | 7.3 |
| III. BUSINESS CORE OPERATIONS – SUPPORT FUNCTIONS | | | |
| ***3.1.1 Administrative Vision and Strategy** | **2.07** | **0.563** | **83.9** |
| Supply Chain Logistics | 1.91 | 0.64 | 7.3 |
| 3.1.2. Alignment, Systematic Business, and Service Process Design | 1.86 | 0.616 | 5.5 |
| Materials Requirement Planning (MRP)/Enterprise Resource Planning (ERP) | 1.8 | 0.737 | 9.4 |
| Lean Accounting | 1.34 | 0.769 | 9.1 |
| IV. QUALITY, COST & DELIVERY MEASURES | | | |
| ***4.1.1 Quality Results** | **3.8** | **0.447** | **100** |
| ***4.2.1 Cost and Productivity Results** | **3.77** | **0.632** | **98.2** |
| ***4.3.1 Delivery and Customer Service Measurement** | **2.79** | **0.594** | **89.1** |

| | | | |
|---|---|---|---|
| Quality Management System (QMS) | 1.96 | 0.719 | 14.8 |
| International Organization for Standardization (ISO) and Lean | 1.79 | 0.706 | 7.3 |
| V. BUSINESS RESULTS | | | |
| Lean Business Metrics | 1.96 | 0.533 | 41.1 |
| 5.1.1 Customer Satisfaction Results | 1.96 | 0.687 | 12.7 |
| 5.2.1. Profitability Measurement | 1.4 | 0.743 | 18.9 |
| Total Supply Chain Cost | 1.3 | 0.737 | 5.6 |

## 6. Conclusion

This role delineation study was conducted to refine the body of knowledge for the SME/AME/Shingo lean manufacturing certification examinations. A Delphi technique with both qualitative and quantitative components was used to collect data, and to obtain feedback and suggestions from experts in the field of lean manufacturing. A convergence of opinion on the competency areas provided a basis for validating the body of knowledge for Bronze, Silver, and Gold levels of lean certification examinations.

It is noteworthy to recognize the high level of professionalism of the panel of experts that participated in the study exemplified through their prompt and thorough responses. The comments and ratings provided by these experts were good indicators of the fact that the study was of high importance for the lean manufacturing discipline, and that it was also of high quality. Forty-two prioritized competency areas that emerged from the study were organized as a body of knowledge and were grouped into five major domains: (a) Enablers for Lean, (b) Lean Core Operations, (c) Business Core Operations – Support Functions, (d) Quality, Cost and Delivery Measures, and (e) Business Results. This body of knowledge serves as a model for developing an undergraduate-level curriculum in lean manufacturing.

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