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From Editor’s Desk

The importance of manufacturing sector in national growth and economy is recently realized by the policy makers. The success of any firm revolves around how well it manages its resources and operations. A higher degree of integration of resources with the capabilities of human resource and a synergy with supply chain management functions are essential. Strong supply chain management can improve a firm's reputation both with consumers and business partners. Manufacturers must keep a close watch on three key drivers: Quality, efficiency and productivity. However, these three functions often have conflicting objectives. Optimization of these objectives will result in reduced manufacturing cost and enhanced quality leading to customer satisfaction and market share which is essential for the survival in the competitive open market scenario.

At such a juncture of time, this **Volume 11, No.1, 2** will make modestly contribution towards the same goal by bringing together researchers, academicians, manufacturers and managers from industry on the same forum.

CONSULTING EDITOR & EDITOR IN CHIEF

Call for papers: Vol. 12, No.1, 2019

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A Review on Optimization and Analysis of Various Sheet Metal Forming Processes

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Abstract—The review focused in this paper is consist of various metal forming processes and methods used to analyse and optimise forming process. Various processes are introduced for high rate of production and formability. Formability and test methods are discussed together with the variables occurred in sheet metal forming process. Defects occurred during forming process are highlighted and important factors, work concerning the process principle, deformation of work piece, interactions of parameters are discussed. The methodical review of literature based on the optimization methods and analysis is highlighted in the paper corresponding to future research in the field of material forming.

Keywords: *Sheet metal forming, FEA, DOE, Simulation, Statistical methods, Optimization.*

I. INTRODUCTION

Computer aided engineering (CAE) approaches are widely applied in metal forming integrated design. The implementation of advanced high strength steels, has improved the incidence of spring back. Subsequently the request for tools concerned with spring back reduction and optimization is also increases. The factors which changes the formability of the part are determined by using formability study. Frequency and mode shapes of assemblies are defined by vibration analysis. The cost related to prototypes and introduction to market are dropped due to FE simulation which are based on modern computational tools and intricate mathematical models [1].

Before development of tool numerous industrial formations are carried finite element simulation to understand formability of sheet metal parts, due to simulation tools and high speed computer technology. Much cost is involved for individual forming tool in every forming process. Forming defects such as rupture, wrinkling, thinning are predicted and controlled with the aid of CAE tools. The relation between the numerous forming parameters are considered with the application of design of experiments (DOE) procedures [2].

II. LITERATURE REVIEW

Metal forming is considered as integrated design of product and process. Die set up, material characteristics and process defects may affect the quality of product. Use of computer aided modelling, simulation, manufacturing and FEA are applied widely to integrate process set and shape design. By considering different punch and die clearances, several experiments were performed. Experimentally it is validated that, spring back and thinning effects were linearly increasing beyond a particular clearance and causes fracture propagation for every thickness of sheet metal [3]. Effects of significant parameters such as blank thickness, elastic layer thickness and hardness, blank property and punch elements on spring-back are extensively examined by FE simulations and experimentations. Pure copper and stainless steel are used as materials for trials. A negligible reduction is detected for spring back by increasing the thickness but the dimensional variations before spring back is increased because of non-uniform deformation characteristics. It is required to select accurate size of punch, as it leads to a momentous effect of spring-back, [4]. Ironing behaviour on thickness scattering regarding temperature was studied and simulating ironing process was developed. FE simulation for temperature and deformation in warm forming process is carried out using LS-DYNA. Accuracy in the simulation process can be increase by considering more number of integration points, [5]. At component design stage, the FE code is adopted to evaluate stamping force and to obtain overview of the general formability. Die compensation is an instance of this process. Accuracy of the linear coefficients can be affected by the accuracy of stamping nodal force [6]. Optimization of deep drawing process can be performed using genetic algorithm to investigate effect of related parameters. Variety of forming parameters can be considered in combinations of control system. Effect of punch, die profile and drawing force are the most vital parameters in metal forming [7]. Small variations in die radius profile shape is resulted in expressively decrease tool life. Small and localized variations from a die profile shape are examined and the effect on tool life is determined by FE simulation by explicit finite element code. Small defects at the die corner radius can effect a major rise in local contact pressures affects adverse changes in tool life. [8]. The probability of failure or the reliability of the design can be efficiently evaluated by the most probable point (MPP) analysis based on response surface methodology (RSM) [9]. Parts defect is observed due to displacements of the press components and punch tool. The machine has influence on work piece quality. This impact is important in the metal forming as a result of resulting ram movements and high forming forces. For representing the machine characteristics a hybrid multi-body simulation is a suitable approach [10]. The several process parameters such as friction conditions, expansion ratio and die cone angle as the input process condition are critically analysed. Signal to noise ratio (S/N) analysis and the analysis of variance (ANOVA) methods are used to find the optimal combination of the process parameters. Taguchi method is used to find the effective optimised process parameters and ANOVA is used to find percentage contribution [11]. The process parameters chosen for the flow forming method are speed of the mandrel, roller radius and axial feed of the roller. Effect of process parameters on mean diameter of flow formed tube are investigated by taking trials on a single roller flow forming machine using RSM. Roller feed and roller radius are the most important parameters effecting the mean diameter of flow-forming process. Strength of the material can be increase by addition of manganese, which controls the grain structure and produces superior strength [12]. The force exerting on the travelling tool is evaluated by examine the deformation behaviour, the tool path on the punch load and blank thickness. Sheet thickness, part geometry, wall angle and distribution of equivalent plastic strain is also discussed. Optimization of the incremental forming process of sheet metal is also determined by the numerical simulation [13]. Applications of the existing DOE and RSM techniques are used in the sheet metal forming component followed by vibration analysis and gauge optimization. Forming variables and their influence on formability and thinning of the sheet metal is given by DOE. Thinning of the bracket can be reduced by keeping friction and thickness as low as possible [14].

Multi objective reliability-based design optimization (MORBDO) procedure is proposed to highlight the vehicle door design. The optimization of the parameters is carried out using Multi objective particle swarm optimization (MOPSO) algorithm. Pareto frontier of reliable solutions can be generated by the proposed optimization procedure [15]. The global Pareto solutions are found by model based on the response surface, process combination of the blank holding force and the stamping velocity. Advantage of the multi-objective genetic algorithm are studied to optimize the responses of the effective parameters. A set of reliable solutions is proposed considering all-purpose optimization method to deal with complex hot stamping processes. This approach is verified as effective and robust for finding the optimal parameters by conducting experimental trials [16]. Kriging interpolation and Sequential Quadratic Programming (SQP) algorithm are used to optimise forming parameters in multistep stamping tool. The numerical technique are suggested to decrease the number of forming stages and therefore increasing the process productivity. Finite element code ABAQUS is developed using integrated optimization approach for constructing the objective function as per the design variables and numerical results are validated with the experimental tests [17]. FEA and DOE are used to optimise the effective process parameters for warm forming of lightweight component to offer fast and relatively precise design of process. When the punch and die friction are maintained at the similar level, decrease of formability is observed with rising coefficients of friction [18]. Experimentations are conducted to control the spring back using optical measurement technology for metal forming analysis and optimisation. It is becoming more affordable to use optical measurement equipment and software based on photogrammetric [19]. The principles of multi-point die forming (MPDF) and multi-point press forming (MPPF) are defined and then the rules to control a scope of an element are stated. A flexible forming technique proposed for sheet metal part, multi-point forming (MPF) technology is also discussed. Large size steel plate is bent with the line heating technique, in which geometrical precision and forming quality is mainly subject to experience in shipbuilding field. Using CAD data, shape of the element group changed rapidly by various MPDF methods like sectional MPDF for big size sheet forming, flexible blank holder procedure for thin sheet metal forming, closed loop MPDF for great accuracy forming and reverse engineering were investigated in detail. In finds application in various field of engineering like vehicle engineering, aeroplane engineering and medical engineering [20]. Many intricate sheet metal forming problems can be solved using FE simulation as, inverse methodologies and alternative approaches. The shape optimization and parameter identification problems are solved using analysis and simulation technique. Parameter identification problems is to evaluate the input parameters that lead to the best precise results related to experimental trials. Shape optimization is used to determine initial geometry of a given component to provide anticipated final geometry after the process. A finite element codes are developed using optimisation approach to solve optimisation approach. Final results of both approaches are tested using algorithm and found satisfactory [2]. Linking mathematical optimisation with simulation shows good contribution in improvement of product and overall cost reduction. Numerous expertise in optimisation is required in metal forming process, which will be the obstacle in general industrial application. Only the most important design variables are selected by screening to minimise the depth of optimisation problems and solved using well organised optimisation algorithm. Optimisation problems and structured method for solving these problems to improve their products and processes, allows non-optimisation specialists to apply optimisation practises. The optimisation approach is effectively applied in a hydroforming process to validate the importance of the optimisation in metal forming processes [21]. Concurrent engineering approach using integrated system greatly reduce cost and the development time for availability of product in market. At the time of formability analysis an optimal die face is identified, as stamping parts are sharp edged and complex in geometry. This type of analysis can significantly decrease the trial period and forming failure percentage. Design process time is reduced drastically by using the solid model of the component. This model is gone through interference analysis and structural analysis to avoid defects [22]. The increased rate of production is explained using example of gun smiting which was a craft-bound cottage industry earlier the industrial revolution shown in Figure 1. In 1848, industry was able to produce only 10,000 rifles per year although the requirement was more. When the rifles were finally used in 1866, it was required 26 years to make 300,000 [23].

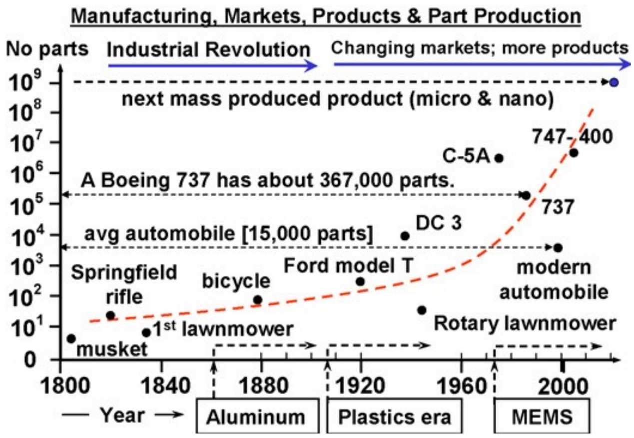

Figure 1. The upsurge in intricacy of parts from the industrial revolution [23]

III. Conclusion

Literature explained in the paper shows that much more things are still remains in all areas of metal forming. Manufacturing with lightweight materials and warm forming are vigorously used in production processes nowadays. In changing economic scenario, aid of CAE is vital in metal forming technology to provide the changes in technology and productivity aspect.

The future work should focused on improve the optimum set of effective process parameters as tool path, friction, wall angle, sheet thickness, clearance, tool diameter, spring back characteristics, geometrical accuracy, punch load and forming limit. The defects in the forming process can be minimised by optimization through properly selecting the effective process parameters. Optimization methods, FE simulation & analysis of process create the major impact in defects reduction in sheet metal forming process.

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Experimental Study and Optimization of Process Parameters in Electric Discharge Machining for Material Removal Rate in Carbon Tool Steel (SK2MCr4) Using Copper Electrode

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Abstract- Tool steels are usually worked upon to give them desired shape and creating features for holding/fixing before final heat treatment and finishing. Adding new features/geometry elements after hardening and finishing is extremely difficult with conventional machines and the tools. Electric discharge machining is a technique which can be employed for machining of heat treated and finished tool materials without loss of their important properties. Alternative application of special cutting blades needs new geometric features likes holes to be created for holding and fittings. Being a new application study on machining parameters for optimization is needed for such work materials. The analysis and optimization of MRR became finished the usage of Taguchi approach to locate the contribution of various process parameters on MRR. The principle results from the present experimental work are summarized because the maximum prompted parameter with admire to MRR. The percentage contribution of the current, pulse on time and servo voltage are found to be 64.29%, 25.78% and 4.04% respectively on material removal rate in fractional DOE technique, whilst in full factorial DOE method, the share contributions are 62.05%, 26.39% and 1.09% respectively. The finest optimal value of current, pulse on time and servo voltage for maximizing MRR is found as 12 A, 60 **µ**s and 3 V respectively.

Keywords- MRR, Taguchi Method, ANOVA Analysis, SK2MCr4, Copper

1. Introduction

Electric Discharge Machining (EDM) is an electrically thermal nonconventional machining process, wherein electrical energy is used to generate an electrical spark and elimination of material mainly because of the thermal energy of the spark. EDM is a modern machine, which can be used for drilling, milling, grinding and other conventional machining operations. The EDM is now one of the most considerable accepted technologies for metal machining and the complicated 3D shapes can be machined by way of simple size tool electrode. In the manufacturing enterprise, EDM is typically used for the production of mold and die components. The EDM is used because the ability of the machining manner is very accurate in creating complex or simple shapes within parts and assemblies. For the reason that inception of EDM, lots of theoretical and experimental works were executed to find the fundamental approaches involved. There is no direct physical contact between the electrodes; consequently, no mechanical stresses are developed on the work piece. The precise manufacturing parameters of the process are the material removal rate (MRR) and electrode wear rate [1, 2]. EDM techniques have developed in many areas. Trends on activities done by using researchers depend on the industry requirement, available material and contemporary manufacturing technologies.

2. Need of Optimization in EDM

Optimization is used for performing in order to obtain the best (optimum) desired result under the given specified experimental conditions. The most significant objective is either to minimize the effort/time required or maximize the desired results/benefits of the product or advantage in term of economics. In EDM, traditional method of choice of parameters combinations does not provide satisfactory or desired results. Optimization of process parameters of EDM has been handled as single objective optimization process and multi-objective optimization problem. Design of experiment (DOE) technique like Taguchi method is used to lessen the experimental runs in real way. According to this, it is best method for optimization of process parameters-pulse on time, pulse off time, current, servo voltage and many others of EDM [3].

Die-sink EDM is used to machine extremely hard materials, which are might be tough to system inclusive to machine such as tool steels, alloys, tungsten carbides and forth so. [4-6]. Proper choice of EDM parameters such as discharge current, pulse on time, pulse off time, discharge voltage, servo voltage, voltage gap, fluid pressure, dielectric fluid, duty cycle, etc. [7-11]. From the literature overview it can be visible that copper is the most broadly used as EDM electrode for its excellent electric and thermal resistance (ASM, 1990). A copper electrode has better EDM wear resistance than brass and graphite electrodes. It is the best material for the removal of material along with machining parameters such as the discharge current, pulse on time and servo voltage [12-16]. SK2MCr4, which is a widely used material within the manufacturing of tool steel blades, cutting tools and so on. From the numerous literature surveys, it is far understood that a whole lot work has not been executed for the machining of machining of SK2MCr4 carbon tool steel material [17, 18]. Design of experiment (DOE) technique like Taguchi method is used to lessen the experimental runs in actual manner. Analysis of variance (ANOVA), correlation and regression is employed to study the performance traits at different condition according to DOE. In step with these, it is best method for optimization of selected process [19-21].

In the present work experimental study is carried out for electric discharge machining of SK2MCr4 carbon tool steel material. The evaluation is completed with the aid of using design of experiment (DOE) and analysis of variance (ANOVA) strategies for most advantageous material removal rate.

3. Material and Methods

The present work through the complete set of experimentation is carried out on an Electric Discharge Machine, ZNC-250 (die-sinking type) available in the workshop of the Mechanical Department, CTAE as shown in Fig. 1 is used. ZNC-250 has the provisions of programming in the Z-vertical axis-control and manually operating X and Y axes. Divyol spark errossion oil-25 (specific gravity= 0.750 @ 29.5°C, Min.) was used as dielectric fluid.

Fig.1. Experimental set-up for EDM.

3.1 Control parameters and their levels

First begin with five levels and three parameters: contemporary (i), pulse on time (T_{on}) and servo voltage (v) are varied as a substitute at the same time as pulse off time (T_{off}) as a steady. At some point of the experiments material removal rate has been referred to down.

After dropping the redundant statistics L9 orthogonal array turned into fashioned with three parameters and three levels given in Table 1.

Table 1: Experimental levels of independent parameter

S. No.	Symbols	Independent parameters	No. of levels	Level 1	Level 2	Level 3
1.	T_{on}	Pulse on time	3	20	60	100
2.	V	Servo Voltage	3	3	4	6
3.	I	Current	3	4	8	12

4. Results and discussion

The fractional DOE approach is primarily based on the Taguchi DOE. Experimental run table generated the use of orthogonal array and now after performing the experimentation as proposed in the Fig. 2, the consequences of optimum material removal rate are collected as shown in Fig. 3 for current, pulse on time & servo voltage are 12 A, 60 **μ**s & 3 V. The Fig. 4 additionally indicates the value of S/N ratio obtained by Minitab-17 software using 'The larger is the better' technique [22, 23].

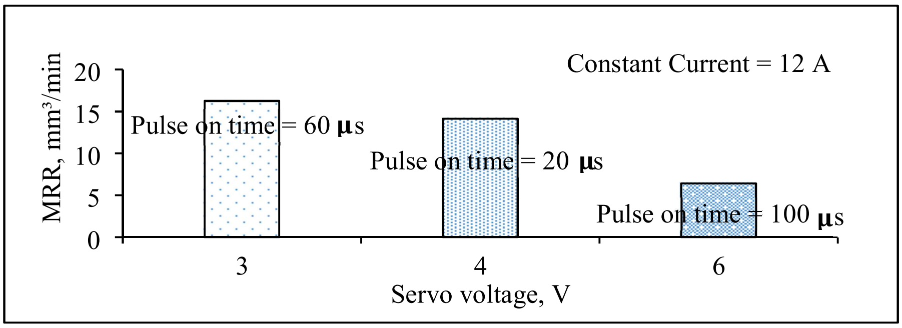

Fig. 2. Optimum value of I, T_{on} & V of MRR

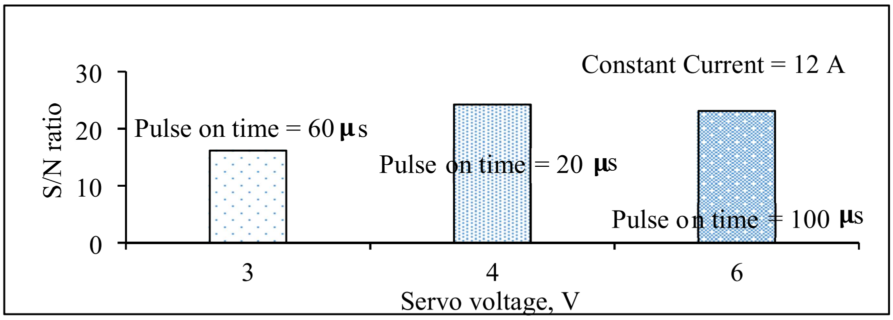

Fig. 3. Optimum value of I, T_{on}, & V of S/N ratio

4.1 Main effect plots for MRR

It can be evaluated from the main effect plots of means that to reap the optimized value of material removal rate, the current must be set to its maximum value (12A), pulse on time and servo voltage i.e. 60 **μ**s and 3 V respectively as because of optimization, largest MRR must be employed in Table 2 and Fig. 4.

Table 2: Rank Table for MRR with process parameters

Level	**I**	**T_{on}**	**V**
1	3.266	4.759	8.867
2	8.051	10.399	8.129
3	12.319	8.477	6.639
Delta	9.052	5.640	2.228
Rank	1	2	3

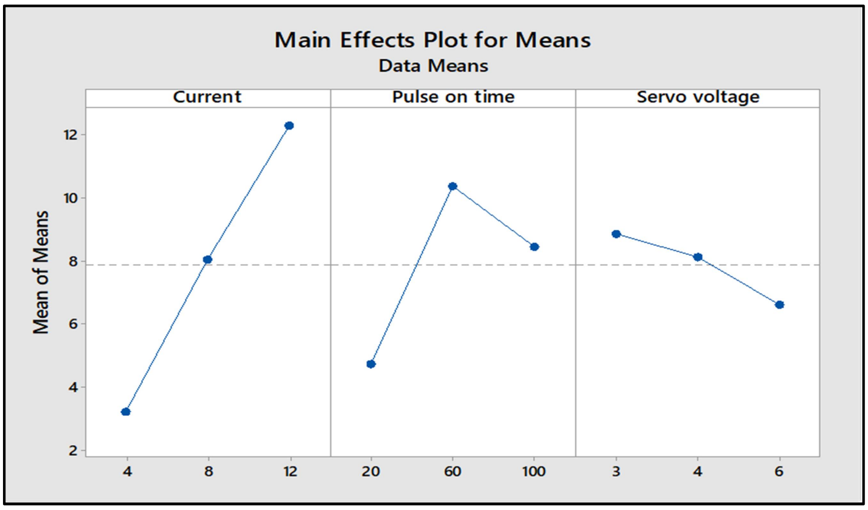

Fig. 4: Main effect plots of different parameters on MRR

4.2 Analysis of S/N Ratio for MRR

Fig. 5 suggests the primary effect plots of S/N ratio of different parameters terms such as current, pulse on time and servo voltage on MRR. Here we select the options for higher or 'larger is better (LB)'. It is observed from this Fig. 5 and Table 2 that MRR have highest S/N ratio for current at the level 3, but for the case of T_{on} (μs) it is having highest for the second level and for servo voltage at first level. Similarly MRR have optimal value for current (I) at 4 A, pulse on time (T_{on}) at 60 μs and servo voltage at 3 V while pulse off time as a constant at 6 μs.

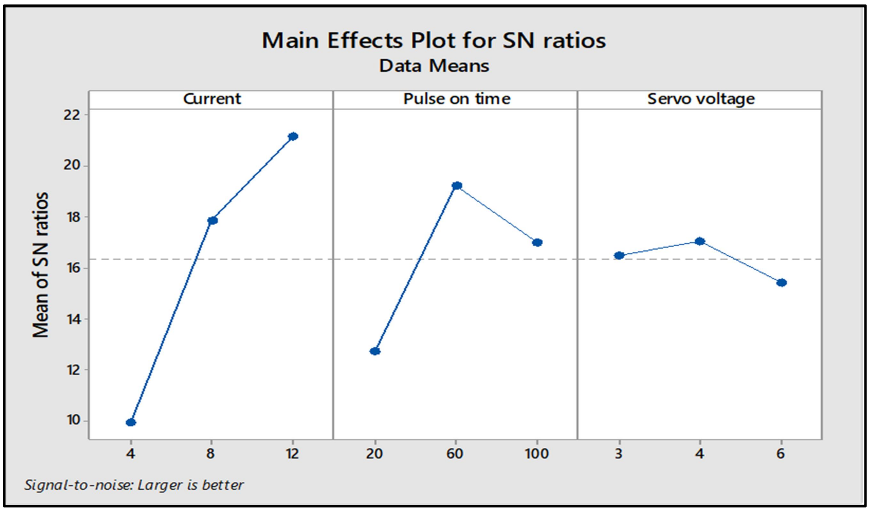

Fig. 5. S/N ratio plots of different parameters effects on MRR

4.3 Analysis of Variance (ANOVA) For MRR

According to the Analysis of variance, the percentage contribution of the current is 64.29%, pulse on time is 25.78% and servo voltage is 4.04% on the material removal rate, which is in a similar order as shown in the rank Table 2. The R-sq value represents the significance of the experimental work which is 94.11%. In ANOVA, "F" value also indicates more and less affecting parameter. The below Fig. 6 indicate that the current (I), have the highest affecting parameters on MRR which is 64.29% contribution among the all.

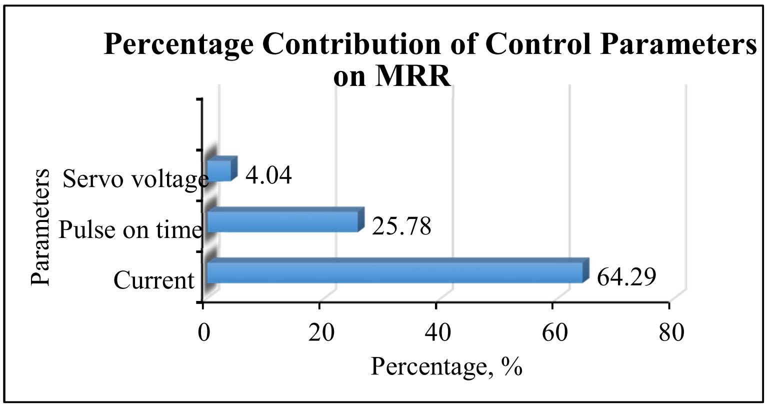

Fig. 6. Contribution ratio of each parameter to MRR

4.4 Full Factorial design of approach: After dropping the redundant data

In line with the approach of the present experimental work, this is a method after the dropping the redundant data with three one-of-a-kind parameters and three levels of the experimentation in which a full factorial experimental runs are created as in (Fig. 7, 8, 9 & 10).

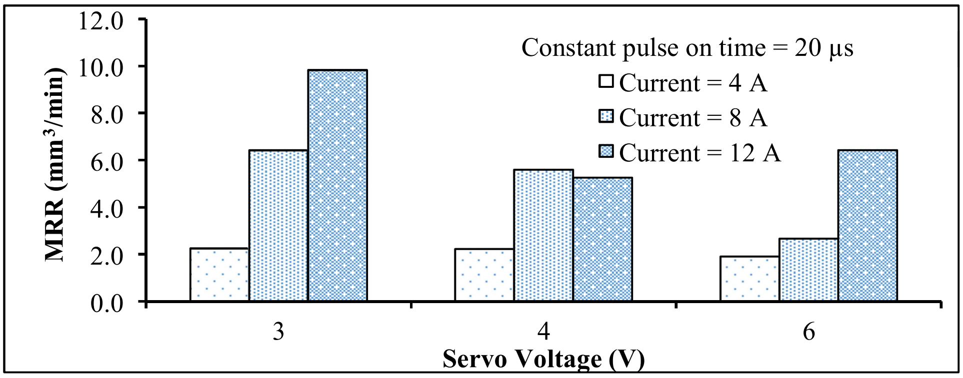

Fig. 7. Effect of V, & I on MRR at constant $T_{on} = 20$ **μ**s

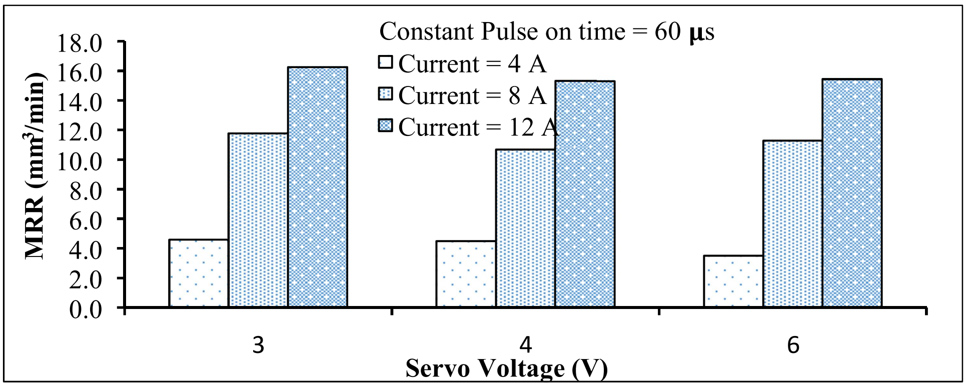

Fig. 8. Effect of V & I on MRR at constant T_{on}= 60 **μ**s

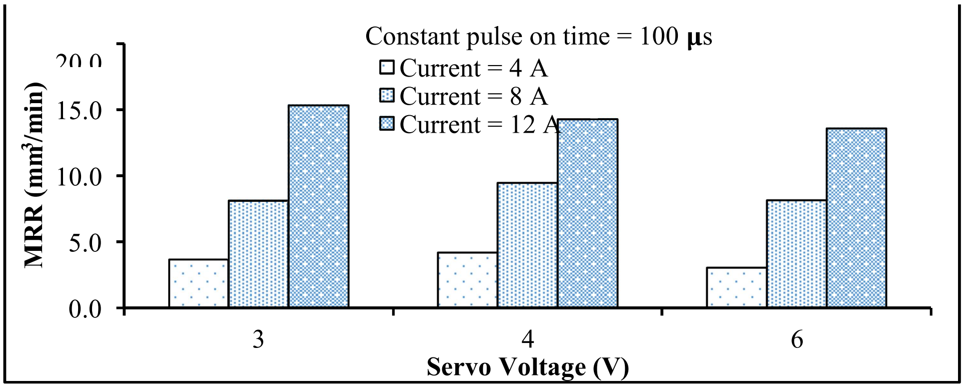

Fig. 9. Effect of V & I on MRR at constant T_{on}=100 **μ**s

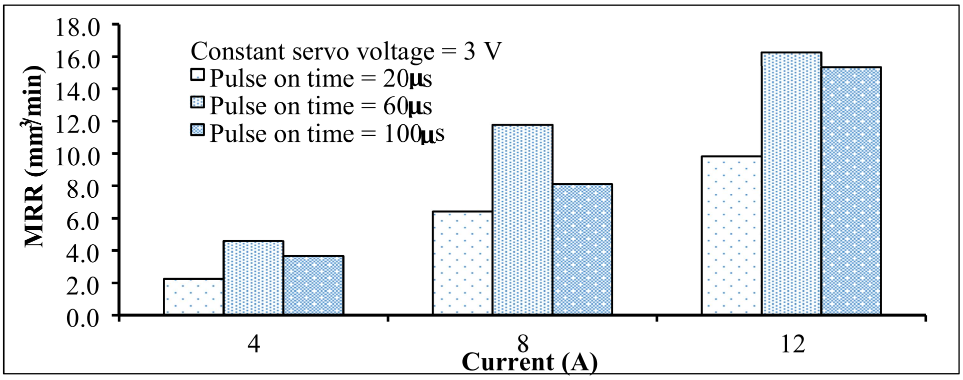

Fig. 10. Effect of I & T_{on} on MRR at constant V=3V

From the Analysis of variance, the contribution of the I is 62.05%, T_{on} is 26.39% and V is 1.09% on material removal rate. R-sq value represents the significance of the experimental work which is 89.51%.

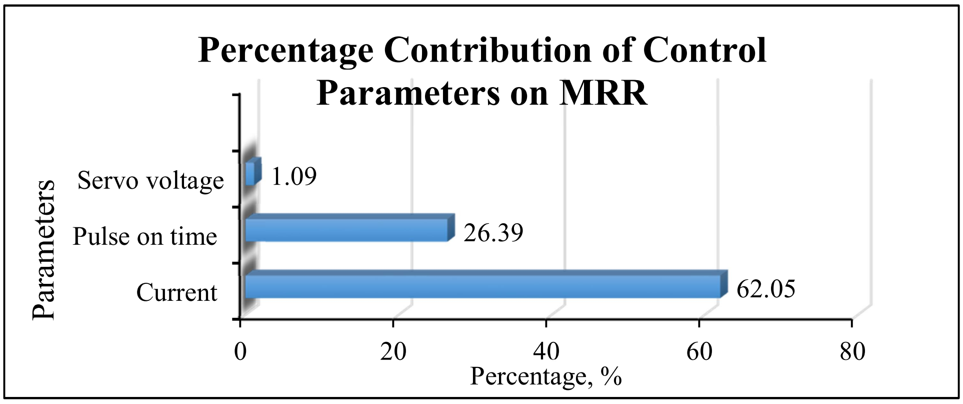

Fig. 11. Percentage Contribution of parameters on MRR

5. Conclusions

The present analytical study has been completed in order to acquisition, the optimal parameters to maximize the Material Removal Rate.

- Material removal rate (MRR) increases linearly with appreciate to increase in current from 4 A to 12 A. The current value is restricted to 12 A due to safety reasons and occurrence of firing in dielectric fluid.
- MRR increases initially with increase in pulse on time from 20 µs to 60 µs, however it decreases later on with further increase in pulse on time from 60 µs to 100 µs.
- The effects of servo voltage on MRR are having variable trend. The MRR to begin with increases and then decreases with increase in the servo voltage from 3 V to 7 V. In aggregate with current and pulse on time, the servo voltage of 3 V is preferable.

- Amongst the control parameters, the MRR is strongly affected by current, even as the pulse on time and servo voltage have lesser effect on MRR.
- L9 Orthogonal array was used.
- The value of max. MRR is 16.24 mm^3/min and the combination of parameter values as I, T_{on} & V are 12 A, 60 **µ**s and 3 V.
- The rate of error by way of Fractional DOE was found to be 5.89% that is lower in contrast to full factorial DOE which become observed to be 10.49%.

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Design and Development of Coal Dust Filled Aluminium Alloy Composite

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ABSTRACT

In this current study, lignite coal dust reinforced into Al 5083 alloy composites are fabricated by adopting stir casting approach by changing coal dust (CD) weight percentages from 0 wt.%, 6 wt.%, 8wt.% and 10 wt.%. The coal dust particulates of size less than 53 µm size were consistently blended in molten aluminum 5083 accompanied by stirring process. The physical as well as mechanical properties of coal dust filled AA 5083 alloy composites were evaluated experimentally. In result, void percentage of AA 5083 composites varied from 0.75% to 0.79% for 0 to 8 weight percent coal dust whereas value got reduced to 0.41 % for 10 weight percent coal dust composite and micro-hardness value raised from 71 HV to 76 HV with the increasing coal dust amount. Dry sliding wear tests were conducted for coal dust filled alloy composites by implementing Taguchi approach at four distinct loads (10N – 40N), sliding speed (100 rpm – 700 rpm), sliding distance (500-2000 m) and coal dust weight percentages (0 wt.% - 10 wt.%) respectively using pin-on-disc machine. Although, a series of steady state wear examination is also carried out by altering the speed of disc to 100 rpm (0.52 m/s), 300 rpm (1.57 m/s), 500 rpm (2.61 m/s) and 700 rpm (3.66 m/s) and normal loads 10N, 20N, 30 N and 40 N one by one while keeping other parameters constant before studying the Taguchi experimental outcome. Finally, for finding the wear characteristics of fabricated composites, the damaged faces were observed under scanning electron microscope (SEM).

Keywords

Specific wear rate, Steady state, ANOVA, Taguchi

1. INTRODUCTION

The alloy composites find its tremendous applications in diverse areas because these materials possess many tailorable properties; also it is capable of delivering enhanced quality and endurable survival. With the passing days and ever escalating technologies and researches, engineers are developing novel materials that are capable of demonstrating outstanding and phenomenal properties. With the cutting-edge technology and investigation in the field of aluminium, it has brought forth development of its alloys with additional properties like reduced density, increased strength and lighter weight ratio, wear resistant and corrosion resistant. Past literatures revels the importance of electing reinforcement material in order to get desirable properties in the final alloy composites. Special focus is given to attain the enhanced mechanical properties in the final composites. There has been a growing interest into metal alloy composites possessing lower density and economical reinforcements.

Kukshal et al. [1] fabricated Al_2O_3-filled cast aluminium alloy A356 grade (by altering wt. % percentage of Al_2O_3 content from 0, 5, 10, 15, 20 and finally to 25) using stir casting technique. By performing theoretically and experimentally the performances were noted for mechanical, physical, fracture toughness and their results were compared by utilizing finite element analysis method. The outcomes exhibited improved hardness and enhanced impact, tensile, flexural strength with the incorporation of Al_2O_3 particles. In another study conducted by Kukshal et al. [2], fabricated SiC reinforced aluminium 365 alloy composites by stir casting technique. One such study was composed of evaluating properties like physical, mechanical and fracture toughness for the fabricated alloy composites, in which results showed that void content, tensile strength and hardness increased with the increment of SiC particles weight percentage into the alloy. Mamatha and her team mates [3] conducted a study in order to find out the thermal and thermo-mechanical, physical and mechanical properties of stir casted Alumina (Al_2O_3) filled Zinc-aluminium (ZA-27) in result observed that porosity content got escalated with the rise in weight proportion of filler content. The contributing fact for this increase in porosity content was poor wettability amongst alloy matrix and reinforcement. Dhingra and Gulbransen [4] reported that the composite structures have proved to be the reduction of somewhat 25% over metal counterparts and reduced operational and maintenance cost.

Exceptional wear resistance can be classified as the utmost desirable trait in metal alloy composites. Past literature revealed that particle-reinforced metal composites under varying load ranges exhibits wear resistance that is 10 times greater than the un-reinforced materials [5].

Taguchi optimization technique is a method that exceptionally helps in reducing the total experiments that are mandatory to design the response function in comparison to the full factorial design of experiments. The Taguchi system basically formulated for obtaining procedure optimization and recognition of most advantageous fusion of the factors for a given response [6]. Considering the above mentioned facts, the Taguchi L_{16} method was taken on to examine the end result of each process parameters (i.e. coal dust wt. %, normal load, sliding speed and sliding distance) in predicting specific-wear rate for fabricated AA 5083/ coal dust reinforced composites. Fixing all other parameters constant at stable levels, the impact of normal load and sliding speed were studied individually. For this purpose, an attempt is made to examine and figure out the significance of more than one variable upon the wear rate values of metal alloy composites, because in actual process outcome wear rate is mixed effect of numerous factors and their intercommunication [7-11].

2. EXPERIMENTAL DETAILS

2.1 Specimen preparation

AA 5083 as matrix material and coal dust (Lignite coal; purchased from Matasukh coal mines, Rajasthan state mines and minerals limited, Rajasthan, India) particles as a reinforcement filler were used for fabricating the desired composites. Table 1 represents the composition of procured Al 5083 plates (Al 5083 alloy; purchased from Nextgen steel and alloys, Mumbai, India) in accordance with the test reports of Brukers' optical emission spectroscopy at Materials and research center lab, MNIT, Jaipur.

Table 1. Composition of aluminium 5083 alloy

Al %	Mg%	Zn%	Fe%	Mn%	Cr%	Ti%	Cu%	Ni%	Others
93.2	5.04	0.148	0.56	0.065	0.065	0.023	0.024	0.016	0.484

2.2 Composite Fabrication

In this research, coal dust (CD) particles filled AA 5083 alloy composites are manufactured at 4 distinct weight quantity (0 wt. %, 6 wt. %, 8 wt. %, 10 wt. %) by adopting stir-casting technique. The aluminium 5083 alloy was melted using muffle furnace and this metal melt is controlled at 760°C for about 10 minutes; subsequently, the temperature of the furnace is reduced to 600°C to keep the melt between solidus and liquidus temperature. AA 5083 alloy when reached its liquidus temperature, the micron size (less than 53µm) low grade lignite CD particulates (density 1.3 g/cm^3) were added within this melt and is mixed using a mechanical stainless steel (SS) stirrer rotating at a speed of 300 rotation/min so as to blend the coal particulates uniformly in the matrix of alloy for 3-4 minutes. Hereafter, the liquefied mixture is drained into cast iron permanent mold of desired dimensions, held together and allowed to cool to a low temperature i.e. to room temperature, moderately. By this method various compositions of samples were fabricated.

Afterwards, once solidification process completed, composites were later removed from the mould and markings were completed according to test standards.

Physical and Mechanical characterization

Density

Void percentage and theoretical density of a composite was evaluated by Agarwal and Broutman in regards of weight fraction as per given equations (1) and (2). Composite density is evaluated by employing rule of mixture as mentioned below;

$$\rho_{composite} = \frac{1}{\frac{W_A}{\rho_A} + \frac{W_P}{\rho_P}} \qquad (1)$$

Where, W_A and W_P represents the weight fraction of alloy 5083 and particulate filler, whereas, $\boldsymbol{\rho}_A$ and $\boldsymbol{\rho}_P$ represents density of alloy and particulate filler. The void content (V_c) in the composites is evaluated using following equation:

$$V_c = \left(\frac{\rho_{th.} - \rho_{exp.}}{\rho_{exp.}}\right) \text{x } 100 \qquad (2)$$

Where, $\boldsymbol{\rho}_{th}$ is theoretical density and $\boldsymbol{\rho}_{exp.}$ is experimental density.

Micro-hardness

Most of the researchers observed that with the increment in reinforcement percentage, hardness also improved [12]. Sahin et al. [13] discovered that, by increasing the volume rate of SiC particulates into Al 2024 alloy matrix, the composite hardness increased linearly which may be contributed due to larger ceramic phase in the matrix of alloy. Micro-hardness test was executed using UHL Vickers hardness tester machine. Because of hardness variations in composites due to distribution of reinforcement particles a single micro hardness test value may not be illustrative for the overall hardness. Hence, four series of reading were noted.

Tensile test

The tensile test as per ASTM standard was performed on aluminium alloy composite using universal testing machine to discover their mechanical properties. It is elaborated in [14] that the strength of composite can be increased by making changes in strength due to the dislocations, sub grains and residual stress respectively.

Tribo-performance evaluation

In accordance to ASTM G 99 test standard, for dry sliding wear test pin-on-disc (figure 1) test rig (MAGNUM, India) equipment was operated for the tribological assessment of friction materials under room temperature. Specimen was hooked and settled in the tool holder and load was enforced against the specimen in such a way that face of the desired specimen comes in touch with the rotating disc built of hardened steel (EN-32, surface roughness of 0.6 μRa and hardness about 72 HRC). The resulting height loss in the specimen experienced during wear testing was measured in microns. Calculation for specific wear loss (mm^3/N-m) was done using formula:

$$\text{Specific wear rate} = \frac{\Delta m}{\rho \text{ x } v \text{ x } F \text{ x } t} \quad (3)$$

Δm = mass loss, in kg, $\boldsymbol{\rho}$ = Experimental density, kg/mm^3, v = Sliding speed, m/sec, F = Normal load, N, t = Time, seconds.

Figure 1 The arrangement of pin-on-disc wear test apparatus at tribology lab, MNIT

2.3 Experimental design

As discovered from past studies, the wear rate gets affected by a considerable number of process variables like sliding speed, sliding distance, reinforcement type, size of reinforcement, normal load, weight percentage of reinforcement, time. Thus, important concerning factors are shortlisted at the start and experiments are run to discover the inconsequential factors as earliest as possible. Performing conditions under taken to accomplish wear tests are shown in table 2.

Table 2 Levels of factors used for wear test experiment

Control factors	Level				
	I	II	III	IV	Units
A, Coal dust wt.	0	6	8	10	%
B, Normal load	10.00	20.00	30.00	40.00	N
C, Sliding speed	0.52	1.57	2.61	3.66	m/s
D, Sliding distance	500	1000	1500	2000	m

Taguchi's experimental approach reduces the number of experiments to 16 runs only offering an ease of doing the experiments and thereby saving time [15]. In current work, S/N ratio was chosen in accordance to the principles of "the smaller-the better" characteristics.

3. Results and discussions

3.1 Physical and Mechanical Characterization

3.1.1 Density and void percent of coal dust alloy composite

Experimental density of CD reinforced AA 5083 alloy composites is calculated by making use of Archimedes principle based densitometer and this calculated experimental density is compared with theoretical density whose results are presented in table 4. The results illustrates that with the increasing CD quantity into the alloy, the void percentage in the fabricated composites is also increasing. It can be concluded from the data that the experimental density of alloy 5083 composites containing 0, 6, 8 and 10 wt.% CD is less when compared to the theoretical density. The reason being that theoretical outcomes are generally established on the basis of idealistic assumptions that differs from the values attained experimentally and also could be due to the presence of porosity. However, in comparison to unreinforced AA 5083 alloy, the CD particle reinforced composites showed lower density and further it tend to decrease with the increase in coal content.

Table 3 Density of CD filled AA 5083 alloy composites

Composite	Experimental density (g/cm^3)	Theoretical density (g/cm^3)	Void content (%)
AA5083 + 0wt.% coal dust	2.63	2.65	0.75
AA5083 + 6wt.% coal dust	2.51	2.53	0.79
AA5083 + 8wt.% coal dust	2.50	2.52	0.79
AA5083 + 10wt.% coal dust	2.45	2.46	0.41

In stir casting procedure for casting particulate filled composites, it is very tough to ignore voids in any fabricated composite as it is an unpreventable parameter. The density of fabricated composites tends to decrease with the rise in weight percentage of CD particulates. Whereas, void content increases from 0.75 % to 0.79 % from 0 weight percent to 8 weight percent of CD filled alloy composite, but the value decreases to 0.41 % for 10 weight percent CD filled alloy composite.

3.1.2 Micro-hardness of coal dust alloy composite

The change in the value of micro-hardness with respect to the CD filled AA 5083 composite is demonstrated in figure 2. Micro hardness of CD particulate filled AA 5083 alloy composites considerably got increased with the increase in CD particulates in contrast to the unfilled AA 5083 alloy. The hardness value of fabricated composites was found to be 76 HV which was the maximum hardness value amongst all the fabricated composites at 10 wt. % CD particulates. Particle strengthening and grain refinement effects could be considered as the leading factors that attributed for the increment in the hardness value with the increasing wt. % of the coal particles.

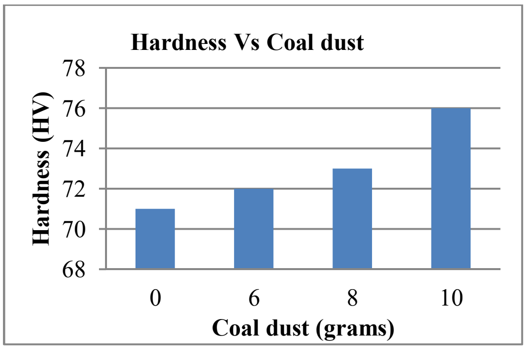

Figure 2 Variation of micro-hardness with amount of coal dust

3.1.2 Tensile strength of coal dust alloy composite

For determining the mechanical properties of fabricated 5083 alloy composites, the tensile tests was conducted using computer-aided universal testing machine as per the standards of ASTM. It is very clear from figure 3 that tensile strength is increasing with the increment in the amount of CD particles, i.e. tensile strength value observed was 142 MPa for 0 wt. % CD, which increases to 147 MPa for 6 wt. % CD, 182 MPa for 8 wt. % CD and it increases to 199 MPa for 10 wt. % CD particles in 5083 alloy composite. The thermal inconsistency between the metallic matrix and the reinforcing particles leads to the increase in tensile strength value, which in return contributes in a significant mechanism of increasing the dislocation density of the matrix and consequently leading to increase in the overall strength of the alloy composite [16].

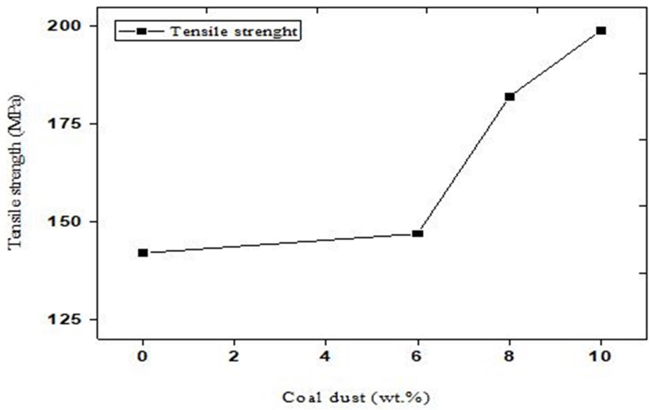

Figure 3 Graph for tensile strength with amount of CD particle

3.2 Taguchi experiment analysis

The results of experimental design for L_{16} orthogonal array are displayed in table 5. The overall mean was found to be -8.77 dB for the S/N ratio of W_s (specific wear). Taguchi experimental technique is implemented to determine dominant factors responsible for overall decrease in specific wear rate of CD filled AA 5083 alloy composites. This interpretation for wear rate was made by making use of software generally utilized for the designing of experimental applications called MINITAB 16 software.

Any product which is under investigation, its variation in quality characteristics is denoted by "signal" in response to a factor introduced in an experimental design. However, there are other external factors as well that are not included in the actual experiment but somehow affects the outcomes of an experiment. It can be clearly perceived by looking at table 7 that coal dust weight percentage has more remarkable effect on the specific wear rate thereafter by sliding speed, load, and sliding distance.

Table 5 L_{16} orthogonal experimental array design

Sr. No.	Coal filler (%)	Normal Load "N"	Sliding Speed "m/s"	Sliding distance "m"	Specific wear rate (mm3/N-m) $\times 10^{-13}$	S/N ratio (db)
1	0	10	0.52	500	5.193	-14.54
2	0	20	1.57	1000	2.594	-8.49
3	0	30	2.61	1500	5.190	-14.52
4	0	40	3.66	2000	1.529	-3.92
5	6	10	1.57	1500	5.386	-14.63
6	6	20	0.52	2000	4.616	-13.29
7	6	30	3.66	500	3.858	-11.74
8	6	40	2.61	1000	6.448	-16.12
9	8	10	2.61	2000	2.952	-9.82
10	8	20	3.66	1500	1.968	-6.29
11	8	30	0.52	1000	1.845	-5.73
12	8	40	1.57	500	1.848	-5.74
13	10	10	3.66	1000	1.466	-4.14

14	10	20	2.61	500	1.833	-6.08
15	10	30	1.57	2000	1.038	-1.14
16	10	40	0.52	1500	1.465	-4.14

The effect of leading control factors on the specific wear rate for the overall mean value of S/N are plotted onto graphs as shown in figure 4.

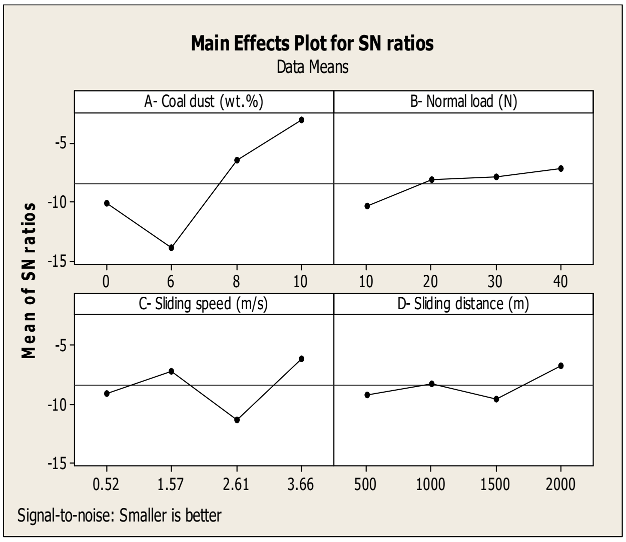

Figure 4 Effect of coal dust, normal load, sliding speed and sliding distance on wear rate

3.3 ANOVA

The function of Analysis of variance (ANOVA) was applied to determine which control factor undertaken i.e. coal dust wt. %, normal load, sliding speed and sliding distance significantly affects the quality characteristics. It is observed that P value of coal dust factor is 0.014 is lowest amongst normal load (0.244), sliding speed (0.083) and sliding distance (0.296).

Table 6 ANOVA table for specific wear rate- Coal dust filled- AA 5083 alloy composites

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Coal dust (wt. %)	3	228.180	221.180	76.060	22.12	0.014
Normal load (N)	3	23.797	23.797	7.932	2.41	0.244
Sliding speed (m/s)	3	61.641	61.641	20.547	6.25	0.083
Sliding distance (m)	3	19.393	19.393	6.464	1.97	0.296
Error	3	9.867	9.867	3.289		

Total	15	342.879	

3.4 Steady state specific wear

Impact of load and sliding speed on wear rate

The steady state wear rates is measured as a function of normal load on coal dust filled AA 5083 alloy composites as illustrated in figure 5. Results of this study illustrated that unfilled aluminium alloy showed more wear rate in comparison to the coal particulate - AA 5083 alloy under steady state sliding velocity: 0.52 m/sec, test duration: 15 minutes, and sliding distance: 468m respectively. It is discovered in this study that there is difference in specific wear rate values when compared between the unfilled and CD filled composites (Figure 5). Based on the wear test data it is revealed that with the increase in CD weight percentage the wear rate tend to decrease. Specific wear rate keeps on increasing as the load applied is increased for all speeds. The reason being that higher load tend to increase the frictional thrust which in result leads to increased debonding and ultimately fracture [17].

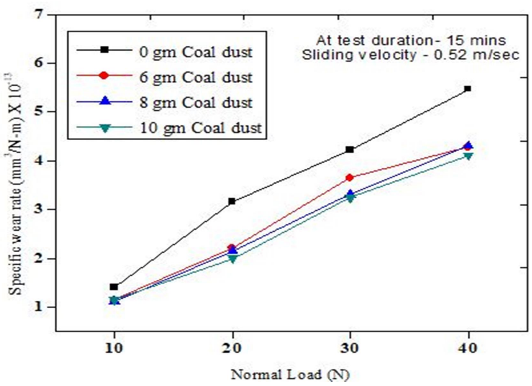

Figure 5 Variation in specific wear rate with normal load for CD filled AA 5083 alloy composites (at constant sliding velocity: 0.52 m/s (100 r/min), test duration: 15 minutes, and sliding distance: 468 m)

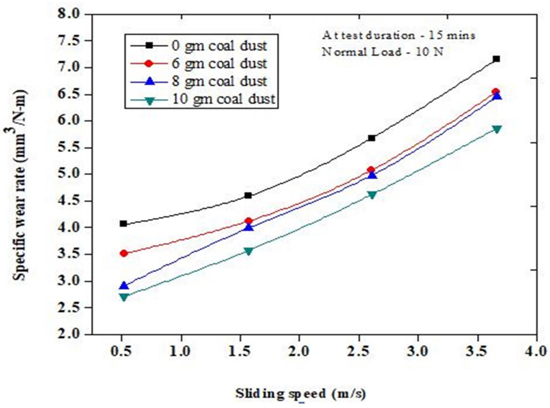

Figure 6 Variation in specific wear rate with sliding velocity for CD filled AA 5083 alloy composites (at constant normal load: 10N, test duration: 15 minutes, and sliding distance: 468 m)

Four different sliding velocities (i.e. 0.52 to 3.66 m/s) were undertaken for studying wear rate. It is observed that as sliding velocity is increasing, the wear rate is also escalating (figure 8). Specific wear rate without CD particulate is more for all range of sliding velocity in comparison to when CD is added in certain amount i.e. with the reinforcement of CD particles specific wear decreases slightly. The wear rate curve (figure 6) illustrates highest wear in case of unfilled AA 5083 composite and lowest for 10 wt. % CD-filled AA 5083 alloy composites. The contributed reason for this type of behaviour in 10 wt. % CD composites is reinforcement of higher amount of reinforcing particulates into the alloy AA 5083.

Wear surface morphology

The use of SEM images makes it convenient to qualitatively identify the dominant mechanism that operates, and thus, gain insight into the influence of the coal particulates on the wear process of metal alloy composites. From figure 9, long and continuous grooves in the direction of sliding could be observed. Also with the increasing speed under constant load condition cavities reduces and formation of deep grooves takes place. Whereas with the increase in both load and speed, grooves grow wider and deeper with some matrix area smeared along the sliding direction. Deep cracks at an angle with respect to the direction of sliding were observed.

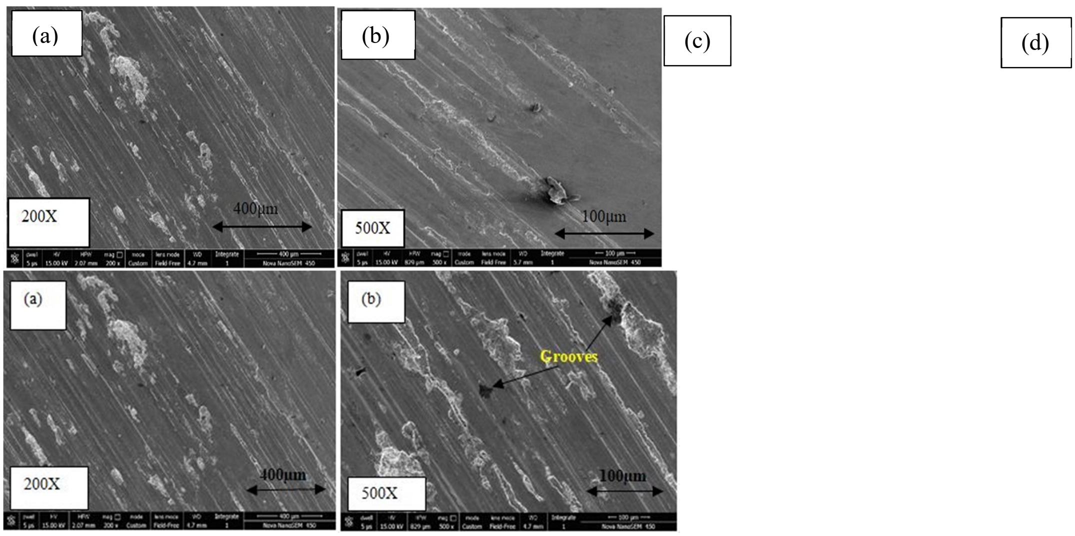

Figure 7 (a),(b) SEM micrographs of 0 wt. % CD 5083 alloy at speed 700rpm and 10N load, and (c),(d) SEM micrographs of 10 wt. % CD 5083 alloy at speed 700rpm and 10N load

Conclusion

The following conclusions were acquired from the observed outcomes:

1. Compared to the unreinforced AA 5083 alloy, the CD particle reinforced composites showed lower density and further it tend to decrease with the increase in coal content. Slight increase in micro-hardness (from ~71 to 76 HV) was observed when weight fraction of the composite increased from 0 wt.% to 10 wt.% of coal dust, which prevents the deformation of material resulting in increased hardness value.
2. Tensile strength amount noted to be 142 MPa for 0 wt. % CD, which increased to 147 MPa for 6 wt.% CD, 182 MPa for 8 wt.% CD and it got increased to 199 MPa for 10 wt.% CD particles in 5083 alloy composite.
3. CD weight percentage displayed a direct correlation with the wear rate. Fusion of 6, 8 and 10 wt. % of CD particles with AA 5083 alloy resulted in a reduction of wear rate at lower load values (10, 20, 30 and 40 N).
4. Sliding speed shows a direct relationship with the specific wear rate of fabricated composite, i.e. as the sliding speed increased, the specific wear rate increases because of rise in temperature that lead to the softening of the matrix and composite, whereas bonding efficiency decreased with the increase in wear rate.
5. Taguchi's design method is implemented so as to procure optimal parameter for specific wear rate. As the CD weight percentage is raised from 0 to 10 wt. %, the specific wear rate value got increased for all sliding speeds (100, 300, 500 and 700 rpm) and loads (10, 20, 30 and 40N).

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Optimization of process parameters for cutting force and surface roughness of a tie rod component

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ABSTRACT: Surface finish and cutting force of a machined component, are undoubted, factors that significantly affect its functionality and service life. A judicious selection of machining parameters like cutting speed, feed, depth of cut etc. is a key decision that has to be made to achieve the required surface finish and cutting force. In the present work, we analyzed the effect of these parameters on cutting force and surface roughness of a tie rod mild steel component machined on a lathe machine. A popular statistical approach namely Taguchi's design of experiment was employed to determine optimum values of process parameters for a given set of conditions and desired response variables. A suitable orthogonal array L9 was used, and signal-to-noise (S/N) ratio was calculated for each experimental run. The response variables so obtained were used to determine the optimum setting of machining above parameters. The results show that the depth of cut effect cutting force significantly with 94.5% as compared to other parameters and feed rate effect surface roughness significantly with 92.25%. We finally compared the obtained results with a confirmation experiment.

Keywords: *Design of Experiments, Taguchi Method, Orthogonal Array, S/N Ratio,*

I. Introduction:

In the current environment, quality is a key approach for all manufacturing sectors to compete in the global market. There is a need for industries to satisfy the customers with a higher quality of the product in minimum cost. The product quality is influenced by machining parameters and working environments. The geometry of tools, the coating of inserts, machine control parameters, cooling and lubrication systems have been identified as the variables which affect the quality and manufacturing costs of the products.

Initially, traditional experimental design procedures were used to optimize the process variables, but these methods are very difficult to perform when the number of variables and levels are large. Due to the increase in variables, the number of experimental runs is required, which results in extended time and resources. The Taguchi proposed a unique design of experiment matrix which also called orthogonal arrays to the identified effect of controllable factors and non-controllable factors on the response variables with less number of experimental run [2]. Taguchi experimental designs are extensively used to study the behaviour of a given process outcome depending upon various parameters [3]. In this method, the less number of experimental runs are required with less experiment time in reduced cost to identify the significant factors. In the present study, the effect of process parameters on cutting force and surface roughness of a mild steel component machined on a lathe machine was analyzed.

II. Literature Review:

Various methods, such as the regression analysis and conventional optimization techniques have been implemented by researchers in developing the mathematical model and optimizing machining attributes for limited parameters. Various techniques like Taguchi method, response surface methodology (RSM), and weighted principle component analysis (WPCA) are used for a large number of variables [4–6].
A study was carried out on the effects of cutting speed and feed rate on tool wear, and surface roughness of machined SiC-p reinforced aluminium metal matrix composite. Better surface quality was observed with higher cutting speed and lower feed rates [7]. In a study on the intrinsic relationship between tool flank wear and operational conditions in metal cutting processes using carbide cutting inserts it was revealed that cutting speed affects tool life more significantly than feed rate [8]. Taguchi approach was used to optimize process parameters for end milling operation on hardened steel. After analysis, it was observed that adhesion and chipping were the main causes of tool wear. Multiple regression analysis was applied for estimating the effect of machining variables on surface finish and tool wear. Cutting speed was found to be the most significant factor affecting surface finish and tool wear [9]. Correlation between surface roughness and cutting tool vibration for the turning operation was studied . The study concluded that the surface roughness of the product was observed to be affected significantly by vibrations due to the overhang of the cutting tool. Surface roughness was found to be increased with an increase in feed rate [10]. The effect of cutting speed, feed rate and depth of cut on surface roughness was analyzed in CNC turning operation of EN354 alloy steel with CNMG 120408 GT cutting tool. The Taguchi design of experiments was used in optimizing the process variables with the regression model and analysis of variance (ANOVA) for further analysis. It was found that surface roughness is significantly affected by the cutting speed. However, feed rate and depth of cut also affect the surface roughness to some extent [11]. The effects of cryogenic treatment and drilling variables on surface finish and hole quality in dry drilling operation on AISI 304 stainless steel were studied . Taguchi method was used to achieve better surface roughness and minimize roundness error while RSM was used to find the most significant variables affecting surface finish and roundness error. Experimental results showed that cutting speed and feed rate were the most significant factors affecting surface finish and roundness of the hole [12].

III. Methodology:

In this study, the tie rod component was selected which has 20 mm diameter and 50 cm in length. The turning operation has been done on the lathe machine with single point cutting tool for experimental investigation. Cutting force and surface finish were taken as response variables for the finished components. Objectives of the study are as:

1. To find the process parameter which has a more significant effect on cutting force and surface finish of the tie rod product in turning operation.
2. To optimize the machining variables for cutting force and surface finish.

The following steps have been done in this study.

a) Identification of various control factors
b) Selection of Taguchi orthogonal array for an experimental run
c) Experiment runs and surface finish and cutting force measurement
d) Analyze the results of experiments; (S/N ratio)
e) ANOVA analysis
f) Confirmation experiment

III (a). Identification of control factors: There are two factors in every experiment which are responsible for variations in the process. The control factors that affect the response variables on a lathe machine are identified as Cutting speed (rpm), Feed rate (mm/min) and Depth of cut (mm). The various noise factors affecting response variables are vibration, raw material variation and machine condition etc. These noise factors are not considered as process parameters in the Taguchi design of experiments. The various control factors and their selected levels are shown in Table1.

Table 1. Control factors and levels

Control Factors	Levels		
	A	B	C
Cutting speed (rpm)	120	180	240
Feed rate (mm/min).	45	60	75
Depth of cut (mm)	0.5	0.75	1.0

III (b). The selection of orthogonal array: The selection of orthogonal array depends upon the degrees of freedom. The total degree of freedom for the study is seven which is as follows, 1 for mean value and 6 for factors and their levels (2x3), L9 array orthogonal array was found appropriate for experimentation. So L9 orthogonal array is selected for experiment runs. The L9 array is required 9 experiments to find out the effect of process variables on the response variables and also to optimize the parameters.

Table 2. L9 orthogonal array for experiment runs

Experiment Run	Cutting speed (rpm)	Feed rate (mm/min)	Depth of cut (mm)
1	120	45	0.5
2	120	60	0.75
3	120	75	1.0
4	180	45	0.75
5	180	60	1.0
6	180	75	0.5
7	240	45	1.0
8	240	60	0.5
9	240	75	0.75

III (c). Experiment run and measurement: Experiments are done on engine lathe according to Taguchi orthogonal array. Surface finish and cutting force are two response variables measured during each experiment run. The cutting force is measured by lathe tool dynamometer while surface roughness tester is used to measure the surface finish.

Table 3.Output Response and S/N ratios for cutting force and surface roughness

Experim ent Run	Cutting speed (rpm)	Feed rate (mm/min)	The depth of cut (mm)	Cutting Force (kgf)	Surface Roughness (Ra)	S/N ratio for cutting force	S/N ratio for surface roughness
1	120	45	0.5	20	1.25	-26.0206	-1.9382
2	120	60	0.75	38	3.12	-31.5957	-9.88309
3	120	75	1.0	48	4.56	-33.6248	-13.1793

4	180	45	0.75	32	1.45	-30.103	-3.22736
5	180	60	1.0	47	2.69	-33.442	-8.59505
6	180	75	0.5	18	4.12	-25.1055	-12.2979
7	240	45	1.0	42	1.89	-32.465	-5.52924
8	240	60	0.5	12	3.87	-21.5836	-11.7542
9	240	75	0.75	36	4.58	-31.1261	-13.2173

III (d). Analysis of the S/N Ratio: The variability in the experimental results and mean of results are analysis with the help of Signal to Noise (S/N) ratio. The value of S/N ratio greatly depends on the quality attributes of the process or product which require optimization of process variables. Three types of performance measures, lower-the-better, the higher-the-better and the nominal-the-better are used in the S/N ratio analysis. In the present study function, "smaller the better" is used for optimizing the cutting force and surface roughness. The levels which have the highest S/N ratio are selected as the optimized value for the corresponding factors. The mathematical formula for S/N ratio is shown in equation1.

S/N = -10 log ((l/n) (Σy2))……………(1)

Minitab software is used to analysis the S/N ratio of cutting force and surface roughness with three machining variables individually. In the main effects graphs, X-axis indicates the values machining variables and Y-axis denotes the output response. These plots are suitable to find optimum conditions for the response variable.

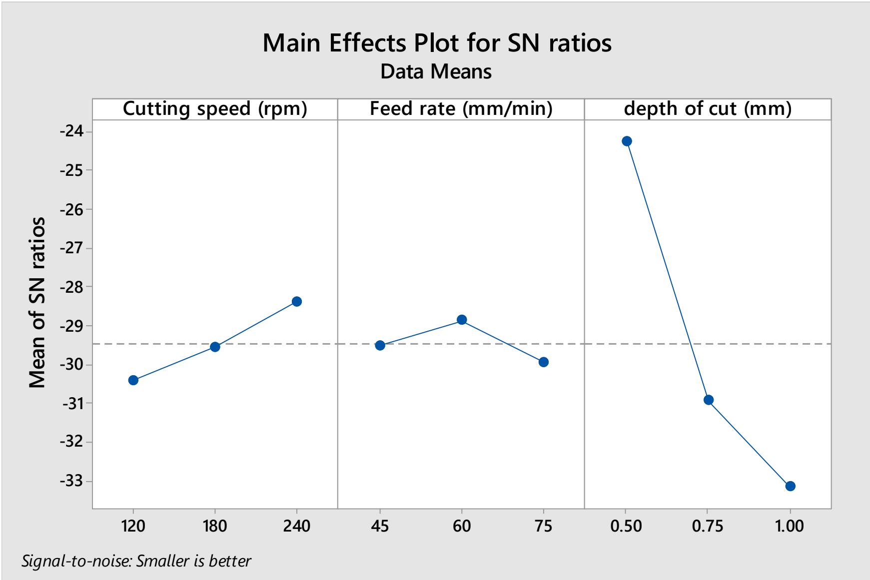

Figure 1(a). Main effect plots for S/N ratios for cutting force

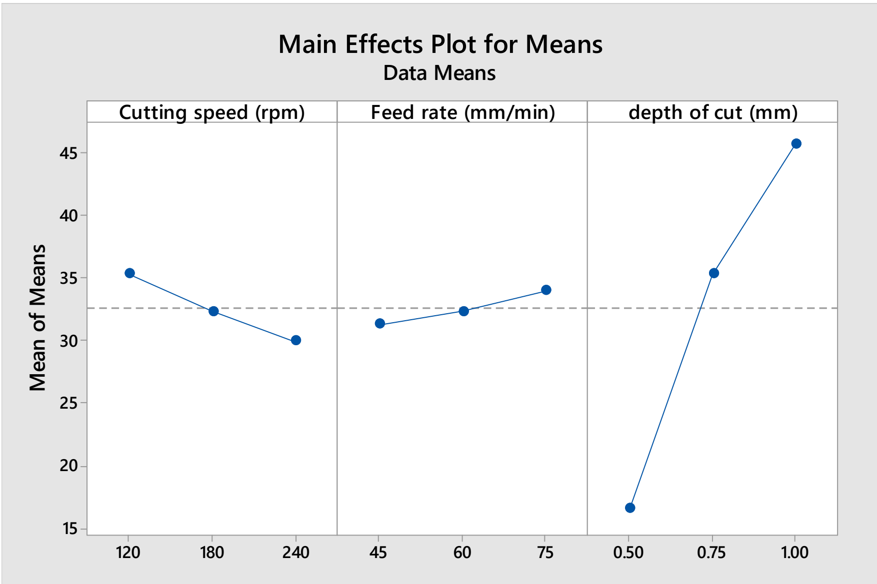

Figure 1(b). Main effect plots for means for cutting force

Figure 1(a) & (b) show that the main effect plots for cutting force, the graph shows that increase in cutting speed, decreases the cutting force but it increases with increase in feed rate. It is found that an increase in the depth of cut, increases the cutting force significantly.

Table 4. S/N ratios for cutting force (Smaller the best)

Level	Cutting speed (rpm)	Feed rate (mm/min)	depth of cut (mm)
1	-30.41	-29.53	-24.24
2	-29.55	-28.87	-30.94
3	-28.39	-29.95	-33.18
Delta	2.02	1.08	8.94
Rank	2	3	1

Table 4 gives the values for the S/N ratio of different machining parameters for smaller is the better function. The depth of cut significantly dominates the machining compared to other parameters.

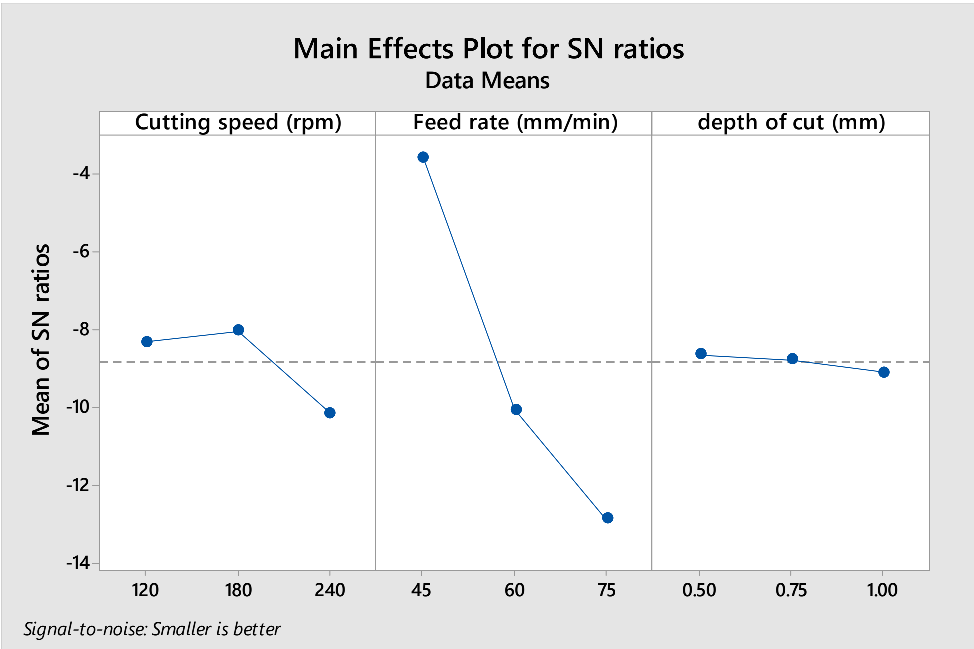

Figure 2(a). Main effect plots for S/N ratios for surface roughness

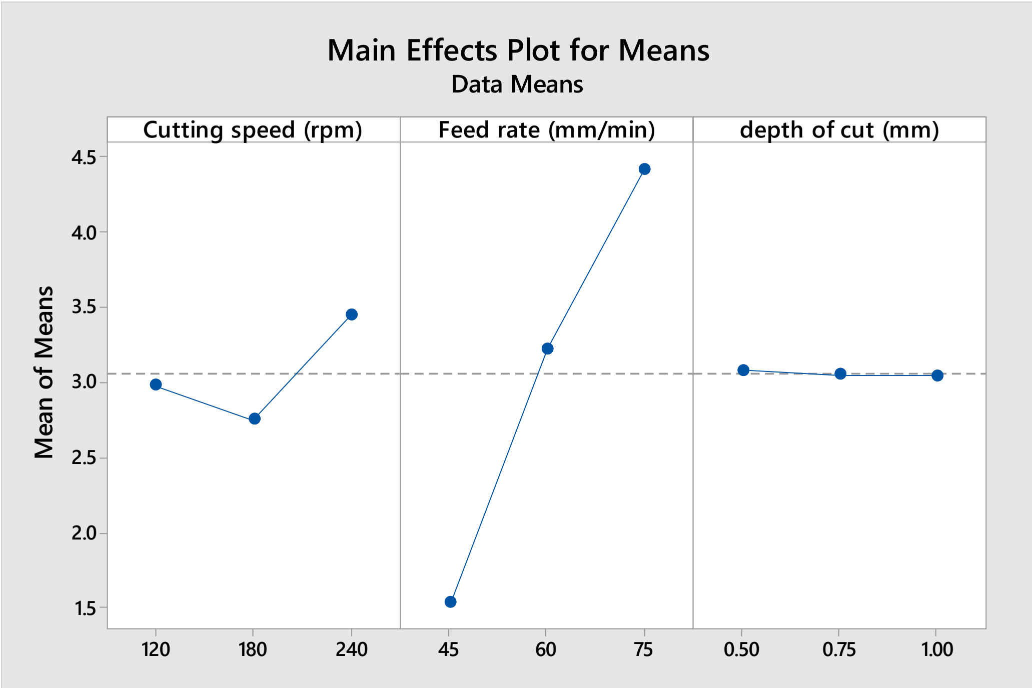

Figure 2(b). Main effect plots for means for surface roughness

Figure 2(a) & (b) show that the main effect plots for surface roughness, As the plot, indicates an increase in cutting speed, increases the surface roughness. The significant increase in the surface roughness is seen with the corresponding increase in the feed rate.

Table 5.Response Table for Signal to Noise Ratios for surface roughness (Smaller the best)

Level	Cutting speed (rpm)	Feed rate (mm/min)	depth of cut (mm)
1	-8.334	-3.565	-8.663
2	-8.040	-10.077	-8.776
3	-10.167	-12.898	-9.101
Delta	2.127	9.333	0.438
Rank	2	1	3

The table 5 shows that the rvalue of S/N ratio at various levels of machining variables for smaller is the better function. The feed rate significantly dominates the machining compared to other parameters.

Table 6. Optimal Conditions

Optimal parameters for turning mild steel			
	Cutting speed (rpm)	Feed rate (mm/min)	depth of cut (mm)
Cutting Force (kgf)	240	60	0.5
Surface Roughness(Ra)	180	45	0.5

III (e). Analysis of variance (ANOVA) analysis: ANOVA is a technique which investigates the effect of individual process parameters on response magnitude. ANOVA checks the level of impact of process variables on responses at a different trial.T he ANOVA table is consists of sum squares (SS), mean squares (MS), the degree of freedom (DOF), P-value, F-value and percentage contribution of each factor.

Table 7. ANOVA analysis for cutting force

Source	DF	Adj SS	Adj MS	F-Value	P-Value	% Contribution
Cutting speed (rpm)	2	42.89	21.444	2.12	0.320	3.13
Feed rate (mm/min)	2	10.89	5.444	0.54	0.650	0.79
Depth of cut (mm)	2	1296.22	648.111	64.10	0.015	94.5

Error	2	20.22	10.111			1.47
Total	8	1370.22				100

Table 7 shows the ANOVA analysis; it gives the contribution of the individual process variable. From the ANOVA table, it can be concluded that the depth of cut effect cutting force significantly with 94.5% as compared to other parameters.

Table 8. ANOVA analysis for surface roughness

Source	DF	Adj SS	Adj MS	F-Value	P-Value	% Contribution
Cutting speed (rpm)	2	0.7515	0.37574	2.43	0.292	5.47
Feed rate (mm/min)	2	12.6548	6.32741	40.91	0.024	92.25
Depth of cut (mm)	2	0.0020	0.00101	0.01	0.994	0.014
Error	2	0.3094	0.15468			2.25
Total	8	13.7177				100

Table 8 shows the contribution of the individual process parameter. ANOVA table shows that the feed rate affects the surface roughness significantly with 92.25% as compared to other parameters.

III (f). Confirmation experiment: The final step of the study is to conduct the confirmation tests to authenticate the optimum values of the control factors obtained from the analysis of experimental runs. In the present study, confirmation experiments are conducted for turning mild steel work piece and found that results are good.

Conclusion: It is found that the Taguchi design of the experiment is very useful to optimize the process variables when there is less time to conduct experiments. It provides a systematic methodology with a less number of experimental runs, when compared with full factorial analysis and found similar results. In this experimental study, Taguchi's method is selected to find out the optimal cutting variables in the turning operation of the mild steel tie rod component. The experimental test results are evaluated by the ANOVA analysis. The results show that the depth of cut effect cutting force significantly with 94.5% as compared to other parameters and feed rate effect surface finish significantly with 92.25% as compared to other parameters.

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Cellular Manufacturing: Literature Review and Trends

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Abstract: A big challenge for today's batch production industry is to offer fast delivery of a variety of products to the customer. To meet this challenge, manufacturing industries are turning to cellular manufacturing (CM). Cellular manufacturing has engrossed severe research attention in the recent past. CM based on group technology approach where workstations arranged in the form of manufacturing cells and part families are assigned to these cells. Each manufacturing cell performs all or most of the operations required by part families. The primary purpose of CMS is to reduce setup time, cycle time, and improve machining utilization.

This paper intends to perform an investigation of the literature of CM. The paper examines 170 research papers, different definitions of CM, research methodology used and systematic classification. Based on this, the suggestions for possible research issues and development are identified. The investigation results will help academicians, researchers, and experts with an emphasis on the evolution, suitability and research advances in the CM.

Kew words: Cellular manufacturing, Group technology, literature review, trands

1. Introduction

Cellular Manufacturing (CM) is an improvement tactic in the production of job shops and batch shops. Group Technology (GT) in CM is used to build part family members according to the same job processing. Machines and parts are then grouped based on in order or immediate techniques. GT is defined as "A manufacturing philosophy in which similar parts are identified and grouped to take advantage of their similarities in design and production." GT is a method in which parts are manufactured by grouping these parts and successively applying similar technological operations for each group. (Mitrofanov, 1966). Cellular manufacturing (CM) is the application of GT, which group machines, dedicated to the part family of similar components (Dekkers, 2018). CM does not just have the adaptability of job shops in creating a wide range of items yet, also, has high production rate and efficient flow (Liu, Wang, & Leung, 2018).

The implementation of a cellular manufacturing system can achieve substantial advantages. (Sakhaii, Tavakkoli-Moghaddam, Bagheri, & Vatani, 2013).

- Reduced handling of materials
-Reduced tooling and equipment
-Minimized set-up time
-Minimized work-in-process inventory
-Minimized part makespan
-Enhanced operator capability

The main goal of CMS ' design is to categorize family parts, machine cell formation and machine cell allocation for machine cells in order to minimize the movement of parts between cells. (B. Wu, Fan, Yu, & Xi, 2016). GT and CM are suitable for the plant which currently follows batch production and a process type layout. The required condition to apply GT is that the parts can be grouped into part families. Part Family is a collection of components that match form and size. Part families are essential features of GT.

Mitrofanov was the first who introduced the concept of GT philosophy and the machine grouping problem in the late 1950's. The other early pioneers in the field of GT are Burbidge and Ham. Burbidge in 1960 proposed production flow analysis technique for GT. From 1960-2017 numbers of methods, models and algorithms developed related to various issues in CM.

The aim of this study is to conduct a broad review of CMS literature. This study comprised 170 research papers from more than 15 journals and international conferences. All the more accurately, the purpose of this investigation is to:

- Classify cellular manufacturing research papers according to their approach and methodology
- Explore the trend in cellular manufacturing and identifies future research agenda.

2. Literature review

Numerous articles dealing with the CMS have been published over the last four decades. This study included the work in the area of CMS, published in refereed journals and international conferences. The Table I shows the distribution of research papers in different journals and international conferences. It is shown by bar chart in Figure 1. Figure 2 shows some paper selected year wise.

Journal	*No. of Papers*	*%*
International Journal of Production Research	31	21.6
Computers and Industrial Engineering	21	14.6
Journal of Industrial Engineering	10	6.9
International Journal of Advanced Manufacturing Technology	9	6.3
Journal of Manufacturing System	6	4.2
European Journal of Operation Research	6	4.2
Journal of Intelligent Manufacturing	5	3.3
International Journal of Industrial Engineering Computations	5	3.3
International Journal of Computer Integrated Manufacturing	4	2.6
International Journal of Manufacturing Technology and Management	4	2.6
Applied Mathematical Modelling	3	1.9
International Journal of Production Economics	3	1.9
Advances in Manufacturing	2	1.3
Advances in Production Engineering and Management	2	1.3
Engineering Optimization	2	1.3
Expert Systems With Applications	2	1.3
International Journal of Engineering Science and Technology	2	1.3
International Journal of Flexible Manufacturing Systems	2	1.3
International Journal of Manufacturing Research	2	1.3
International Journal of Service and Operation Management	2	1.3
Journal of Operations Management	2	1.3
Operations Research	2	1.3
Production and Operations Management	2	1.3
Production Engineering	2	1.3
Production Planning and Control	2	1.3
System Engineering	2	1.3
Journal of Chinese Institute of Industrial Engineering	2	1.3
Manufacturing Research and Technology	2	1.3
Other	12	8.2
Total	151	100

International Conferences	19

Table I. Distribution of research papers

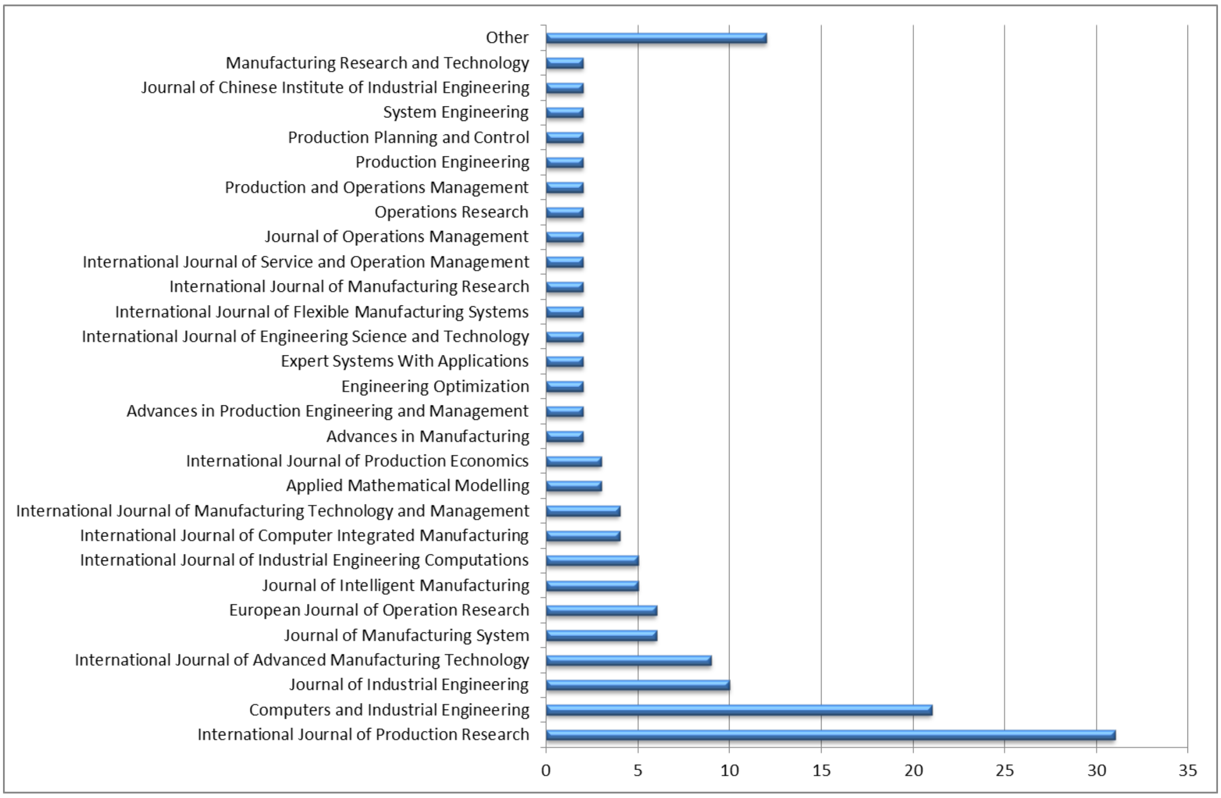

Figure 1. Distribution of Research Papers

Note: Other includes, *Decision Science, Iberoamerican Journal of Industrial Engineering, Information and Control, Innovative Production Machines and Systems, International Journal of Precision Engineering and Manufacturing, Journal of Brazilian Society of Mechanical Science and Engineering, Journal of Information and Optimization Science, Journal of Service Science and Management, Omega, Research Journal of Applied Sciences, Engineering and Technology, Robotics and Computer Integrated Manufacturing, Sadhana Indian Academy of Science.*

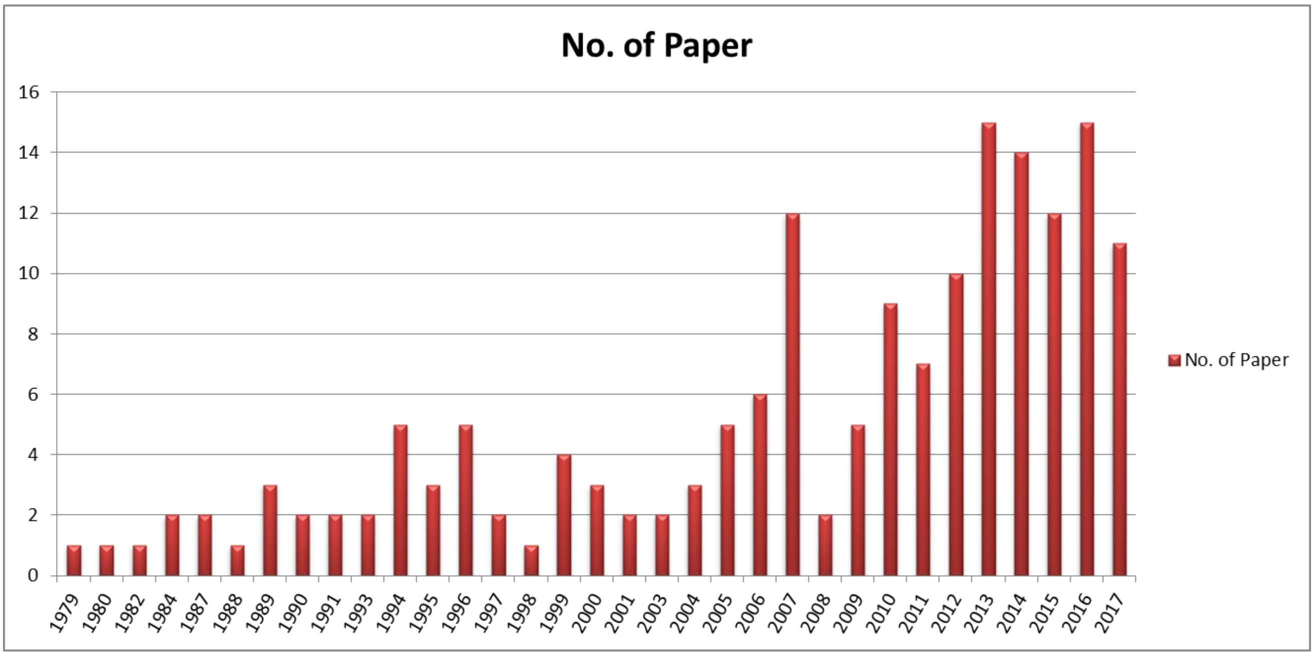

Figure 2. Number of Paper Year Wise

Different meanings of CM given by different researcher are exhibited in Table II.

Author	Connotations of CM
Timothy (1984)	Cellular manufacturing is the physical division of the functional job shop's manufacturing machinery into production cells. Each cell is designed to produce a part family.
Urban (1987)	Cellular manufacturing comprises processing of part families on dedicated groups of different machines (cells).
Heragu (1994)	Cellular manufacturing (CM) can be defined as an application of GT and involves grouping machines or processes on the basis of parts or part families they process
Gursel *et al.* (1995)	Cellular Manufacturing can be defined as the implementation of Group Technology (GT) principles in a manufacturing environment.
Sarker and Mondal (1999)	In cellular manufacturing (CM), parts with similar processing requirements are identified and grouped to form part-families to achieve the benefits of economy
Pillai and Subbarao (2008)	Cellular manufacturing is the practical application of GT in which functionally different machines are grouped to produce a family of parts.
Yousef *et al.* (2011)	In cellular manufacturing (CM), parts requiring a similar production process are grouped in distinct manufacturing cells.
Siva Prasad *et al.* (2014)	Cellular manufacturing systems act as a negotiation between job shop production and flow line production.
Won and Logendran (2014)	CM involves processing a collection of similar parts on a dedicated group of machines.

Table II. Different meanings of CM given by researcher

The research contribution, methodology, and problem -solving approach of all reviewed paper are as shown in Table III.

Researcher	Year	Methodology	Approach	Contribution to research

Beeby	1979	Conceptual	Type A[1]	Presented a broader view of GT
Witte	1980	Descriptive	Type A[1]	Introduced a method for designing cell based on similarity coefficient
Vaithianathan and McRoberts	1982	Descriptive	Type B[2]	Examines a group technology from a scheduling point of view and presented a modified approach to scheduling in GT
Waghodekar and Sahu	1984	Descriptive/Applied	Type A[1]	Discusses the problem of machine-component cell creation in GT and presents a heuristic approach founded on the similarity coefficient.
Greene and Sadowski	1984	Conceptual	Type A[1]	Discusses the capabilities and merits of a group technology cellular manufacturing system.
Chandrasekharan and Rajagopalan	1987	Applied	Type A[1]	Develop an algorithm for simultaneous formation of part-families and machine-cells in GT.
Wemmerlov and Hyer	1987	Empirical	Type C	Recognizes a substantial number of research points for cellular manufacturing and discusses the requirement for their investigation and proposes proper methods for their study.
Shaw	1988	Descriptive	Type B[2]	Describes artificial intelligence based approach for dynamic scheduling method for cellular manufacturing systems.
EIMaraghy and Gu	1989	Applied	Type B[1]	Presented a technique for the direct and automatic assignment of parts to flexible manufacturing cell.
Chu	1988	Empirical	Type C	Focuses on a state-of-the-art review on the use of clustering techniques in cellular manufacturing.
Gunasingh and Lashkari	1989	Applied	Type A[1]	Proposed a 0-1 integer programming formulations to group the machines in CMS based on tooling desires of the parts, tooling accessible on the machines and the preparing times.
Harhalakis *et al.*	1990	Applied	Type A[2]	Presented a simple twofold heuristic algorithm for cell manufacturing capable of minimizing inter-cell material movement.
Vohra *et al.*	1990	Applied	Type A[2]	Presents a non-heuristic network method for cell formation with less intercellular interactions.
Sule	1991	Descriptive	Type A[1]	Develops a process in GT to decide groupings of machines, the aggregate number of machines required and the aggregate of material exchange between the cells so parts can be prepared with least aggregate cost.
Gupta	1991	Comparative	Type A[1]	Exhibited results from an examination

				performed to discover the seriousness of chaining problem and other features related to different linkage clustering algorithms.
Siier and Saiz	1993	Conceptual	Type B[1]	Confers the control of manufacturing cells and emphases on cell loading aspects.
Wu and Salvendy	1993	Applied	Type A[1]	Presented a basic network model for the cell formation given operation sequences.
Alford	1994	Empirical	Type C	Explore the current state and history of the ideas behind cellular manufacturing and its application in industry.
Srinivasan	1994	Applied	Type A[1]	Introduce a grouping algorithm for machine-cell formation using a minimum spanning tree.
Seifoddini and Hsu	1994	Comparative	Type A[1]	Present a new execution measure and conducted a reasonable investigation of three distinctive similarity coefficients approach.
Logendran *et al.*	1994	Applied	Type A[1]	Presents a realistic approach to the problem of selecting machines and a unique process plan for each part of a cellular manufacturing system.
Heragu	1994	Empirical	Type C	Provides a through a survey of papers on GT and CMS design.
Siier *et al.*	1995	Descriptive	Type B[1]	Depicts manufacturing cell loading principles and algorithms for associated cells.
Srivastava and Chen	1995	Applied	Type A[1]	Endorse a quadratic programming model for machine cell creation with congestion constraint, which also finds the optimal number of machine cells.
Malmborg	1995	Applied	Type A[1]	Develop a buffer storage resource allocation model for cellular manufacturing system.
Sridhar and Rajendran	1996	Applied	Type B[2]	Presented a genetic algorithm for scheduling and flow line based CMS is considered with the objectives of minimizing makespan, total flow time and machine idle time.
Batocchio and Irani	1996	Descriptive	Type A[1]	Addressed the feasibility of rapid computer implementation of production flow analysis.
Drolet *et al.*	1996	Empirical	Type A[1]	Focuses on exposing fundamental roots of dynamics cellular manufacturing and virtual cellular manufacturing.
Shambu	1996	Empirical	Type A[1]	Presented a performance evaluation of cellular manufacturing systems.
Rheault *et al.*	1996	Conceptual	Type A[1]	Gives a dynamic cellular manufacturing system (DCMS) that withstands the intense

				situation of small make-to-order producers and subcontractors.
Reisman *et al.*	1997	Empirical	Type C	Focuses on entire life cycle literature of cellular manufacturing as a module of OR/MS addresses the research strategy employed and exhibited by the authors.
Seifoddini and Djassemi	1997	Descriptive	Type A[1]	Introduced a method for the affectability investigation of the execution of a CMS considering changes in product mix.
Selim *et al.*	1998	Empirical	Type C	Confers and reviews an critical issue in CM focusing on cell formation.
Sarker and Mondal	1999	Empirical	Type C	Presents a brief comparative study of some existing grouping efficiency measures in CM.
Suer *et al.*	1999	Descriptive	Type B[1]	Mentioned growing importance of cellular manufacturing and introduce new rules for cell loading considering a multi-cell environment.
Ernzer and Kesavadas	1999	Conceptual	Type A[1]	Discusses numerous cell formation and visualization methods developed particularly for the outline of the virtual industrial facility.
Lozano *et al.*	1999	Applied	Type A[1]	Presents a tabu search algorithm that deliberately investigates possible configurations of the machine cell that determines the corresponding part families using a linear network flow model.
Islam and Sarker	2000	Applied	Type A[1]	Developed a mathematical model using similarity coefficient for optimally solving the cell formation problem in CM.
Sarker and Xu	2000	Applied	Type A[1] Type A[3]	Developed a 3-step operation sequence and cost-based method that incorporates the cell formation and the layout of intracell to lessen the aggregate cost of the machine investment and materials flow.
Davis and Mabert	2000	Applied	Type B[1]	Developed and assessed mathematical programming-based procedures that exploit the structure of both independent and linked CM settings for making labour assignment and order dispatching decisions before the start of the shift.
Onwubolu and Mutingi	2001	Applied	Type A[1]	Demonstrated the issue of cell formation with three objective functions: a) minimization of intercellular movements, b) minimization of cell load variation, and c) mix of these options.
Low *et al.*	2001	Descriptive	Type A[1]	Concentrated on seven cell formation techniques used in cellular

				manufacturing. The performance of each method was measured using grouping measures.
Agarwal *et al.*	2003	Applied	Type A[1]	Proposed an Analytic Hierarchy Process (AHP) based framework for the assessment of the cell formation methods.
Wang	2003	Applied	Type A[1]	Proposed a linear assignment algorithm for machine-cell and part-family formation for the design of CMS.
Solimanpur *et al.*	2004	Applied	Type B[2]	Talks about the scheduling of manufacturing cells in which parts may need to visit different cells and proposed a two-step heuristic to solve the problem.
Malakooti *et al.*	2004	Applied	Type A[1]	Developed an integrated approach to solve cell formation based on process planning and production planning simultaneously.
Johnson and Wemmerlov	2004	Empirical	Type A[1]	Reconnoitre why cell implementation breaks in companies that already have cells.
Sakazume	2005	Comparative	Type C	Compared the similarities and differences between Japanese Cell Manufacturing and Cellular Manufacturing.
Prabhaharan *et al.*	2005	Applied	Type A[2]	Suggested an ant colony system approach for cell formation with the goal of decreasing the aggregate cell load difference and the total intercellular transfers.
Durmusoglu and Nomak	2005	Descriptive	Type A[1]	Described GT cells design and its execution in a glass mould manufacturing industry.
Franca *et al.*	2005	Applied	Type B[2]	Suggested Genetic Algorithm and a Memetic Algorithm for the scheduling of part families in a flow shop manufacturing cell.
Moghaddam *et al.*	2005	Applied	Type B[1]	Built up a mathematical model with the objective function of minimalizing the idle time of machine in cells and delivery time to the clients.
Dimopoulos	2006	Applied	Type A[1]	Present's multi-objective GP-SLCA, an evolutionary computation approach for the multi-objective cell-formation problem.
Murugan and Selladurai	2006	Applied	Type A[1]	Studies three array-based clustering algorithms for cell formation, with a real

				case study to exhibit the viability of algorithms.
Hachicha *et al.*	2006	Applied	Type A^1	Apply correlation analysis (CA) for solving cell creation problem
Nsakanda *et al.*	2006	Applied	Type A^1	Present a comprehensive model for designing CMS for multiple process plan and routing using a genetic algorithm
Bansee and Chowdary	2007	Conceptual	Type A^1	Considers the new concept of virtual cellular manufacturing (VCM) to improve the effectiveness of manufacturing operations by varying the methods of production.
Dimopoulos	2007	Applied	Type A^1	Described a new methodology based on multi-objective GP-SLCA, for the multi-objective cell-formation problem.
Pham *et al.*	2007	Applied	Type A^1	Proposed Bees Algorithm based optimization technique for solving cell formation problem.
Das *et al.*	2007	Applied	Type A^1	Revealed a multi-objective mixed integer programming model for CMS design that diminishes aggregate cost and enhances the machine reliabilities in a cell.
Wang *et al.*	2007	Applied	Type A^1	Presents a new clique partitioning (CP) model for the group technology problem.
Balakrishnan and Cheng	2007	Empirical	Type C	Review research to addresses CM under states of multi-period planning horizons, with demand and resource suspicions.
Mak *et al.*	2007	Applied	Type A^1	Presents ant colony optimization based algorithm for production scheduling and manufacturing cell formation.
Kulkarni and Shanker	2007	Applied	Type A^2	Presents a mathematical model using GA for layout problem in cellular manufacturing.
Venkataramanaiah	2007	Applied	Type B^2	Developed a simulated annealing based algorithm for scheduling of parts with the goal of minimizing idle time, flow time and makespan.
Hachicha *et al.*	2007	Applied	Type A^1	Apply multivariate approach based on a correlation analysis for cell formation problem.
Wu *et al.*	2007	Applied	Type A^1	Developed a hierarchical GA for forming machine cells and for determining the group layout of a CMS.
Wu *et al.*	2007	Applied	Type A^1 Type A^2	Proposed a conceptual framework and developed a hierarchical genetic algorithm

			Type B^2	that integrates cell formation, cell layout, and group scheduling.
Mahdavi and Mahadevan	2008	Applied	Type A^1 Type A^2	Talks about the joint problem of the cell formation and the cellular layout using the CLASS algorithm.
Pillai and Subbarao	2008	Descriptive	Type A^1	Established a robust design methodology for designing CMS that involve dynamic and deterministic production requirement.
Sangwan and Kodali	2009	Applied	Type B^1	Proposed a multicriteria Quadratic Assignment Problem for CMS layout with the objective of increasing the closeness rating and reducing the material handling cost
Ahi *et al.*	2009	Applied	Type A^1 Type A^2	Suggested a two-step method for cell formation, cell layout, and intracellular machine layout as three necessary steps in the design of CMS by applying multiple attribute decision making concepts.
Ahkioon *et al.*	2009	Descriptive	Type A^1 Type B^1	Examines the problem of designing CMS for various factors like operation sequence, multi-period production planning, machine capacity, dynamic system reconfiguration, and machine procurement.
Kioon *et al.*	2009	Applied	Type A^1 Type A^2	Projected a model for CMS design considering production planning and system reconfiguration decisions and solved it using integer non-linear program
Aliabadi *et al.*	2010	Applied	Type A^1	Presented a mathematical approach for modelling the CM system design problem for assembly aspects.
Abadi *et al.*	2010	Applied	Type A^2	Proposed a model for the design and layout of CMS for dynamics demand.
Papaioannou and Wilson	2010	Empirical	Type C	Presents cell formation literature survey with the focus on different cell formulation methods proposed by researchers during 1997-2008.
Ribeiro	2010	Applied	Type A^1	Presented a method of colouring graphs for cell formation in CM.
Aryanezhad *et al.*	2010	Applied	Type A^1 Type B^2	Proposed a mathematical model for cellular manufacturing system design problem considering scheduling and cell formation issues concurrently.
Kesen *et al.*	2010	Applied	Type B^2	Proposed a GA based heuristic approach for job scheduling in the design of CM cells.
Ghosh *et al.*	2010	Empirical	Type A^1	Discusses various metaheuristic techniques of cell formation problem in cellular

				manufacturing
Sarac and Ozcelik	2010	Applied	Type A^1	Proposed GA for cell formation in a cellular manufacturing system.
Elmi *et al.*	2011	Applied	Type B^2	Suggested an integer linear programming model for the scheduling issues to reduce the makespan considering movement between inter-cell and non-consecutive multiple processing of parts on a machine in CMS.
Garbie	2011	Empirical	Type A^1	Offered a concept for transforming job shop manufacturing systems into cellular manufacturing system (CMS) considering globalization issues.
Modak *et al.*	2011	Comparative	Type A^1	Employed SLCA, C-Linkage, and K-Means algorithms to form part families.
Akturk	2011	Applied	Type B^1	Developed a hierarchical multi-objective heuristic algorithm for the cell loading decisions, lot sizes for every item and sequencing of items containing the GT families at each manufacturing cell with the objective function of reducing the setup, inventory holding, overtime and tardiness costs.
Taghavi-fard *et al.*	2011	Applied	Type B^2	Presents a position-based learning model in CMS for group scheduling in flow shop systems with the objective to minimize makespan and total tardiness.
Arora *et al.*	2011	Empirical	Type C	Confer different techniques of cell formation and show the significant research work done in the past years to bring up the research gap.
Kanani *et al.*	2011	Applied	Type B^2	Presents a new mathematical model for a multi-criteria GT problem in CMS to reduce the makespan and costs of intercellular movement, tardiness, and sequence-dependent setup, simultaneously.
Kruger	2012	Empirical	Type C	Presented a case study on employing CM in a make to order manufacturing system.
Zee	2012	Descriptive	Type B^1	Presented family-based dispatching with batch availability
Egilmez and Siier	2012	Empirical	Type B^1	Works on a cell loading problem for a multi-period as a case study in an organization with the objective of minimizing the total tardy jobs.
Arkat *et al.*	2012	Applied	Type A^1	Developed branch and bound algorithms for the cell formation problem in CMS.
Arkat *et al.*	2012	Applied	Type A^1 Type A^2	Presents a mathematical model for simultaneously identifying the cell formation, cellular layout and the

				operation's sequence of jobs in a cell with the objective to minimize makespan as well as total transportation cost of parts.
Karthiikeyan *et al.*	2012	Descriptive	Type B^2	Tended to the issue of scheduling in cellular manufacturing systems that comprises of various manufacturing cells with the aim to minimize the penalty cost.
Mutingi *et al.*	2012	Applied	Type A^1 Type A^2	Presents an improved algorithm for discourse cell formation and cell layout problems simultaneously considering the sequence of data.
Aghajani *et al.*	2012	Applied	Type A^1	Introduce a mixed-integer nonlinear programming model to lessen the cost of determining the number of kanbans, size of the batch, and the total number of batches in CMS.
Pasupuleti	2012	Applied	Type A^1	Proposed a methodology for arranging the parts, as well as scheduling in a cellular manufacturing system.
Zadeh *et al.*	2013	Descriptive	Type A^1	Presented a broad framework of integrated production planning, process planning and control in CM and also developed an integrated model based on Integrated Modelling Language.
Dixit and Gupta	2013	Empirical	Type C	Presents the results of a survey carried out in implementing cellular manufacturing system in Indian industries
Arora *et al.*	2013	Empirical	Type C	Confer different techniques of cell formation and show the major research work done in the past years to bring up the research gap.
Javadi *et al.*	2013	Applied	Type A^2 Type A^3	Presented a novel mathematical model for the inter-cell and intra-cell layout problem in designing CMS under the dynamic environment.
Chang *et al.*	2013	Applied	Type A^1 Type A^2	Formulated a two-stage mathematical programming model to incorporate cell formation, cell layout and intracellular machine sequencing issues considering alternative process routings, operation sequences, production volume, and the cellular layout type.
Alhourani	2013	Applied	Type B^1	Developed a novel broad similarity coefficient that includes multiple process routings, the sequence of operations, production quantity, duplicate machines, and machines capacity in CM.
Metternich	2013	Descriptive	Type A^1	Focuses on finding appropriate performance indicators to assess economic

				fields of application of CM with a practical example of milling.
Solimanpur and Elmi	2013	Applied	Type B[2]	Offered a mixed-integer linear programming model for scheduling issues in CM.
Megala and Rajendran	2013	Applied	Type A[1]	Proposed an improved ant-colony optimization (IACO) algorithm for cell formation.
Askin	2013	Empirical	Type A[1] Type C	Reviews the increases in CM area of particular importance on the IJPR and presented general formulation for the design of CM.
Kia *et al.*	2013	Applied	Type A[2]	Proposed a multi-objective mixed-integer nonlinear programming model for CMS layout design.
Carmo-Silva	2013	Empirical	Type C	Carried out a complete industrial study for changing a production system into CMS in a leather manufacturing company.
Das *et al.*	2013	Empirical	Type A[1]	Provides an overview of the important features of group technology.
Ayough *et al.*	2014	Applied	Type B[2]	Presented a new mathematical model for job shop scheduling problem in virtual manufacturing cells that minimizes the completion time of all jobs.
Baykasoglu and Gorkemli	2014	Applied	Type A[1]	Presented a new agent-based clustering algorithm for cell formation in CM by considering the dynamic environment.
Shiyas and Pillai	2014	Applied	Type A[1]	Presents an algorithm for part families and manufacturing cells design with the objective to maximize grouping efficiency.
Li *et al.*	2014	Applied	Type A[1]	Developed a combinational ant colony optimization (CACO) approach, for the single-processing machines and the batch-processing machine, respectively.
Arkat and Ghahve	2014	Applied	Type B[2]	Proposed a bi-objective mixed integer programming model for scheduling in virtual manufacturing (VM) cells with outsourcing.
Neufeld *et al.*	2014	Descriptive	Type B[2]	Emphases on the flow shop group scheduling problem with the objective to minimize makespan.
Halat and Bashirzadeh	2014	Applied	Type A[2]	Developed an integer linear programming model, considering intercellular movement times, exceptional elements and sequence-dependent family setup times.
Khanna *et al.*	2014	Empirical	Type C	Presents a succinct review of the literature in group technology.
Raja and	2014	Applied	Type A[1]	Presents a new heuristic approach

Anbumalar			Type A[3]	considering the flow matrix which simultaneously finds part grouping and cell formation, intracellular layout, and voids issues for the design of CMS.
Darla *et al.*	2014	Applied	Type A[2]	Developed a mathematical model considering intercellular movement and cell load variation and optimize the solution using GA.
Seifermann *et al.*	2014	Empirical	Type A[1]	Presents an evaluation of work measurement concepts for cellular manufacturing.
Won and Logendran *et al.*	2014	Applied	Type A[1]	Proposed an effective two-phase p-median approach for the cell formation (CF) in the CMS design.
Costa *et al.*	2015	Applied	Type B[2]	Developed a hybrid genetic algorithm (GA) incorporating features from random sampling to minimize the makespan in a flow shop scheduling problem.
Ulutas	2015	Applied	Type A[1]	Introduce a Clonal Selection Algorithm to solve cell formation problem and generate optimal cell assignment based on machine/part matrix.
Pimentel and Martins	2015	Empirical	Type C	Implemented cellular manufacturing concept in Durit company with the objective of minimizing non-value added operations.
Zeng *et al.*	2015	Applied	Type B[1]	Presented a nonlinear mathematical programming model to find out the sequences of the parts processed on the machine.
Alhourani	2015	Applied	Type B[1]	Developed a novel similarity coefficient which integrates machine capacity, machine reliability and parts alternative process routing.
Egilmez and Suer	2015	Descriptive	Type B[1]	Addresses a multi-period cell loading problem with objectives to reduce the number of tardy jobs and optimize the scheduling of tardy job.
Haraguchi *et al.*	2015	Descriptive	Type B[2]	Proposed operator allocation and scheduling method using skill index for practical training under the stable order condition.
Liu *et al.*	2015	Applied	Type A[1]	Introduced a new optimization model for CMS under dual-resource constrained setting along with an efficient discrete bacteria foraging algorithm (DBFA)
Karim and Biswas	2015	Empirical	Type A[1]	Address the major works within the field of cell formation problem in a batch-oriented production system with a focus on models

				and algorithms established for obtaining the solution for the primary issue of the design of cell manufacturing.
Kumar and Sharma	2015	Applied	Type A[1]	Develop an easy and simple to understand cell formation technique by considering the number of production and manufacturing flexibility-related factors.
Ghosh *et al.*	2015	Applied	Type A[2]	Suggested a new Immune Genetic algorithm (Immune- GA-RS) for inter-cell layout in the CMS.
Li *et al.*	2015	Applied	Type B[2]	Presents a hybrid harmony search for flow line manufacturing cell scheduling problem (FMCSP) with the objective of minimizing total tardiness and mean total flow time.
Delgoshaei *et al.*	2016	Empirical	Type C	Presents a review of material moving techniques with their effects on CMS.
Houshyar *et al.*	2016	Applied	Type A[1]	Proposed the linear mathematical model for dynamic CMS for grouping the machines in the cell.
Kamalakannan *et al.*	2016	Applied	Type A[1]	Proposed an ant colony algorithm to solve the cell formation problem based on machine-index and part assignment rule with the objective of increasing group efficacy.
Karthikeyan *et al.*	2016	Applied	Type A[1]	Proposed a meta-heuristics for the design of Dynamic Cellular Manufacturing System (DCMS) using a genetic algorithm to minimize holding cost, back order cost, machine cost, and salary cost.
Imran *et al.*	2016	Applied	Type A[2]	Proposed a simulation integrated hybrid GA for layout design in CMS to minimize the cost of value-added work in processes.
Hazarika and Laha	2016	Applied	Type A[1]	Proposed a heuristic approach based on Euclidean Distance matrix for cell formation in multiple routes, process sequential and parts volume problems.
Mohammadi and Forghani	2016	Applied	Type A[2]	Present a S –shaped new layout framework, for the design of the layout of CMS.
Amruthnath and Gupta	2016	Applied	Type A[1]	Presented a modified rank order clustering (MROC) method for cell formation considering weight and data reorganization.
Raja and Anbumalar	2016	Applied	Type A[1]	Proposed a newly generalized similarity coefficient method to integrate feasibility assessment and cell formation problem with the consideration of operation sequence
Saad	2016	Descriptive	Type A[1]	Investigated the effects features associated with demand variation like the arrival of

				material and the product mix in CMS.
Fahmy	2016	Applied	Type A^1 Type A^2 Type B^2	Presented a GA to solve cell formation, GT layout, and scheduling problem concurrently.
Suemitsu	2016	Applied	Type A^2	Proposed a new multi-objective layout design optimization technique for robotic cellular manufacturing system layouts that can simultaneously determine the task scheduling and positions of manufacturing components.
Yang *et al.*	2016	Applied	Type A^1	Proposed an improved discrete particle swarm optimization method to reduce the makespan.
Bychkov and Batsyan	2017	Applied	Type A^1	Proposed a novel mixed-integer linear programming model for solving the problem of cell formation with a variable number of manufacturing cells.
Bychkov *et al.*	2017	Applied	Type A^1	Presents a new heuristic algorithm for solving the cell formulation problem.
Romero - Dessens	2017	Empirical	Type A^1	Designed an efficient value stream mapping to improve the flow of materials and increase the productivity by eliminating non-value added activities at an electronic components manufacturer
Allahyari and Azab	2017	Applied	Type A^2 Type A^3	Formulated a bi-level mixed-integer non-linear programming model to discuss the problem and to identify the relationship between intra-cell and inter-cell layout design.
Delgoshaei and Ali	2017	Applied	Type B^1	Proposed a method for location-allocation of skilled workers in CMS and solved the model using ant colony optimization
Feng *et al.*	2017	Applied	Type A^1 Type B^1	Introduce a linear model for allocation of machine, parts, and the worker using particle swarm optimization
Tariq and Bulgak	2017	Applied	Type A^1	Presented a mixed integer linear programming model for production planning and the cell formation problem
Yiyo and Liu	2017	Applied	Type B^1	Proposed a mixed-integer programming model for worker assignment considering inter-cell workforce transfer.
Jawahar, and Subhaa	2017	Applied	Type A^1 Type B^1 Type B^2	Proposed a linear model for part machine assignment to the cell, number of cell and scheduling. Author solved the model using GA.
Rezazadeh *et al.*	2017	Applied	Type A^1	Presents a mathematical model to improved

				product quality and reliability of CMS. Author solved the model using GA.
Almonacid *et al.*	2017	Applied	Type A[1]	Employ the firefly algorithm and Egyptian vulture optimization algorithm for the cell for cell design problem.

Table III. Methodology and problem solving approach

Different research studies are divided into four types – conceptual, descriptive, empirical and comparative. (Dangayach and Deshmukh, 2001). The connotation of these research methodologies is given below:

- *Conceptual:* basic or fundamental concepts of CM
- *Descriptive:* explanation or description of CM content or process, performance measurement issues.
- *Empirical:* data for the study has been taken from existing database, review, case study, taxonomy, or typological approaches.
- *Comparative:* comparison between two or more practices or solutions and the evaluation of the best method or a solution.

Apart from these, many researchers also used applied type research methodology refers to scientific study and research that seek to solve practical problems in cellular manufacturing.

The different problem-solving approaches used by different researchers are cassified into six types- Type A^1, type A^2, Type A^3, Type B^1, Type B^2 and Type C. The meaning of these approaches is given below:

Type A^1: Conceptual and cell formation related approach

Type A^2: Arrangement of the cells within the shop floor (inter-cell) related approach

Type A^3: Arrangement of the machine within each cell (intra-cell) related approach

Type B^1: Cell loading and assignment pertaining approach

Type B^2: Cell scheduling pertaining approach

Type C: Review and case study related approach

3. Descriptive analysis of the research papers

Some of the discussion and explanations on the literature review from Table III are offered in this section.

Dispersion of different research methodologies utilized by multiple researchers appears in Table IV and Figure 3. A result shown in Table IV represents that around 63 percent of papers are applied based research in CM. This is a healthy sign that most of the researchers are focusing on the design of CM. Table IV also reveals that comparative studies are less detailed when contrasted with other methodologies and only 1 percent studies based on a blend of different research methodologies.

Methodology	Percentage
Applied	63 %
Empirical	17 %
Descriptive	12 %
Conceptual	4 %
Comparative	3 %
Mixed	1 %

Table IV. Percentage distribution of different methodology

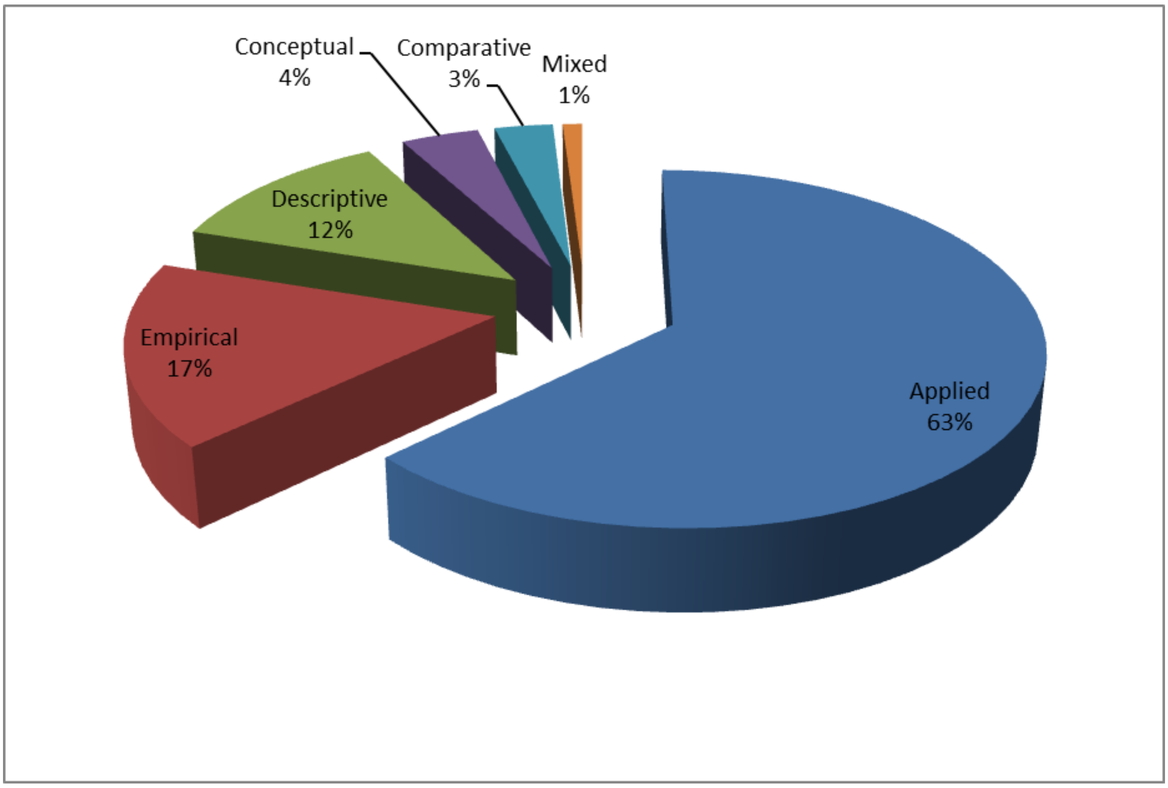

Figure 3. Distribution of Methodology Used In CM Literature

Distribution of various problems solving approach related to CM utilized by researchers appears is shown in Table V and Figure 4. The result shown in Table V shows that 51 percent of papers are Type A^1 problem-solving approach that is discussing cell formation related issues in CM. It is evident from this data that the cell formation aspects appear to lead research theme throughout the literature and layout and scheduling related issues seem to have gotten less consideration from researchers. Furthermore, there is less attention to combination type approach.

Problem-solving approach	Percentage
Type A^1	51 %
Type B^2	11 %
Type C	10 %
Type B^1	10 %
Mixed	10 %
Type A^2	8 %
Type A^3	0 %

Table V. Percentage distribution of different problem solving approach

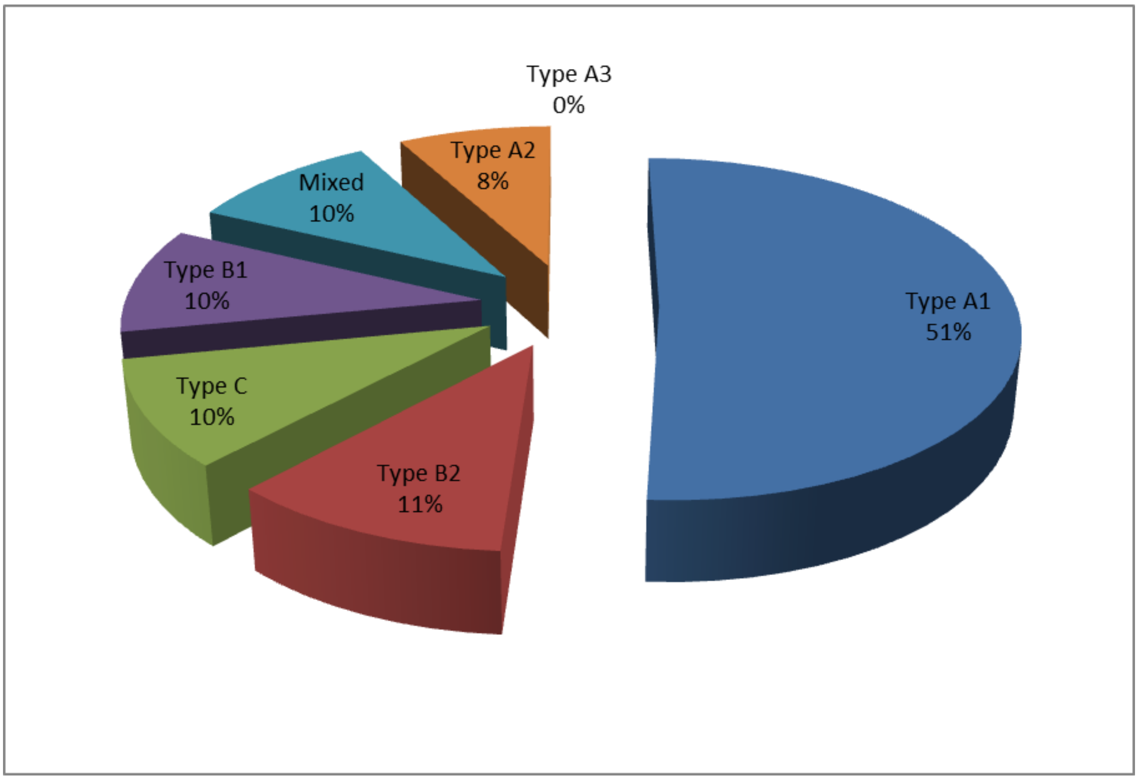

Figure 4. Distribution of Various Problems Solving Approach Related To CM

The trend of authorship countrywide is as follows. United States of America (USA) drove the research with more than 22 % of total articles followed by India with more than 19 % of full articles. Iran came third by producing 13 % of the research articles. Contributions of other countries are China 6 %, Canada 4 %, and Turkey 4 %. Contributions of the countries with less than 3 % are Germany, Hong Kong, Italy, Japan, UK, South Africa, Malaysia, Mexico, Netherlands, Singapore, Oman, Korea and West Indies.

As cell formation aspects have a dominant research theme in the literature, the following section discusses various cell formation techniques in brief.

4. Cell formation technique

Early techniques developed for solving group technology, and cellular manufacturing problems are as follows:

Visual inspection is the technique where parts are classified into part families, based on the components or pictures of the parts. However, this technique is unsuitable for large-scale and though this approach is easy to understand its success is depended on human experience.

Classification and coding are an improvement on the previous technique where parts are classified into appropriate families, based on the number of attributes, such as dimensions of the part; a shape of the part; material of part; tolerance requirement. Usually, each part is assigned a code and each code representing an attribute of the part. Parts with the same codes are formed into the same part family. It may be because of the design orientation and exclusive nature of most coding techniques; they are not famously known as the research literature of CM. Like other, this technique also tries to group parts into families assuming likenesses in design and manufacturing attributes. This idea was first presented by Mitrofanov [1966] and Opitz et al. [1969].

Production flow analysis (PFA) is the technique where parts are classified into appropriate families using routing information or operation sequences. This technique also identifies machine cells using input as a complete list of machines and machine capabilities.

In last few decades' numbers of researchers have developed methods for formation of cells in cellular manufacturing as shown in Table VI.

Cell Formation Methods			
Mathematical Programming	**Cluster Algorithm**	**Heuristics and Meta-heuristics**	**Artificial Intelligence**
Assignment	Bond Energy Analysis	Ant Colony Optimization	Fuzzy Approach
Integer Programming	Rank Order Clustering	Bees Algorithm	Neural Network
Linear Programming	Modified Rank Order Clustering	Discrete Bacteria Algorithm	
Mixed Integer Linear Programming	Similarity Coefficient	Egyptian Vulture Optimization Algorithm	
Quadratic Programming		Genetic Algorithm	
		Particle Swarm Optimization	
		Simulated Annealing	
		Tabu search	

Table VI. Different cell formation methods

Mathematical programming methods are commonly in use in cellular manufacturing systems. A researcher proposes mathematical methods of programming such as linear programming, goal programming and dynamic programming. Mathematical programming methods can easily include some design logic in their objective functions and constraint functions. One of the first to apply linear programming in the GT program was Purcheck (1975). In the case of part families and machine grouping, Srinivasan proposed an assignment model. These techniques solve the machine-part grouping problem optimally. Being an optimization method, the objective of this method could be to maximize the total sum of likenesses between each pair of machines or parts. The researchers, who utilized distinctive mathematical programming techniques to formulate the cell formation problem, are presented in Table VII.

Mathematical Technique	Researchers
Assignment	(Srinlvasan, Narendran, & Mahadevan, 1990) (J. Wang, 2003) (Sangwan & Kodali, 2009)
Integer Programming	(Gunasingh & Lashkari, 1986) (Balakrishnan & Cheng, 2007) (Ah kioon, Bulgak, & Bektas, 2009) (Egilmez & Suer, 2012) (Javani, n.d.)
Linear Programming	(Davis & Mabert, 2000) (Malakooti, Malakooti, & Yang, 2007) (Aliabadi & Aryanezhad, 2010) (Akturk, 2011) (Askin, 2013) (Zeng, Tang, & Yan, 2014)

	(Houshyar et al., 2016)
Mixed Integer Linear Programming	(Das, Lashkari, & Sengupta, 2007) (Kia, Shirazi, Javadian, & Tavakkoli-Moghaddam, 2013) (Costa, Cappadonna, & Fichera, 2014) (Fahmy, 2016) (Aljuneidi & Bulgak, 2017) (Kuo & Liu, 2017) (Bychkov & Batsyn, 2017)
Quadratic Programming	(Srivastava & Chen, 1995) (H. Wang, Alidaee, Glover, & Kochenberger, 2006)

Table VII. Mathematical techniques and researchers

Cluster algorithm incorporates numerous assorted methods for identifying structure in a complex data set. Incidence matrix of machines is used for the array based clustering. This matrix represents handling necessities of parts of machines. Different clustering algorithms that have been proposed are Bond Energy Analysis (BEA), Rank Order Clustering (ROC), Rank Order Clustering 2 (ROC2), Modified Rank Order Clustering (MODROC), and Direct Clustering Algorithm (DCA). In Hierarchical clustering technique's, machine cells are formed employing a similarity or distance function between machines or parts and then machines or parts is detached into a couple of giant cells, every one of which is further subdivided into smaller groups. Common Hierarchical clustering technique that has been proposed is Single Linkage Clustering (SLC) algorithm. McAuley was the first author that applied similarity coefficient to solve the cell formation problems in 1972. The Rank Cluster (ROC) method was developed by King in 1980, which is designed to generate a diagonal grouping of the machine component matrix. McCormick in 1972 developed bond energy algorithm. In the machine component matrix, a bonding energy is formed between the pair of row elements and the column elements, which is the result of the connection pair of element values. The researchers, who used different clustering techniques to formulate the cell formation problem, are presented in Table VIII.

Clustering Technique	Researchers
Rank Order Clustering	(Murugan & Selladurai, 2007) (Amruthnath & Gupta, 2016)
Similarity Coefficient	(Witte, 1980) (Waghodekar & Sahu, 1984) (Gupta, 1991) (Seifoddini & Hsu, 1994) (Islam & Sarker, 2000) (Alhourani, 2013) (Raja & Anbumalar, 2016)

Table VIII. Clustering techniques and researchers

Heuristics and Meta-heuristics techniques provide an alternative basis for solving a cell formation problem. Although a heuristics technique does not insure for the optimum solution, they are beneficial in giving a feasible solution. In order to solve a wide range of optimization problems, particularly combined problems, metaheuristic techniques are used. Different algorithms that have been proposed are Genetic Algorithm (GA), Simulated Annealing (SA), Tabu search, Particle Swarm Optimization (PSO), Ant Colony Optimization (ACO).

At first, Holland [1975] developed a methodology for GA that comprises an arrangement of steps, which are followed to move from one generation to another. Venugopal and Narendran in 1992 proposed a solution procedure based on GA for part-machine cell formulation. Kirkpatrick was the first researcher to use SA in 1983. SA, in fact, is the replication of the actual annealing process in which a system, at a higher energy level, is permitted to be cooled progressively in a controlled situation until it attains its lowest energy level. The researchers, who used different heuristic and meta-heuristic techniques to formulate the cell formation problem, are presented in Table IX.

Heuristics and Meta-heuristics Technique	Researchers
Ant Colony	(Prabhaharan, Asokan, Girish, & Muruganandam, 2005) (Mak, Peng, Wang, & Lau, 2007) (Megala & Rajendran, 2013) (Li, Meng, Li, & Tian, 2016)
Bees Algorithm	(Pham, Afify, & Koc, 2007)
Discrete Bacteria Algorithm	(Liu, Wang, Leung, & Li, 2016)
Egyptian Vulture Optimization Algorithm	(Almonacid, Aspée, Soto, Crawford, & Lama, 2017)
Genetic Algorithm	(Sridhar & Rajendran, 1996) (Onwubolu & Mutingi, 2001) (França, Gupta, Mendes, Moscato, & Veltink, 2005) (Kulkarni & Shanker, 2007) (Wu, Chu, Wang, & Yan, 2007) (Pillai & Subbarao, 2008) (Aryanezhad, Aliabadi, & Tavakkoli-Moghaddam, 2011) (Taghavi-Fard, Javanshir, Roueintan, & Soleimany, 2011) (Saraç & Ozcelik, 2012) (Jamal Arkat, Farahani, & Hosseini, 2012) (Javadi, Jolai, Slomp, Rabbani, & Tavakkoli-Moghaddam, 2014) (Shiyas & Madhusudanan Pillai, 2014) (Jamal1 Arkat

	& Ghahve, 2014) (Halat & Bashirzadeh, 2015) (Darla, Naiju, Sagar, & Likhit, 2014) (Ghosh, Doloi, & Dan, 2016) (Saravanan, Karthikeyan, & Rajkumar, 2014) (Imran, Kang, Hae Lee, Zaib, & Aziz, 2016) (Suemitsu et al., 2016) (Jawahar & Subhaa, 2017) (Rezazadeh & Khiali-Miab, 2017)
Heuristic	(Harhalakis, Nagi, & Proth, 1990) (Mutingi, Mbohwa, Mhlanga, & Goriwondo, 2012) (Kumar & Sharma, 2015) (Raja & Anbumalar, 2016) (Hazarika & Laha, 2016) (Yang, Chen, & Long, 2016) (Bychkov, Batsyn, & Pardalos, 2017)
Particle Swarm Optimization	(Aghajani, Keramati, & Javadi, 2012) (Feng, Da, Xi, Pan, & Xia, 2017)
Simulated Annealing	(Venkataramanaiah, 2008) (Elmi, Solimanpur, Topaloglu, & Elmi, 2011) (Karthikeyan, Saravanan, & Ganesh, 2012) (Mohammadi & Forghani, 2016)
Tabu Search	(Logendran, Ramakrjshna, & Sriskandarajah, 1994)(Lozano, Adenso-Diaz, Eguia, & Onieva, 1999) (Chang, Wu, & Wu, 2013) (Solimanpur & Elmi, 2013) (Delgoshaei & Ali, 2017)

Table IX. Heuristic and Meta-heuristic techniques and researchers

The Fuzzy-based approach answers the problem where parts whose heredities are significantly less bright. Fuzzy logic was invented by Lofty Zadeh in 1965. Fuzzy logic is interesting artificial intelligence (AI) tool as it gives a simple way to obtain the specific solution for a problem while utilizing vague or unclear input information. Chu & Hayya in 1991 uses the fuzzy C-mean algorithm to the cell formation problem.

Neural networks techniques commonly applied in cell formation due to their robust and adaptive nature. The application of neural networks to CM is comparatively new and has attracted the attention of a few researchers (Moon, 1990) (Karparthi, 1991) (Venugopal 1992) (Rao & Gu, 1993).

5. Discussions and future directions

The present study, talk about the literature survey of 170 articles on CM published during 1979 –2017. Since the number of published articles on CM is vast and yet rising at a quicker pace, it was chosen for the investigation to think about the intensive arrangement of information for the better impression of history and the future research in CM.

- The magnificence of CMS is developing day by day on account of its useful outcome on the performance of the organization; this made to substantial development in published articles in different journals. In section 3, it is found that most of the research is taking place in cell formation. The accentuation appears to have been on evolving "new" methods instead of on assessing the present commitments. In most research, either matrix manipulation or mathematical programming has often been used to build cells. The majority of the cell formulations endeavor to make "independent" cells by reducing the number of parts processed in various cells. Different formulations address limiting the expenses of copying machines while a couple of attempts to create cells such as that capacity is balanced between and inside cells. Though, very few of them integrate all above objectives. From the perspective of applicability, justification, design and execution, Wemerlov and Hyer (1988) investigated research questions related to CMS. The majority of the problems rose by them need to explore and answer.
- The study found that conceptual and cell formation related approach constitutes around 51 % of total research articles. More attention should be given to layout, scheduling, loading, assignment, capacity planning, and related behavioral issues in CM. Consideration should also be given to integrated approach where different parameters are combining for optimum design and operate the CMS.
- Very little has been done to discuss flexibility in the manufacturing process for cell formation. "Cellular" production flexibility must be addressed as vital and prosperous competitive arms. In the presence of diverse machines, the reliability of machine tools is also a subject to study.
- There are significant numbers of cell formation techniques presented by different researchers. There is a need to evaluate and compare these techniques. Furthermore, these techniques must be verified to assess their performance in practical conditions. Cell formation method ought to incorporate documented and verified supporting software to simplify industrial applications. While mathematical model/ algorithm fit for tending to various aspects of CM have been developed, there does not exist an exhaustive framework to assess these calculations, and select the one that best suits the prerequisite of a manager.
- Findings of exact investigations on CM need to carried out which will undoubtedly be valuable to both academia and industry to propose a framework for its execution. Additionally, research can be done to propose optimal location of machines inside the cell considering facility layout.

- Empirical research is needed to assess the impact of CM in the real industry. There is a need to develop a relationship between CM implementation factors. There is also required to analyze barrier of CM implementation. Little attention has been paid to the key performance indicators (KPIs) analysis. There is a need to make the hierarchical structure to categorize KPIs and to identify and analyse the fundamental relationships between them. More comprehensive studies on the relationships between KPIs and their dependencies to supporting elements are needed. Multi criteria decision making methods like, AHP, ANP, ISM, DEMATEL can be used to identify and prioritize critical factors about CM implementation.
- Concerning authorship, in the study, it has been found that researchers from USA and India are more vigorous towards others in CM research. There is a need to poise the geographical dominion of the authors. There must be a joint effort among Institutes & Industries of created nations with developing and undeveloped nation to energize research in their region.
- There is a need to deploy CM to different manufacturing sectors, regular and non-customary businesses to enhance the overall organization performance. Exact research likewise should be done to learn whether CM is appropriate in unstable demand or not.

6. Conclusion

In this paper, an effort has been made to review the literature on CM. This paper compiles various reported definitions of cellular manufacturing and also presents a literature classification scheme focuses on research contribution, research methodologies, and problem-solving approach. Descriptive analysis of the research papers is also performed, and various cell formation techniques in cellular manufacturing are discussed briefly. Studying the extensive variety of research articles in CM, it can be inferred that the perception of CM mostly affects experts and academicians. The study suggested that there is a need to concentrate more on integrated approach where different parameters are combining for optimum design and operate the CMS. The study further proposes that the academicians need to cooperate with the industries to show signs of improvement come about and comprehend the CM implementation process. To fortify the results of the study, future researchers may take a still more significant sample size of articles to improve the outcomes.

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A life-cycle Assessment of Household Semi-automatic Washing Machine in India

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ABSTRACT

Washing machine is a regularly used device and an integral part of most households all over the world. Increase in the world's population coupled with rapid economic development has resulted in the increased use of washing machines among households for laundry instead of hand washing practices. Washing machines account for 14% of total water consumption by households globally and have the second larger share after toilets (Application, Data, Saly, & Sheelo, 2010), also it is highly energy intensive device that results in many negative impacts on the environment. Its performance is influenced by various parameters such as water temperature, washing load, frequency of use, and the detergent used, which depend mainly on consumer preferences as well as the specifications of every washing machine. The study's primary objective is to quantify the environmental impacts of the current range of 5 kg semi-automatic washing machine. This will be achieved through conducting the 'Life Cycle Assessment' as per ISO 14040/44 standard for washing machine from cradle to grave in Indian scenario to evaluate the various environmental performance indicators such as primary energy demand, global warming potential, blue water consumption, human toxicity, air emissions in a holistic manner using the GaBi version 8.0 software. The study's secondary objective is to suggest and analyze different future scenarios that would reduce the overall environmental impact of the washing machine.

The results of the LCA have indicated that global warming potential, human toxicity potential, primary energy demand, and blue water consumption showed the highest burden on the environment compared to other categories. The use stage of the washing machines is the dominant stage in most of the selected categories. The hotspots in the life cycle of a washing machine have been identified as electricity consumption in the usage phase and the consumption of material resources (such as steel & plastics) in the assembly phase. This quantitative life cycle assessment helps decision-makers to understand the life-cycle environmental impacts of Indian refrigerators and improve its sustainability.

Key Words: Life Cycle Assessment, GaBi, Washing machine, sustainability, ISO 14040/44

1. Introduction

A washing machine is a regularly used device and an integral part of most households all over the world. Also Laundromat is approximately 50% more expensive than using the domestic washer due to machine utilization vending charges (Garcilaso, Jordan, Kumar, Hutchins, & Sutherland, 2007). This has resulted in the increased use of washing machines among households for laundry instead of hand washing practices. According to a DuPont report published in 2013, "Indian Consumer Laundry Study," only 8.8% of all Indian households owned a washing machine (DuPont, 2013). In India growth of washing machine purchase grew from 1.4 million units in 2005-06 to almost between 2.0 to 2.3 million units in 2007-08. For the 5-year span between 2006-07 and 2011-12, the market for washing machines was estimated to rise at 9.3% ("Indiastat," n.d.). The stock of all washing machines in India in 2011 stood at 16.5 million units; out of which rural and urban India contribute 2.2 and 14.3 million units respectively (The World Bank, 2008). Therefore there is a need of practices of various waste management initiatives in

India and there is a bigger scope for enhancement in the waste management (Agarwal, Chaudhary, & Singh, 2015).

Further through various studies, it has been found that the use phase of a washing machine has the highest environmental impact with a major contribution from water usage (~92%), GWP (~73%), Fossil fuel depletion (~62%) and energy use (~60%) of the life cycle impact (McNamara, 2013). WRAP (Waste and Resources Action Programme, 2010) suggests that machine refurbishment is the most environmentally beneficial option because it has a very small contribution to global warming, resource depletion, acidification and photochemical oxidation. Integration of a recovery system able to recover approximately 40% of usable surfactants would cut by half the environmental impacts of current industrial washing machines (Giagnorio, Amelio, & Tiraferri, 2017). Besides, e-wastes generated by the end of life washing machines also hits the environment (Kumar, 2013). Hence, Recycling and eco-design are the best priorities of the washing machine (Park, Tahara, Jeong, & Lee, 2006). The cold washing has the lowest environmental impact due to the fact that extra energy is required to heat the water for the hot cycle but excessive use of detergent or fabric conditioner by even 1% increases the overall impact (Arup, 2010). The impeller machines are less energy intensive than drum washing machines. On the other hand, drum washing machines are more water efficient than impeller ones (Bao et al., 2017). According to Mathews & Beemkumar (2015), front-loading washing machine is superior to a conventional washing machine in every aspect of use phase.

When consumer behavior changes towards waiting until enough laundry is accumulated so that the rated capacity of the washing machine is employed, sustainable use of washing machines with a higher rated capacity could be done (Lasic, 2014).

Based on the above studies a suggestion regarding the provision of proper training and education about the environment to the Indian residents is given based on similar practice adopted in China by Yuan, Zhang, & Liu (2016) for the optimization of consumers' washing habits.

The main objective is to evaluate the environmental impacts associated with the value chain of manufacturing of a low capacity washing machine. As it is found that small capacity washing machines have a slightly more environmental footprint (Rüdenauer, 2005). This will be achieved through conducting the 'Life Cycle Assessment' as per ISO 14040/44 standard for washing machine from cradle to grave in the Indian scenario. Life Cycle Assessment approach is one of the key tools for evaluating and assessing the environmental burdens associated with resource consumption, energy consumption, emissions, effluent, and solid waste generation during the lifespan of the product. To conduct a credible LCA, it is critical to use good quality, current data on all raw materials, energy, and processing aids used as well as the environmental outputs associated with producing a product because this information becomes the platform for performing the life cycle inventories (LCIs) which are the basis for the LCA. The effect of washing machine effect and reverse washing machine effect as suggested by Cullen & Allwood (2009) is taken care in this study.

2. Methods

To carry out the Life Cycle Assessment for the semi-automatic washing machine household product as per the ISO 14040/44 with the help of mid-point CML methodology. This study was conducted in accordance with the principles of the International Organization for Standardization's (ISO) 14040:2006 series of standards for LCA. LCA is usually carried out in four steps: (1) goal and scope definition, (2) life cycle inventory (LCI) analysis, (3) life cycle impact assessment (LCIA) and (4) life cycle improvement analysis and interpretation. These steps are described in detail below.

2.1 Goal and Scope Definition

The goal of the study is to provide the solution of specific questions which have been raised by the target audience while considering the potential uses of the study's results and quantification of environmental impacts of the semi-automatic washing machine product over cradle-to-grave life cycle stages. The scope of the study defines the system's boundary regarding geographical, technological, and temporal coverage of the LCA study.

2.2 System Boundary

The study is a cradle-to-grave LCI study of the washing machine product. That is, it covers all the production steps from raw materials in the earth (i.e. the cradle) to the production of washing machine product, downstream transport, use phase and end of life in Indian Context. The washing machine was dismantled to collect information about the different materials that constitute the washing machine and prepared the bill of materials (i.e., BOM). The outcome of the disassembly process is used as an input for the modeling of the inventory part of the life cycle assessment. The material production includes the raw material extraction, production of the raw materials and auxiliary material production. The production process contains the in-house manufacturing processes and the transport from supplier to the site. The typical life cycle of washing machine product system can be modeled using a system of different process steps in accordance with the system boundary shown in figure 1.

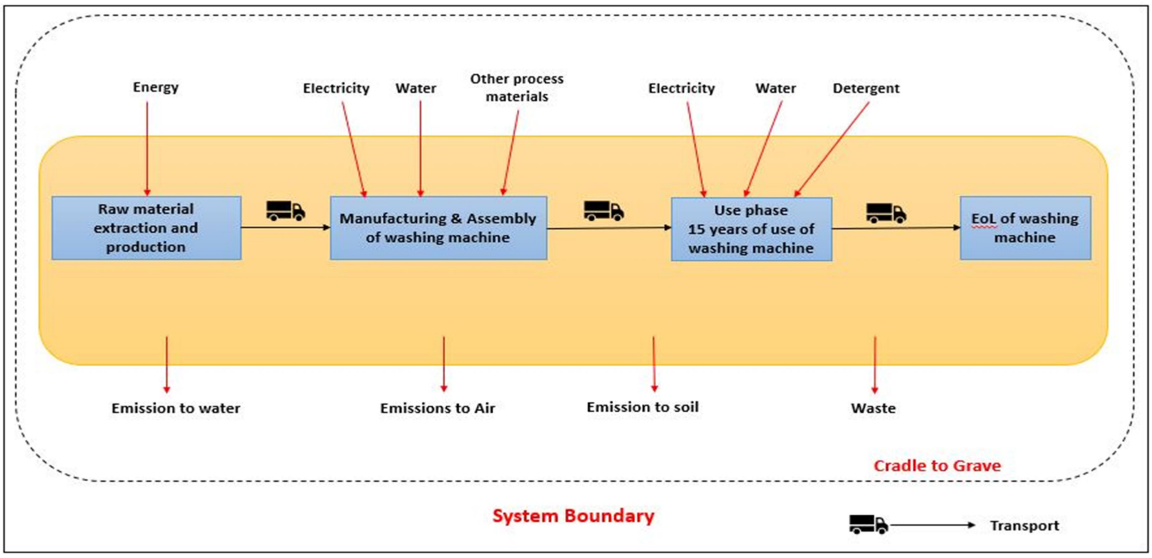


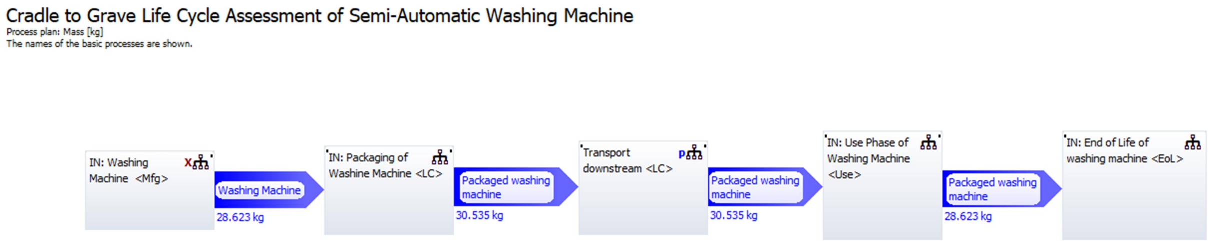
Figure 1. System Boundary for the Selected Products

Table 1: Details of System Boundary Included in the Study

Life Cycle stages	Life Cycle sub-stages	Definitions
Materials	Primary raw materials production	Extraction, production of the raw materials such as plastic tub, sheet metal etc.
Upstream Transport	-	Transport of the raw materials
Manufacturing	Parts production, assembly and packaging	Manufacturing of washing machine products through process
Downstream Transport	-	Transport of the final product i.e. semi-automatic washing machine
Use phase	15 years of use of product	
End-of-Life (EoL)	Reuse/ recycle or disposal	Recycling and/or final disposal in landfill after useful life of product

2.3 Functional Unit

The functional unit, which provides the reference for inputs and outputs throughout the system, in this study functional unit is one piece of a washing machine with an expected lifespan of 15 years. The study covers all the production steps from raw materials in the earth (i.e., the cradle) to the production of washing machine products and delivery at the factory gate. The main reason for choosing the particular load capacity is that 5kg is the maximum load for most of the washing



machines available in the Indian market.

Figure 2. LCA model of Semi-automatic washing machine product in GaBi software

2.4 Data Collection

All data were collected and provided for a semi-automatic washing machine for Indian context by visiting the domestic appliances repair shop in the market. Product specific data collection questionnaire was prepared and filled by teardown process. During the teardown process, the components of the washing machine were divided into material fractions trying to be as detailed as possible to determine the total weight of the washing machine, subparts, and each child parts.After that bill of materials (can be found in Table no.) was prepared and it is used as an input for the modeling of the inventory part of the LCA. Water, energy and other materials consumption data of the machine during their manufacturing and utilization stage were collected from the literature and Bureau of Energy Efficiency (BEE) respectively ("SCHEDULE – 12 Washing Machines," 2016). A Compilation of inventory of all the materials that are used for the manufacturing of the machines study. The secondary source of data was GaBi database 2018 and some of the data used were from average data obtained from the literature.

2.5 Life Cycle Inventory

The life cycle inventory (LCI) stage documents qualitatively and quantitatively analyze the materials and energy used (inputs) as well as the products and by-products generated and the environmental releases regarding non-retained emissions to the environmental compartments and the wastes to be treated (outputs) for the studied product system.

The LCI data are useful for: to understand wastes, total emissions, and resource use associated with the material or the studied product; improve production or product performance; or be further analyzed and interpreted to provide insights into the potential environmental impacts from the system (life cycle impact assessment and interpretation, LCIA)

A bill of materials is a list of the raw materials, sub-assemblies, sub-components, and the quantities of each part needed to manufacture a product. The selected semi-automatic washing machine was dismantled to collect different materials information that constitutes the clothes washer.

Table 2 Bill of material of washing machine

S. No.	Material	Material classification	Components	No. of pieces	Unit	Weight	Manufacturing process

0			Washing Machine	1	Kg	28.623	
1	Plastic	HDPE PE	Bottom Body Trolley	1	g	1650	Extrusion
1	Plastic	HDPE PE	(Washing & Spinning) Body	1	g	6014	Moulding
1	Plastic	EPDM	Wire & Plug (electric)	1	g	55	
1	Plastic	HDPE PE	Switch Panel	1	g	150	Extrusion
1	Aluminium	Aluminium	Shell (Capacitor) Combined	1	g	188	Extrusion
1	Steel	Steel	Side Body Cover	1	g	7000	Sheet Metal
1			Wheel Assembly	4	g	72	
2	Plastic	ABS	Wheel	4	g	32	Extrusion
2	Steel	Steel	Wheel Shaft	4	g	40	Extrusion
Washing Tub							
1			Gearbox & Pulley	1	g	750	Machining, Drilling, Casting
2	Plastic	ABS	Pulley	1	g	75	Extrusion
2	Plastic	Elastomers	Seal	1	g	10	Extrusion
2	Steel	Steel	Gearbox	1	g	665	Forging
1			Wash Motor	1	g	3600	
2	Plastic	EPDM	Insulation & Harness	1	g	18	
2	Copper	Copper	Wire	1	g	450	Drawing
2	Aluminium	Aluminium	Wash Motor Pulley	1	g	200	Casting, Machining
2	Steel	Steel	Nuts & Bolts	4	g	32	Extrusion
2	Steel	Steel	Cover Body	1	g	2900	Casting
1	Plastic	EPDM	Belt	1	g	36	
1			Wash Timer	1	g	112	
2	Plastic	POM	Gear	4	g	8	Extrusion
2	Plastic	ABS	Cover Body	1	g	29	Extrusion
2	Steel	Steel	Nuts & Bolts	8	g	24	Extrusion
2	Aluminium	Aluminium	Shaft	1	g	8	Drawing
2	Plastic	Elastomers	Washer	1	g	3	Thermoforming
2	Plastic	Phenol Formaldehyde Resin	Knob	2	g	20	Extrusion

2	Copper	Copper	Wiring	1	g	15	Drawing
2	Steel	Steel	Shaft	1	g	5	Drawing
1	Plastic	ABS	Pulsator	1	g	450	Extrusion
1	Steel	Steel	Nuts & Bolts	1	g	8	Extrusion
1	Plastic	PVC	Button NET	1	g	20	Thermoforming
1	Plastic	PVC	Over Flow Pipe	1	g	30	Extrusion
1	Plastic	ABS	Wash Door	1	g	508	Thermoforming
1	Plastic	Phenol Formaldehyde Resin	Drain Switch	1	g	25	Extrusion
1	Plastic	Phenol Formaldehyde Resin	Water Selector	1	g	35	Extrusion
1	Plastic	Phenol Formaldehyde Resin	Water Level	1	g	50	Extrusion
1			Buzzer	1	g	80	Extrusion
2	Copper	Copper	Wire	1	g	35	Drawing
2	Steel	Steel	Body	1	g	40	Sheet Metal
2	Plastic	Phenol Formaldehyde Resin	Knob	1	g	5	Extrusion
Spin (Dryer)							
1			Drum Assembly	1	g	3100	
2	Steel	Steel	Shaft	1	g	150	Drawing
2	Steel	Steel	Drum	1	g	2850	Casting
2	Plastic	Elastomers	Seal	1	g	80	Thermoforming
2	Copper	Copper	Sleeve	1	g	20	Casting
1			Spin Motor	1	g	3300	
2	Steel	Steel	Cover body	1	g	2064	Sheet Metal
2	Copper	Copper	Wiring	1	g	400	Drawing
2	Steel	Steel	Pulley	1	g	250	Casting
2	Steel	Steel	Nuts & Bolts	6	g	48	Extrusion
2	Steel	Steel	Brake Plate	1	g	150	Casting
2	Steel	Steel	Spring	1	g	10	Drawing
2			Shocker	3	g	378	
3	Plastic	HDPE PE	PART1	3	g	9	Extrusion
3	Plastic	Elastomers	PART2	3	g	30	Thermoforming
3	Steel	Steel	PART3	3	g	339	Casting
1			Hydraulic Assembly	1	g	370	

2	Plastic	PVC	Drain System	1	g	154	Extrusion
2	Plastic	PVC	Drain Pipe	1	g	132	Extrusion
2	Plastic	PVC	Over Flow Pipe	1	g	32	Extrusion
2			Washer Assembly	1	g	52	
3	Steel	Steel	Spring	1	g	2	Wire Drawing
3	Plastic	Elastomers	Washer	1	g	25	Thermoforming
3	Plastic	HDPE PE	Lid	1	g	25	Thermoforming
1			Spin Timer	1	g	60	
2	Plastic	POM	Gear	4	g	8	Injection Moulding, Cutting
2	Steel	Steel	strip	1	g	8	Sheet Metal, Metal Cutting
2	Steel	Steel	Nuts & Bolts	3	g	6	Cold Extrusion
2	Aluminium	Aluminium	Shaft	1	g	8	Extrusion
2	Plastic	ABS	Cover Body	1	g	15	Extrusion
2	Plastic	Phenol Formaldehyde Resin	Knob	1	g	10	Extrusion
2	Copper	Copper	Wiring	1	g	5	Wire Drawing
1	Plastic	Phenol Formaldehyde Resin	Door Switch	1	g	10	Injection Moulding
1	Plastic	ABS	Spin Door	1	g	420	Injection Moulding
1	Plastic	ABS	Safety Door	1	g	280	Injection Moulding
1	Plastic	ABS	Safety Net	1	g	150	Injection Moulding
1	Steel	Steel	Brake Wire	1	g	100	Wire Drawing

Table 3: Process data for the manufacturing and assembly

S. No.	Input data for manufacturing & Assembly	Unit	Quantity
1	Compressed air	m^3	1.41
2	Steam	kg	0.52
3	Water	kg	4.39
4	Electricity	kWh	47.91
5	Epoxy resin	kg	6.37E-02
6	Phosphating agent	kg	3.82E-03
7	Degreaser	kg	3.97E-03
8	Surface conditioning agent	g	0.19
9	Heavy Fuel Oil	kg	0.18

S. No.	Output data for manufacturing & Assembly	Unit	Quantity
1	Non-methane hydrocarbon	g	0.13
2	waste water	kg	3.82
3	suspended solids (SS)	kg	1.91E-03
4	Chemical oxygen demand (COD)	kg	2.29E-03
5	Phosphate sludge	g	6.49E-03
S. No.	**Packaging data**	**Unit**	**Quantity**
1	Kraft liner	kg	1.10
2	Nylon	kg	8.50E-02
3	Paper	kg	0.13
4	Polyethylene (PE)	kg	0.17
5	Polystyrene (PS)	kg	0.42

Table 4: Use phase data of washing machine

	Energy	Water	Detergent
Main customer segment	Household laundry purpose		
Typical use intensity: Annual amount of cleaned laundry (Kg/year) for a 5kg capacity semi-automatic washing machine	1585		
Specific consumption in use phase (Acc. to BEE Report) maximum value for 2-star rating	0.0157 kWh/Kg	120 litres/wash cycle	55 g/wash cycle
Annual consumption in use phase	24.8845 kWh	38040 litres	17435 g
Annual wash cycle (Acc. to BEE report)	317 wash cycle/machine/year		
Average Life span of semi-automatic washing machine	15 years		
Average cold-water temperature	27° C		
Average Hot water temperature	48° C		

Table 5: End-of-Life details for washing machine

	Base case (%)
Recycle steel	85 (as per world steel LCA report)
Landfill steel	15
Recycle Copper	100
Landfill copper	-
Recycled Aluminium	100
Landfill Aluminium	-
Recycled Plastic	-
Landfill Plastic	100

2.6 LCIA Methods

The LCA of washing machine model was created using the GaBi version 8.0 for life cycle assessment, developed by thinkstep AG ("thinkstep," n.d.). Environmental impact indicators viz. Global warming potential (GWP), Acidification potential (AP), Primary energy demand (PED), Photochemical ozone creation potential (POCP), Abiotic resource depletion (ADP) and Ozone depletion potential (ODP) were evaluated.

The LCIA phase includes the following mandatory elements:

• Selection of impact categories, category indicators, and characterization models

• Assignment of LCI results to the selected impact categories (classification)

• Calculation of category indicator results (characterization)

Classification: a mapping of items in the inventory to known environmental effects or impacts (e.g., global warming, acidification, resource depletion, etc.).

Characterization: a calculation of scientifically-based indices; each index being an estimation of the potential impact of the inventory items contributing to a given environmental effect (e.g., global warming potential, acidification potential, resource depletion, etc.).

The fourth step, Interpretation, consists of the interpretation of LCI and LCIA results which is used to reduce environmental impact.

Table 6 Methodology of Impact Calculation

Impact Category	Units (equivalents)	Source of Impact	Methodology of Impact Calculation
Abiotic Depletion of Fossil elements	kg Sb eq.	Depletion of fossil elements (metals, non-metals etc.)	CML 2016
Acidification Potential (AP)	kg SO_2 eq.	Emission of SO_2, NO_x, NH_4	CML 2016
Eutrophication Potential (EP)	kg Phosphate eq.	Emission of P, PO_4	CML 2016
Global Warming Potential (GWP)	kg CO_2 eq.	Emission of CO_2, N_2O, CH_4 etc.	CML 2016
Human Toxicity Potential (HTP)	kg DCB eq.	Emission of Heavy metals, toxic compounds etc.	CML 2016
Ozone Layer Depletion Potential (ODP)	kg R-11 eq.	Emission of Ozone depleting substances i.e. CFC	CML 2016
Photochemical Ozone Creation Potential (POCP)	kg ethane eq.	Emission of Non-methane volatile organic compounds	CML 2016
Primary Energy Demand	MJ	Energy demand from non-renewable and renewable sources	CML 2016
Blue Water Consumption	m^3	Ground and surface water consumption	CML 2016

3. Result Analysis and Hotspot Identification

3.1 Process-wise Environmental Impacts

The table below shows the process wise life-cycle environmental impacts for production, packaging, usage, and end of life of 5kg semi-automatic household washing machine with an expected lifespan of 15 years. Washing machine Process includes impact for the raw materials consumed, transport of raw material, manufacturing and assembly, use phase, end of life and process emissions. Electricity & Steam includes the impact of fuel combustion. Packaging includes the impact of packaging materials used and its transport.

Table 7: Process-wise Environmental Impacts for 15 years life span of one unit of washing machine

Environmental Indicator	**Source of Impact**	**Manufacturing & Assembly**	**Packaging**	**Downstream-Transport**	**Use Phase**	**End - of – Life**	**Total**
Abiotic Depletion (ADP elements) [kg Sb-Equiv.]	Depletion of fossil elements (metals, non-metals etc.)	9.97E-03	1.36E-06	1.20E-10	9.12E-04	-7.17E-03	3.72E-03
Acidification Potential (AP) [kg SO_2-Equiv.]	SO_2, NOx, NH_4	1.14	1.54E-02	3.98E-05	6.65	-1.42E-01	7.66
Eutrophication Potential (EP) [kg Phosphate-Equiv.]	P, PO_4	0.06	1.94E-03	6.32E-06	4.33E-01	-8.01E-03	0.48
Global Warming Potential (GWP 100 years) [kg CO_2-Equiv.]	CO_2, CH_4, N_2O	1.40E+02	1.92	5.52E-03	9.54E+02	-29.82	1066.31
Human Toxicity Potential (HTP inf.) [kg DCB-Equiv.]	Heavy metals, toxic compound	68.20	0.39	4.81E-04	1.75E+02	-13.38	229.85
Ozone Layer Depletion Potential (ODP, steady state) [kg R11-Equiv.]	ODS i.e. CFC etc.	9.46E-09	4.90E-11	2.79E-14	3.05E-08	-2.49E-10	3.98E-08
Photochemical Ozone Creation Potential (POCP) [kg Ethene-Equiv.]	Non-methyl VOC	0.06	1.24E-03	-9.22E-06	0.35159	-1.59E-02	0.40
Primary energy	Non-	2.23E+03	132.70	7.33E-02	1.43E	-	1.64E

demand net cal. value) [MJ]	renewable and renewable energy				+04	2.71E+02	+04
Blue water consumption [kg]	Ground and surface water	7.96E+02	19.21	8.30E-03	5.77E+05	-67.01	5.78E+05

Impact Profile	Lowest	Highest

3.2 Source wise environmental impacts

Table below shows the environmental impacts for 5kg semi-automatic household washing machine with an expected lifespan of 15 years over the cradle to grave system boundary where impacts are classified on the basis of source of impact generation i.e. Raw Materials, Process Emissions (Impact from manufacturing & Assembly and Use phase of washing machine), Energy (Impact from Electricity consumption), Transport (Transport of Raw Materials), and End of life (credit for the recycled of the metals and plastics).

Table 8: Source wise LCA Impacts for 15 years life span of one unit of washing machine

Environmental Indicator	Source of Impact	Credit	Disposal	Energy	Process Emissions	Raw Materials	Transport	Total
Abiotic Depletion (ADP elements) [kg Sb-Equiv.]	Depletion of fossil elements (metals, non-metals etc.)	-7.17E-03	2.08E-07	3.49E-05	0.00E+00	1.08E-02	9.96E-09	3.72E-03
Acidification Potential (AP) [kg SO_2-Equiv.]	SO_2, NOx, NH_4	-1.44E-01	2.82E-03	6.12E+00	0.00E+00	1.68E+00	5.40E-03	7.66
Eutrophication Potential (EP) [kg Phosphate-Equiv.]	P, PO_4	-1.01E-02	2.50E-03	2.64E-01	5.04E-05	2.27E-01	1.13E-03	0.48
Global Warming Potential (GWP 100 years) [kg CO_2-Equiv.]	CO_2, CH_4, N_2O	-30.72	1.03	5.01E+02	0.00	5.95E+02	0.89	1066.31
Human Toxicity Potential (HTP inf.) [kg DCB-Equiv.]	Heavy metals, toxic compound	-13.41	0.03	165.17	0.00	78.03	0.03	229.85

Ozone Layer Depletion Potential (ODP, steady state) [kg R11-Equiv.]	ODS i.e. CFC etc.	-2.51E-10	2.50E-12	1.21E-08	0.00E+00	2.80E-08	7.45E-13	3.98E-08
Photochemical Ozone Creation Potential (POCP) [kg Ethene-Equiv.]	Non-methyl VOC	-0.02	3.15E-04	2.86E-01	0.00E+00	1.29E-01	-2.00E-03	3.96E-01
Primary energy demand net cal. value) [MJ]	Non-renewable and renewable energy	-2.85E+02	1.63E+01	5.90E+03	0.00E+00	1.07E+04	1.21E+01	1.64E+04
Blue water consumption [kg]	Ground and surface water	-67.04	0.04	3.56E+03	4.39	5.74E+05	0.24	5.78E+05

Impact Profile	Lowest										Highest

3.3 Scenarios wise comparative environmental impacts

The scenario technique aims to show possible futures based on a scientific process. It is the goal of scenarios to spread out possible ways and consequences of development, thus giving support to decision makers. In addition, one or two other (or even more) scenarios are defined giving a clue how major changes would form other futures with different impacts and consequences.

Table 9: Scenarios wise LCA Impacts for 15 years life span of one unit of washing machine

Environmental Indicator	**Source of Impact**	**Base Case**	**Scenario-1**	**Scenario-2**	**Scenario-3**	**Scenario-4**	**Scenario-5**
Abiotic Depletion (ADP elements) [kg Sb-Equiv.]	Depletion of fossil elements (metals, non-metals etc.)	3.72E-03	4.89E-03	3.71E-03	3.73E-03	1.09E-02	3.72E-03
Acidification Potential (AP) [kg SO_2-Equiv.]	SO_2, NOx, NH_4	7.66	2.33	6.28	10.37	7.81	7.68
Eutrophication Potential (EP) [kg Phosphate-Equiv.]	P, PO_4	0.48	0.26	0.43	0.60	0.50	0.49
Global Warming Potential (GWP 100 years) [kg CO_2-Equiv.]	CO_2, CH_4, N_2O	1066.31	644.66	953.36	1287.69	1097.75	1071.25
Human Toxicity Potential (HTP inf.) [kg DCB-Equiv.]	Heavy metals, toxic compound	2.30E+02	9.91E+01	1.93E+02	3.03E+02	2.43E+02	2.31E+02

Ozone Layer Depletion Potential (ODP, steady state) [kg R11-Equiv.]	ODS i.e. CFC etc.	3.98E-08	2.96E-08	3.71E-08	4.52E-08	4.01E-08	3.98E-08
Photochemical Ozone Creation Potential (POCP) [kg Ethene-Equiv.]	Non-methyl VOC	3.96E-01	1.51E-01	3.32E-01	5.23E-01	4.13E-01	3.99E-01
Primary energy demand net cal. value) [MJ]	Non-renewable and renewable energy	1.64E+04	2.16E+04	1.51E+04	1.90E+04	1.67E+04	1.64E+04
Blue water consumption [kg]	Ground and surface water	5.78E+05	5.75E+05	5.77E+05	5.79E+05	5.78E+05	5.78E+05

Impact Profile	Lowest	Highest

The scenario analysis aims to evaluate possible ways and consequences of development, thus giving support to decision makers. The five scenarios were identified to evaluate how significant changes would form other futures with different impacts and consequences. Scenario wise % contribution to LCIA is shown in table 10.

Scenario 1 - Energy substitution

In the base case, energy is used for grid electricity in use phase, but in scenario one energy is substituted from grid to photovoltaic cell, i.e., solar energy.

Scenario 2 – Technology enhancement

In this scenario, five-star rating washing machine is used, and data collected from the BEE report. In the base case, the two-star rating washing machine is used.

Maximum (kWh/kg)	Minimum (kWh/kg)	Star Band	Electricity required in 1 cycle (kWh)
0.0157 ≥	≥ 0.0143	2 Star	0.0785
< 0.0117		5 Star	0.0585

Scenario 3 – Hot water in use phase

In base case of this study, room temperature of water (~27° C) is used in the use phase of washing in all wash cycles. In this scenario, hot water is used in 20% of the wash cycle in a year, i.e., 63 wash cycles are considered as hot water wash cycles in rainy season only. Maximum hot water temperature is 48° C is used according to the BEE report in Indian usage. To achieve the temperature of hot water from the cold water by the direct heating concept is applied.

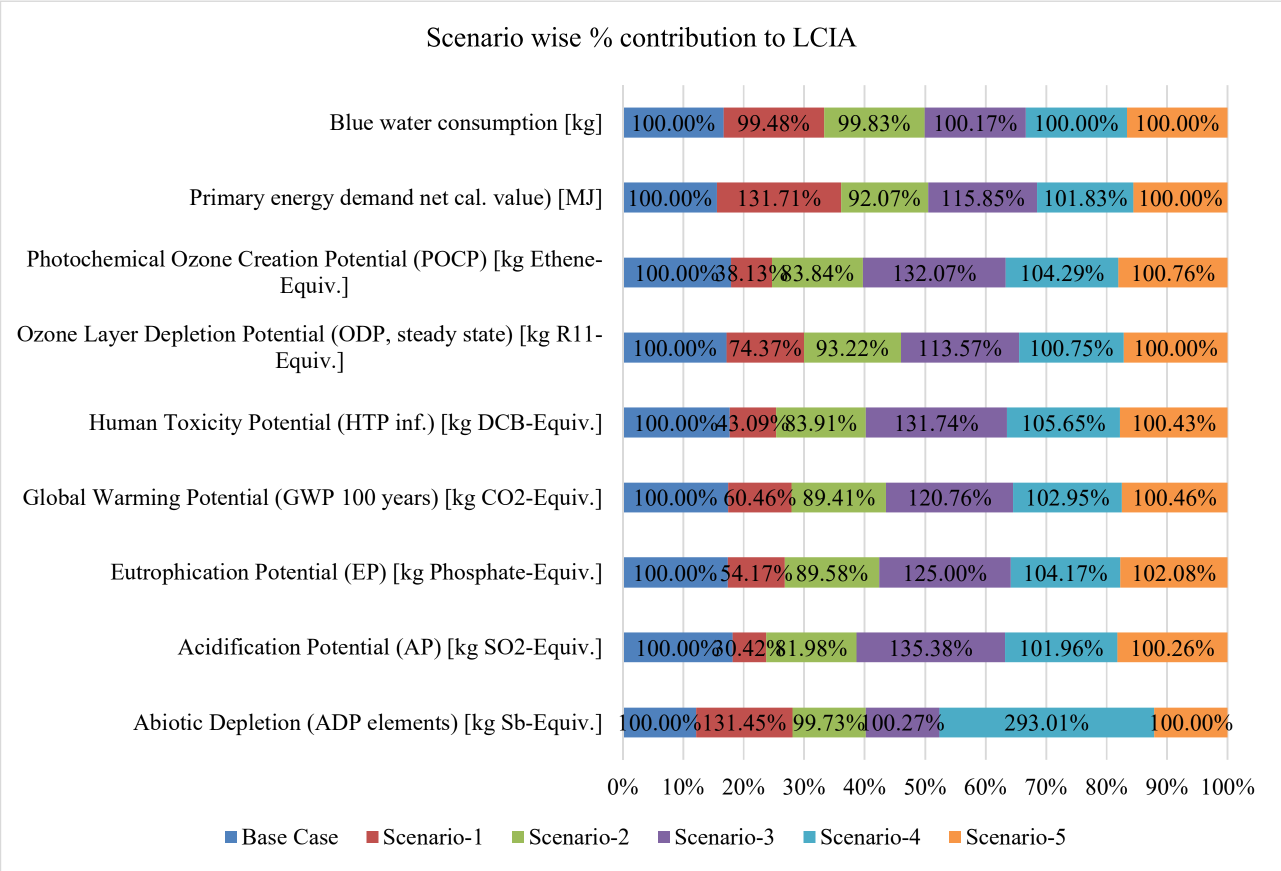
Scenario 4 – No recycling of materials

In this scenario, it is considered that all material components are disposed of in the landfill. With the comparison of base case in this scenario steel, aluminum, copper, plastic completely goes into landfill.

Scenario 5 – Steel and Plastic variation

In scenario-5, it is considered that plastic materials replace steel materials. For that weight of the steel is reduced by 20% from the base case and 15.74% increases plastic weight by assuming that on average mass of the steel components have six-time more massive than of the plastic parts.

Table 10: Scenario Wise % contribution to LCIA Impacts for 15 years life span of one unit of washing machine



5. Conclusions

The objective of the study as well as project, i.e., "Quantify environmental impacts of the household 5 kg capacity semi-automatic washing machine product over cradle-to-grave system boundary and identify the hotspots in the value chain of the products for optimization and further reduction of environmental impacts was achieved as an outcome of this study.

Various environmental impacts across the identified system boundary were quantified, studied across various life cycle stages and hotspot analysis was carried out. Wherever the contribution analysis was more than 25%; a scenario analysis was conducted for the best-case scenario in terms of material optimization and substitution with recycled or environmental efficient material, efficiency improvement, energy mix improvements, service life extension of the product, water temperature scenarios. Through these scenarios, the best-case scenario, practically applicable to Indian situation were applied, studied and inferences were drawn.

There were certain limitations of the study due to non-availability of part level data or material information which resulted in carrying out the analysis one level higher or considering the closed proxies of the uncertain information. However, appropriate data quality considerations in terms of completeness, timeliness, consistencies, geographical references were closely tracked and ensured the overall high-quality data and represents the actual scenario.

Some of the environmental impact categories showed the highest value out of the selected categories. Hotspots have been identified on process and source level in these indicators.

Global Warming Potential is 1066.31 kg CO2-Equiv. with the major contribution from Use phase of the washing machine (~89.46%) and washing machine production and assembly process (~13.15%). In Use phase electricity accounts for 41.57%, tap water accounts for 30.61% and detergent accounts for 17.26% of the total impacts. In the washing machine production and assembly process electricity alone accounts for 5.35% and spin dryer assembly for 2.97% of the total impact, packaging accounts for 0.18% and end of life accounts for -2.79% of the total life-cycle impacts.

Human Toxicity Potential is 229.85-gram DCB- Equiv., with the major contribution from Use phase of the washing machine (~75.98%) and washing machine production and assembly process (~29.67%) and packaging alone accounts for 0.17%, and end of life accounts for -5.82% of the total life-cycle impacts.

Primary Energy Demand is 1.64 E+04 MJ with major contribution Use phase of the washing machine (~87.249%) and washing machine production and assembly process (~13.56%). In Use phase electricity accounts for 31.88%, tap water accounts for 21.72% and detergent accounts for 33.63% of the total impacts. In the washing machine production and assembly process electricity accounts for 4.09% and spin dryer assembly for 2.62% of the total impact, and packaging accounts for 0.81% and end of life accounts for -1.65% of the total life-cycle impacts.

Blue Water Consumption is 5.78 E+05 kg with the major contribution from Use phase of the washing machine for ~99.871% of the total impact.

The outcome of this study can be directly used in the vendor qualification process leading to a business proposition of this study.

6. Future scope:

As a next step extension to the study, a fully automatic machine can be compared with the semi-automated washing machine. This was not the objective of the current study; however, as another goal was to identify hotspots, I am presuming that a fully automated machine will have better savings and lesser impacts which can be recognized as an extension of the study. Future research includes expanding the system boundary to cover cradle to cradle, i.e., recycling benefits. Internal and external benchmarking for the value chain can be initiated. Further product wise LCA can be performed for application of new generation domestic appliances products.

The results obtained, show that an environmentally aware society along with national regulation on energy and water consumption can help decrease the environmental impact significantly. However, the most significant change required is awareness among the consumers and an initiative among individuals to reduce their environmental impact. So, the effect of a washing machine on the environment relies heavily on consumers' behaviour.

Consumer choice and behaviour can be highly variable and a major contributor to the environmental impact of typical household activities such as washing, cleaning etc. Interactions between consumers and products may have a large effect on the overall results of life cycle assessment (LCA) studies. However, the variability in consumer behaviour is often not included in LCAs because these are generally aimed at quantifying the average impact of a process or a product rather than the full extent of possible outcomes like in environmental risk assessment methods.

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Design and experimental evaluation ofsuper alloy bone plates for transverse fractured tibia bone using Inter-fragmentary strain theory.

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Abstract Fractured tibia bone healing is primarily influenced by themechanical and biological environment at the fracture site. Inter-fragmentary strain and Von-Misses stress developed at the callus formation play a crucial role in the timely healing of the bone which isaffected by design and material of the bone fixation plate.This paper presents an investigation on the design of tibia bone plates made of titanium alloy (C, 0.10 %; N, 0.03 %; O2, 0.25 %; H2, 0.015 %; Fe, 0.30 %; and Ti, 99.03 %.)to improve bone remodeling and efficient fracture healing. A time-dependent analysis up to 16 weeks in the interval of 4 weeks is carried out to analyze the healing process of a fractured bone under various loading conditions. The healing of the bone is analyzed using Finite Element Analysis (FEA) to determine the Inter-fragmentary strain (IFS) between 2%-10% to get optimal healing results which depend on different parameters of the bone plates like the plate thickness, working length, thegap between the bone and bone plate. Moreover, these parameters are varied with an objective to minimise the stress on the bone as it hinders the blood supply into the bone. Results indicatethe behaviour of the Inter-fragmentary strain and Von-Mises stress on the bone and bone plate throughout the healing period with varying loading conditions.

Keywords Tibia Bone.Inter-fragmentary Strain Theory.Finite Element Analysis. Bone Plates.Titanium Alloy.

1 INTRODUCTION

Fracture in tibia bone occurs in many ways depending on the external load acting on the bone during impact. Different types of tibia bone fractures such as stable fracture, transverse fracture,oblique fracture, spiral fracture, comminuted fracture, and open fracture and their characteristics depend on the external load acting on the bone during impact [6].Three major phasesof fracture healing are reactive, reparative, and remodelling phase[10]. Bone plates stabilise fractures while allowing for adequate compressive force on the fracture ends and decrease the fracture gap by the formation of endosteal callus [21]. Mechanical loading environment is known to have an influence on bone's mass, structure, the control of interfragmentary movement and implant failure [19].As the callus formation rate is directly proportional to the compressive force between the fracture ends, shielding due to bone plates, delays callus formation, which retards the bone healing rate [2][8].From a biomechanical point of view, fracture fixation must possess sufficient stability, to reduce interfragmentary movement occurring due to external loading and muscle activity to such an extent that it promotes timely and fruitful fracture healing. In general, parameters which influence fixator stiffness are its material properties, geometry of the fixator , fixator position relative to bending direction (plate fixator), number and position of screws, screw type, arrangement of screws, the offset distance from the underside of the fixator to the bone surface (internal plate fixator) [25].The success of any internal fixation depends on the ability to maintain interfragmentary compression. Locked implants like the locking compression plate maintain the interfragmentary compression preliminarily applied by a reduction clamp [14].

Over the years there has been a significant change in the design of bone plates where callus formation, blood supply and stress shielding explains the causes of poor bone healing due to the design of the bone plate.As conventional non-lock plating disrupts the periosteal blood supply and to improve plate fixation even in poor bone stock, the concept of locked plating was developed where the screws are directly fixed to the plate, acting as an internal fixator. Therefore, direct plate to bone contact is no longer required. However, hardware failures such as plate breakage still occur. Required stability and flexibility are measured by the stiffness of the whole bone-plate construct and the movement between the bone fragments at the site of the fracture. Some of the key factors that affect the stiffness and fracture movement are the thickness and material properties of the plate, along with the design, positioning and number of the screws[8].

Hence, this study considers various factors affecting the bone healing process like thickness, working length and gap between the plate and the bone. While designing a bone plate, one should understand the effect of the material surface of the bone plate. From the definition of biocompatibility [3], we can conclude that while choosing proper materials for bone plates one should analyse the corrosion resistance and tissue reaction to the material. Based on corrosion resistance and tissue reactions for various elements and practical alloys, titanium and Ti-alloys categorised as vital and therefore biocompatible and on the contrary that some metallic elements like Cu are categorised as toxic[22].Another aspect deduced from the definition of biocompatibility is the influence of the surface characteristics on bone integration. The previous study sorted that pure Titanium plates with rough surfaces have the best bio-adhesion [4].

In this paper, we focus on the transverse bone fracture in a tibia bone and the design of bone plateplays a crucial role in developing effective, safe and reliable implant especially to reduce problems due to stress shielding, delay of bone healing and formation of weaker bone. In this current study, we analysed the effect of thickness, working length, and the gap distance on healing characteristics of the bone based on two theories namely IFS theory where it suggests that IFS in the fracture gap ranging from 2% to 10% is beneficial for proper callus formation and timely bone healing. The other theory involved isthe design of flexible plating where the plates allow transfer of loads to the bone during initial stages of healing process ensuring a reduction in stress shielding of bones.One should consider the fact that too much flexibility also causes adverse effects due toincreasing in micro movements of the fracture gap, rupturing the tissue around the bone. Therefore, in this study,we primarily focus on designing bone plate for optimal flexibility and obtaining a reduction in stress shielding effect during the initial period of recovery. By maintaining the required fracture gap with proper IFS at the callus formation, considering the effect of thickness of the plate and working length using FEA to find the behaviour of these plate under the given load conditions and during different stages of healing.

2. MATERIALS AND METHODS

2.1Material Selection

Material choices for implementable biomedical products are limited owing to the requirements of biocompatibility, corrosion/fatigue resistance and the difficulties in obtaining regulation clearances. In recent years, Pt alloys are replaced by new titanium alloys owing to the latter's more economical production and better properties [18].There has been a significant increase in the use of titanium and its alloys as biomaterials stem due to their lower modulus, superior biocompatibility, and better corrosion resistance when compared to more conventional stainless and cobalt-based alloys [12]. As a hard tissue replacement, the low elastic modulus of titanium and its alloys is viewed as a biomechanical advantage because the smaller elastic modulus can result in smaller stress shielding. Hence, for the present study, pure Titanium (Grade-2) has been chosen as the test material. The chemical composition of work material taken for experimentation work as follows: C, 0.10 %; N, 0.03 %; O_2, 0.25 %; H_2, 0.015 %; Fe, 0.30 %; and Ti, 99.03 %.

2.2 Designing of bone plate

2.2.1 Geometric Modelling

A Solid Works model developed for both the fractured bone and locking compression plate. A generic plate available in the market and based on vivo studies on different manufactures of bone plates, synthes bone plates are taken as reference due to their smaller length and higher load bearing capacity and modifications are made to obtain the desired results [16].

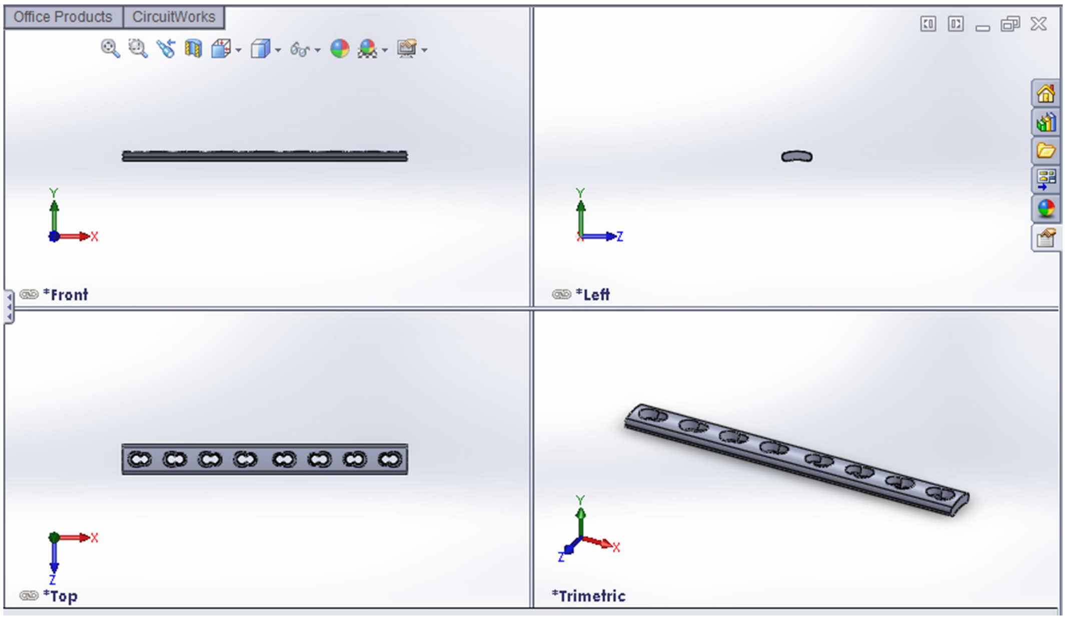

Figure 1a: Geometric Model of Locking Compression Bone Plate

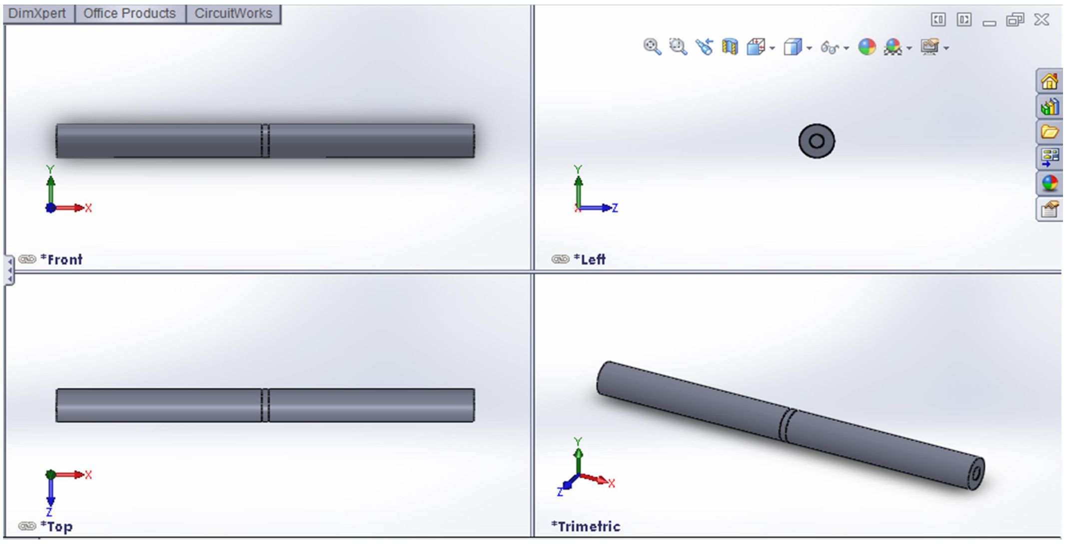

Figure 1b: Geometric Model of Tibia Bone

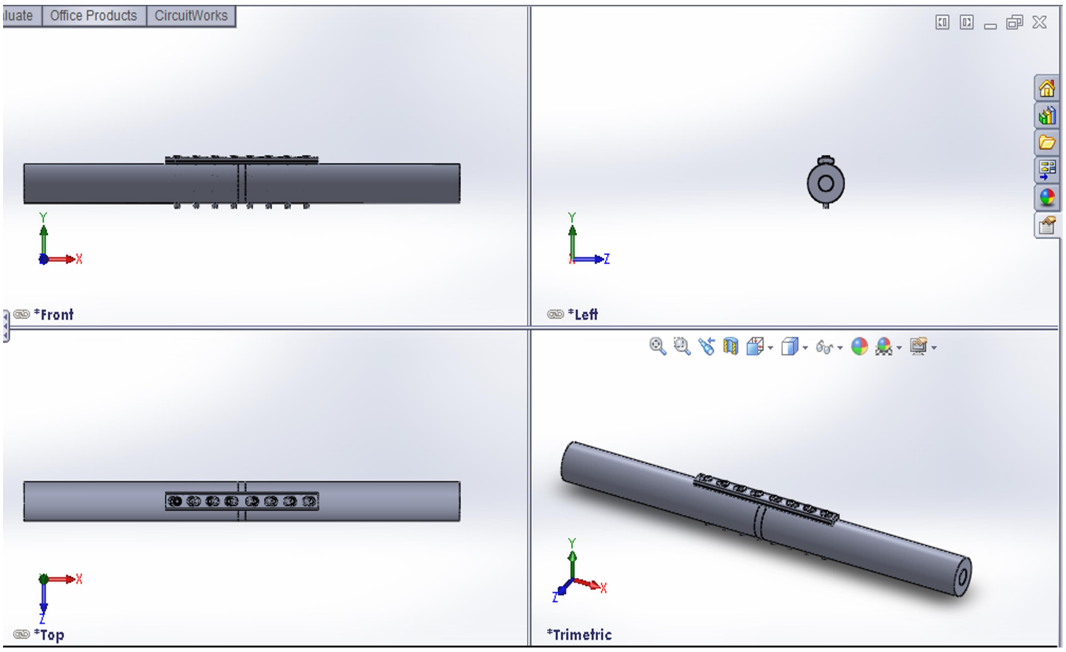

Figure 1c: Assembly of Bone and the Bone Plate

Figure 1a, 1b, 1c shows different geometric models created in this study using SOLIDWORKS software. Tibia bone has an irregular cross-section consisting of a foam-like trabecular bone and cortical bone. To visualise a tibia bone, a cortical bone simplified as a cylinder and the trabecular bone modelled as a circular rod within the cortical bone cylinder [13]. The tibia model has a fracture gap of 5 mm which is filled by the curing tissue (callus) as healing progress; thus, the callus moduli vary throughout the healing period. The bone plate considered in this study has a slender shape with eight screw holes and a curved cross-section.

Different thickness of bone plate starting from 3mm to 4.5mm with an increment of 0.5 mm is used to analyse the effect of thickness of bone plate on IFS and stress-shielding. Table 1a, 1b, 1c and 1d mentions the dimensions utilised in this study for various parts such as trabecular bone, cortical bone, locking compression plate, and locking screw respectively.

Shape	Hollow cylinder
Length	300 mm
Outer Diameter	25 mm

Inner Diameter	10 mm
Fracture Gap	5 mm

Table 1a: Dimensions of Cortical Bone

Shape	Solid cylinder
Length	300 mm
Diameter	10 mm
Fracture Gap	5 mm

Table 1b: Dimensions of Trabecular Bone

Length	105 mm
Width	11 mm
Thickness	3,3.5,4,4.5 mm
Number of holes	8
Gap between holes	13 mm

Table 1c: Dimensions of Locking Compression Plate

Pitch Diameter	3.5 mm
Pitch Distance	0.8 mm
Pitch angle	60
Head Diameter	5 mm
Height	26 mm

Table 1d: Dimensions of Locking Screw

2.2.2 Analysis Condition

The bone with a transverse fracture (5 mm gap) simplified by a hybrid cylinder composed of cortical and trabecular bones[13]. Small sized fractures gaps are filled with the help of bone plates and fractured bone without any bio material [17]. The central callus is most sensitive to the external mechanical stimulus during the healing period [5]. Therefore, our primary focus in this study is to model the central callusfor analysing the IFS acting on it. The isotropic material properties of bones [26], [28] and titanium bone plates listed in Table 2. Although the properties of bone have anisotropic behaviour, yet for this study they are assumed to have isotropic properties along all directions.

Material	**Young's Modulus (Mpa)**	**Poisson's ratio**
Titanium (Grade 2)	105	0.37
Cortical Bone	15	0.3
Trabecular Bone	1.1	0.225

Table 2: Elastic properties of Bone

Calluses generated at the fracture site have different healing rates and properties according to the IFS developed at the site[20].Callus modulus measured at regular, 4-weeklyintervals after surgeryis chosen as thecriterion for timely healing of the bone [9]. Immediately after surgery, only soft granulation tissues (E = 0.02 MPa) are considered to be generated at the fracture site [15]. The callus properties according to the healing period listed in Table 3 [13]. The friction coefficient of 0.4 was taken for all the contact surfaces involved, based on clinical research [7].

S.no	**Duration**	**Young's Modulus (MPa)**	**Poisson's ratio**
1	0-4 weeks	0.02	0.3

2	4-8 weeks	0.19	0.3
3	8-12 weeks	28	0.3
4	12- 16 weeks	30	0.3

Table 3: Time-dependent elastic properties of callus

The second step of the analysis was a loading process under axial compression forces considering the patient's gait cycle where one end of the tibia was fixed in all directions, and an axial force applied to the other end of the tibia. In general, the patient's walking pattern is incomplete—using crutches, the injured leg does not make contact with the ground for a while after surgery. During this period, the injured leg is under a no-load condition; however, some forces are transferred to the tibia by muscles such as the gastrocnemius and soleus around the fracture site [11],[1].In a normal gait cycle, one leg steps on the ground which usually resists a maximum of about 300% of body weight [19].At the same time, the other leg is in a swing phase and does not contact the ground. In the swing phase, some forces are generated by the adjacent muscles, and these forces are known to be in the range of 0–10% of body weight [11]. From these clinical observations, a loading condition of 10% of body weight (700 N x 10%) of a 70kg person during the early period of healing (until eight weeks after surgery) was used in this study. As the healing time elapses, the bony union proceeds and the fracture is partly healed. By considering this healing process, it was assumed that 100% of the body weight was imposed on the tibia until 12 weeks due to the incomplete gait pattern. From 12-16 weeks, it was assumed that the body carries 150% of body weight (Table 4)[13]. These time-dependent loading conditions were applied in the finite element model to calculate the IFSs at the fracture site, and the stresses in the bone plate and bone.

S.no	**Duration**	**Body mass (kg)**	**Loading condition**	**Load (N)**
1	0-4 weeks	70	10 % of Body weight	70
2	4-8 weeks	70	10 % of Body weight	70

3	8-12 weeks	70	100% of Body weight	700
4	12-16 weeks	70	150% of Body weight	1050

Table 4: Time-dependent loading conditions for analysis

2.2.3 Finite Element Analysis (FEA)

FEAis used in the design and evaluation of internal fixation plates and screws to overcome the significant weaknesses of current fixation devices in regards to fatigue failure of the plate and stress-shielding of the bone. The 3D finite element model is analysed using ANSYS Workbench software (version- 15, ANSYS Inc., USA).

Inter-Fragmentary Strain (IFS) defined as the ratio of the fracture gap displacement after the body load applied and the original fracture gap length [27]. In the current study, the IFS theory was used to correlate the level of stimulus (strain) and the corresponding callusstatus. An appropriate mechanical stimulus such as relative micro-movement at the fracture site stimulates generation of callus [20]. IFSs ranging from 2% to 10% suggested as the most appropriate condition for healing bone fractures. Small strains (below2%) have the same effect as an indirect bone healing method. Further, excessive strains (over 30%) cause bone resorption. As the healing period elapses, the fracture gap is filled with curing tissues such as callus, and mechanical properties of the tissues improve. However, this improvement is entirely dependent on the level of mechanical stimulus at the fracture site.

The effects of following conditions were analysed:

(i) Bone plate thickness: Four plate sizes with varying thickness (3mm, 3.5mm, 4mm, and 4.5mm) are analysed with the time-dependent load condition to study its effect on IFS in the fracture gap.

(ii) Working length: The optimal plate is chosen according to plate thickness, and the effect of working length is analysed for proper IFS and better stress shielding effect. In this study, the first step ofthe analysis is carried out with all screws fixed to the bone and furtherremovingtwo innermost screws until better output characteristics obtained.

(iii) Effect of distance between plate and bone: Full contact or no gap between bone and the bone plate results in higher contact stress, and it also diminishes the flow of blood around the fracture gap. As the gap between the bone and plate increases, the rigidity as well as stiffness of the implant decrease. The optimal plate analysed for three gap profiles (0 mm gap, 0.5 mm gap, 1 mm gap).

3. RESULTS

3.1 Effect of bone plate thickness on fractured bone

The effects of plate thickness are analysed where deformation of the callus is studied using the FEA with an increment of 0.5mm starting from plate thickness of 3mm depicting total deformation during the initial recovery period of 4 weeks. Figure 2a, 2b,2c and 2ddepict the results of deformation in meters at the fractured gap which is filled with callus during the application of load and also show the deformationwith achange in thickness of the plate during the initial period of recovery (i.e., 0-4 weeks).

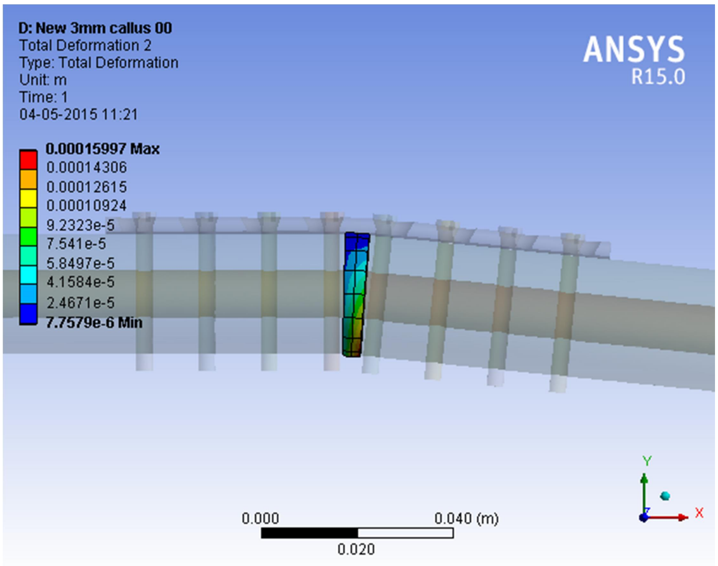

Figure 2a: Deformation at callus for a 3 mm thick bone plate during 0-4 weeks

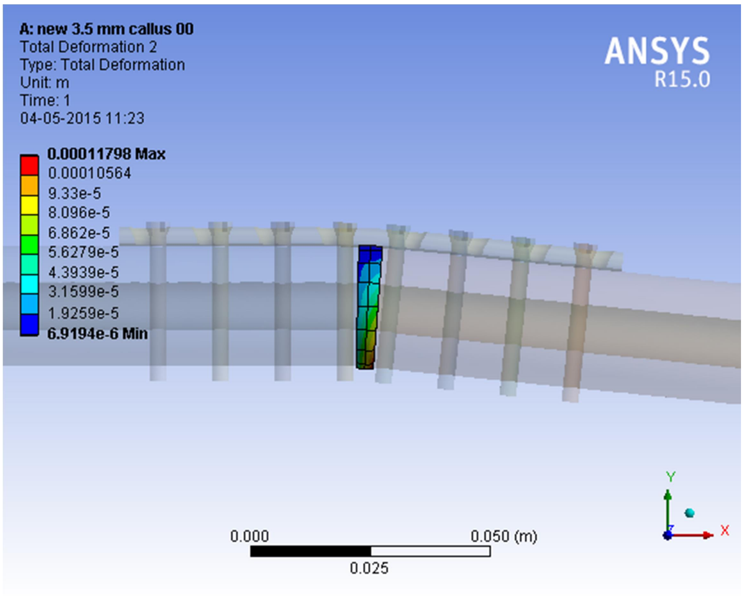

Figure 2b: Deformation at callus for a 3.5 mm thick bone plate during 0-4 week

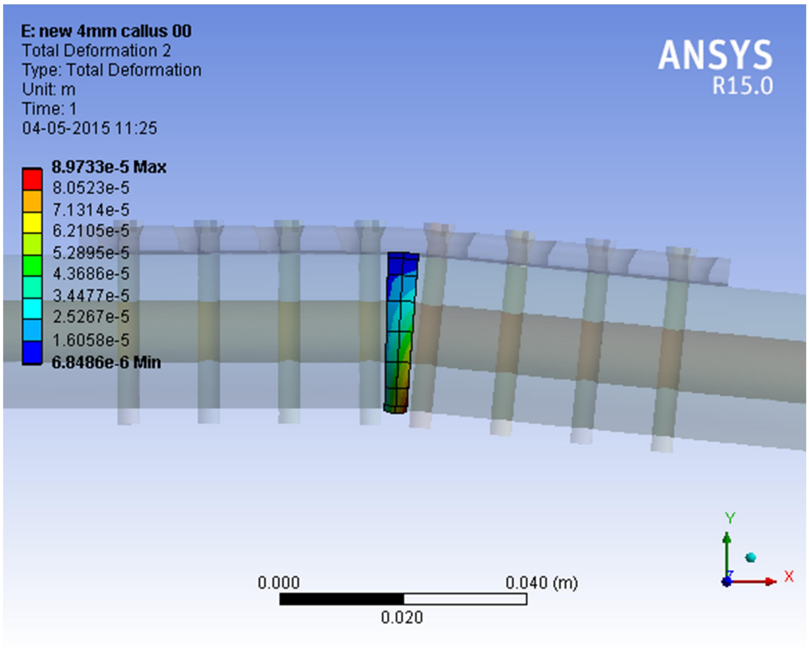

Figure 2c: Deformation at callus for a 4 mm thick bone plate during 0-4 weeks

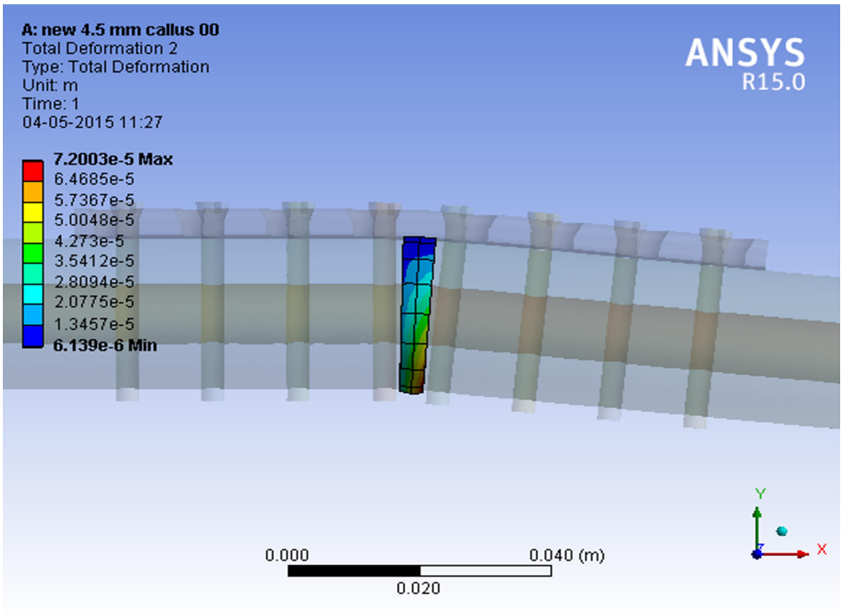

Figure 2d: Deformation at callus for a 4.5 mm thick bone plate during 0-4 weeks

Table 5a, 5b, 5c, 5d depicts the results of IFS and Von-Mises stress acting on the bone and bone plate were obtained by varying the thickness of the plate keeping other parameters constant in the analysis. Deformation in the callus and Max IFS are found with different thickness.

S.no.	Plate Thickness (mm)	Deformation in callus (m)	Max. IFS (%)	Max. Stress on Plate (Pa)	Max stress on bone (Pa)
1	3	1.60E-04	3.1994	8.89E+07	1.47E+07
2	3.5	1.18E-04	2.3596	6.37E+07	1.37E+07
3	4	8.97E-05	1.79466	5.13E+07	1.31E+07
4	4.5	7.20E-05	1.44006	3.89E+07	1.30E+07

Table 5a: Results for IFS and Von-Misses stress during 0-4 weeks with variable thickness

S.no.	Plate Thickness	Deformation	Max. IFS	Max. Stress	Max stress

	(mm)	in callus (m)	(%)	on Plate (Pa)	on bone (Pa)
1	3	1.56E-04	3.1284	8.70E+07	1.47E+07
2	3.5	1.16E-04	2.3212	6.27E+07	1.37E+07
3	4	8.86E-05	1.77264	5.07E+07	1.31E+07
4	4.5	7.13E-05	1.42606	3.86E+07	1.30E+07

Table 5b: Results for IFS and Von-Misses stress during 4-8 weeks with variable thickness

S.no.	Plate Thickness (mm)	Deformation in callus (m)	Max. IFS (%)	Max. Stress on Plate (Pa)	Max stress on bone (Pa)
1	3	3.21E-04	6.4198	1.64E+08	1.62E+07
2	3.5	3.04E-04	6.0848	1.49E+08	1.65E+07
3	4	2.86E-04	5.7124	1.48E+08	1.70E+07
4	4.5	2.66E-04	5.3214	1.33E+08	1.79E+07

Table 5c: Results for IFS and Von-Misses stress during 8-12 weeks with variable thickness

S.no.	Plate Thickness (mm)	Deformation in callus (m)	Max. IFS (%)	Max. Stress on Plate (Pa)	Max stress on bone (Pa)
1	3	4.98E-04	9.95	2.16E+08	1.82E+07
2	3.5	4.20E-04	8.3982	1.96E+08	2.01E+07
3	4	3.97E-04	7.9498	1.95E+08	2.20E+07
4	4.5	3.73E-04	7.4694	1.77E+08	2.33E+07

Table 5d: Results for IFS and Von-Misses stress during 12-16 weeks with variable thickness

Fig 3a, 3b shows the maximum stress acting on the bone and the bone plate during the entire healing period by varying the thickness keeping other parameters constant.

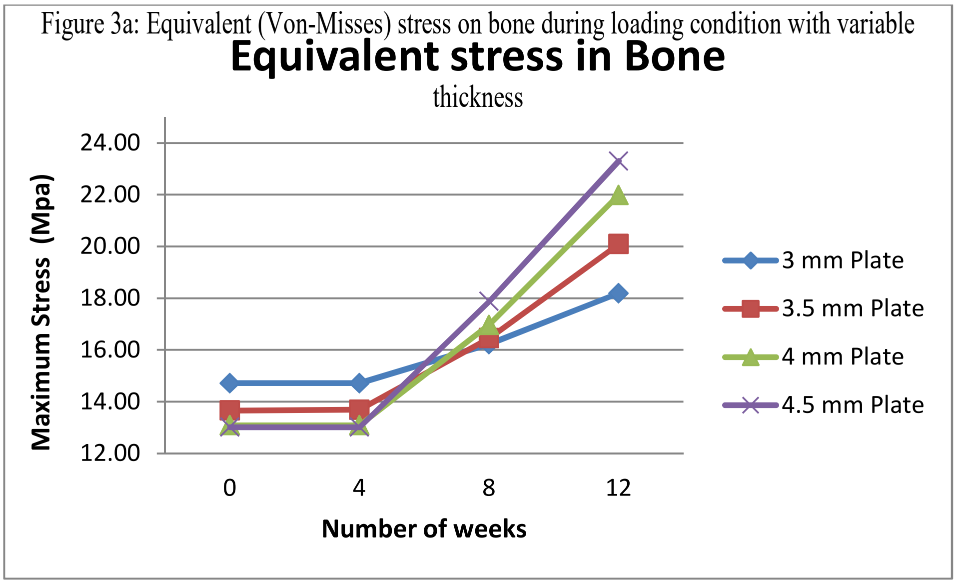

Figure 3a: Equivalent (Von-Misses) stress on bone during loading condition with variable thickness

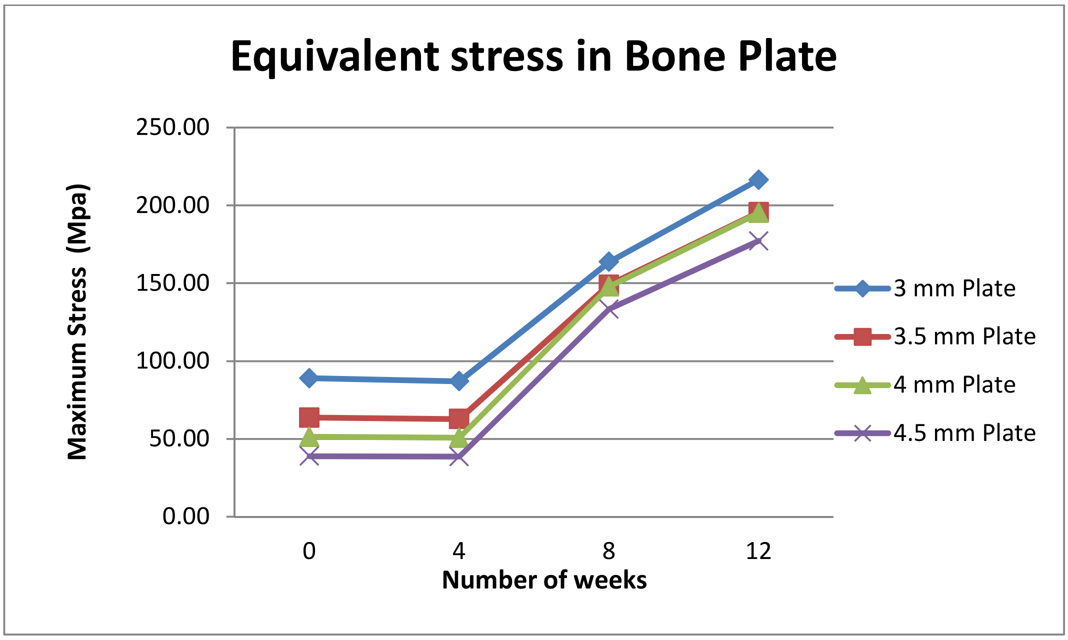

Figure 3b: Equivalent (Von-Misses) stress on bone plate during loading condition with variable thickness

3.2 Effect of working Length

To study the effect of working length, we considered aplate with thickness 3.5 mm as it provides optimum results regarding IFS and stress shielding. Working length is varied by removing innermost screws two at a time from the bone plate. Three working lengths (13 mm, 39 mm, and 65 mm)taken in this study. Fig. 4a, 4b, 4c shows the distribution of stress on the bone plate when different working lengths used.

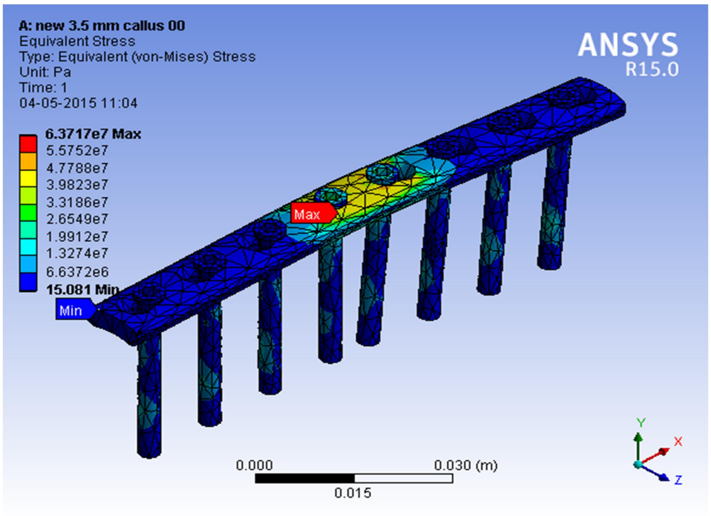

Figure 4a: Von-Misses stress on the bone plate when working length is 13mm

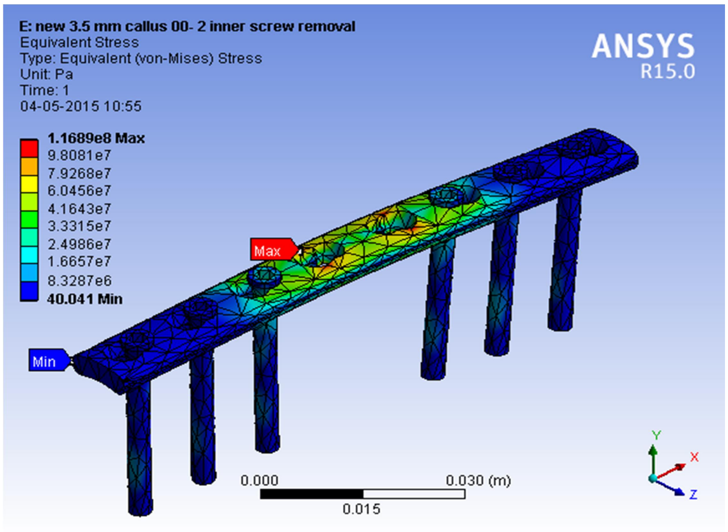

Figure 4b: Von-Misses stress on the bone plate when working length is 39mm

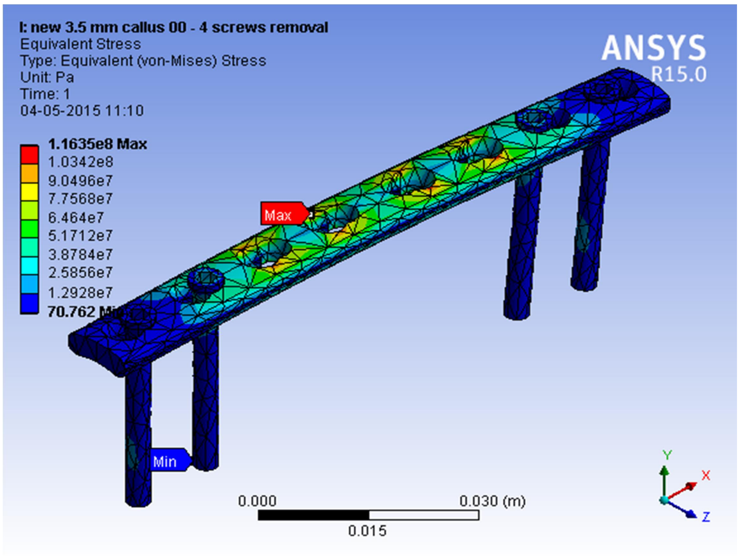

Figure 4c: Von-Misses stress on the bone plate when working length is 65 mm

Table 6a, 6b, 6c, 6d shows the results of IFS and von-mises stress acting on the bone and bone plate during 0-16 weeks varying the working length (13mm, 39mm and 65 mm). Deformation of callus is also found out to understand the behaviour of the callus under loading conditions with varying the working length.

S.no.	Working Length (mm)	Deformation in callus (m)	Max. IFS (%)	Max. Stress on Plate (Pa)	Max stress on bone (Pa)
1	13	1.18E-04	2.3596	6.37E+07	1.32E+07
2	39	3.40E-04	6.8038	1.17E+08	1.39E+07
3	65	5.91E-04	11.8216	1.16E+08	1.24E+07

Table 6a: Results for IFS and Von-Misses stress during 0-4 weeks with variable working length

S.no.	Working Length (mm)	Deformation in callus (m)	Max. IFS (%)	Max. Stress on Plate (Pa)	Max stress on bone (Pa)
1	13	1.16E-04	2.3212	6.27E+07	1.32E+07
2	39	3.20E-04	6.393	1.11E+08	1.38E+07
3	65	5.30E-04	10.6022	1.05E+08	1.24E+07

Table 6b: Results for IFS and Von-Misses stress during 4-8 weeks with variable working length

S.no.	Working Length (mm)	Deformation in callus (m)	Max. IFS (%)	Max. Stress on Plate (Pa)	Max stress on bone (Pa)
1	13	3.04E-04	6.0848	1.49E+08	1.65E+07
2	39	3.47E-04	6.944	1.09E+08	1.58E+07
3	65	3.58E-04	7.1608	6.73E+07	1.39E+07

Table 6c: Results for IFS and Von-Misses stress during 8-12 weeks with variable working length

S.no.	Working Length (mm)	Deformation in callus (m)	Max. IFS (%)	Max. Stress on Plate (Pa)	Max stress on bone (Pa)
1	13	4.20E-04	8.3982	1.96E+08	2.01E+07
2	39	4.74E-04	9.4866	1.42E+08	1.69E+07
3	65	4.87E-04	9.7432	8.70E+07	1.73E+07

Table 6d: Results for IFS and Von-Misses stress during 12-16 weeks with variable working length

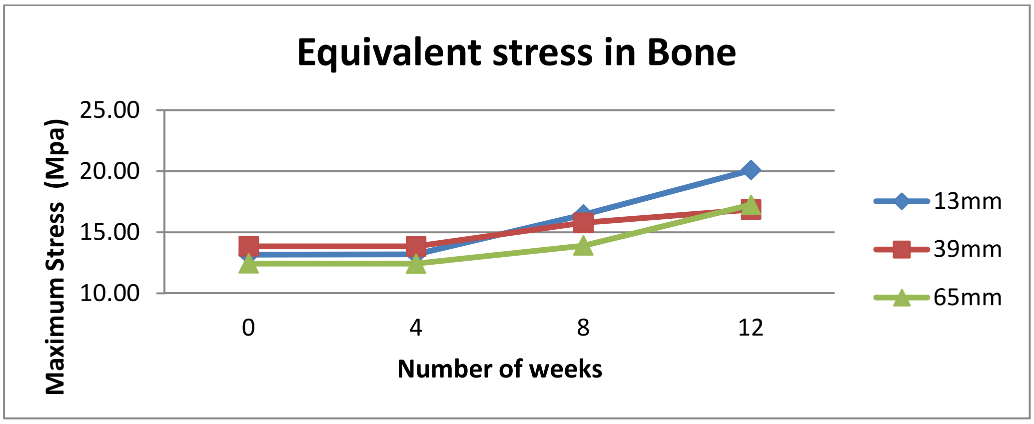

Figure 5a: Equivalent (Von-Misses) stress on bone during loading condition with variable working length

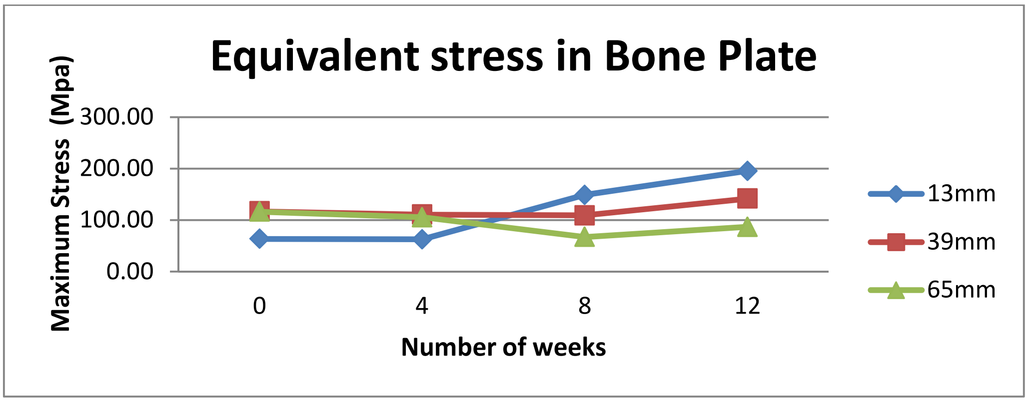

Figure 5b: Equivalent (Von-Misses) stress on bone plate during loading condition with variable working length

Fig 5a, 5b shows the maximum stress acting on the bone and the bone plate during the entire healing period by varying the working length (13mm, 39mm, 65mm) keeping other parameters constant.

3.3 Effect of Gap

The effect ofthe gap distance between bone and bone plate studied after choosing appropriate plate thickness (3.5 mm) and working length (65 mm) from the results above. Here, three configurations of gap distance are studied (no gap, 0.5 mm gap, 1 mm gap). Table 7a, 7b, 7c, 7d depicts the results of interfragmentary and Von Mises stress acting on the bone and bone plates during 0-12 weeks with variable gap distance.

S.no.	**Gap (mm)**	**Deformation in callus (m)**	**Max. IFS (%)**	**Max. Stress on Plate (Pa)**	**Max stress on bone (Pa)**
1	0	1.45E-04	2.9056	7.27E+07	1.20E+07
2	0.5	3.40E-04	6.8038	1.17E+08	1.39E+07
3	1	3.61E-04	7.2292	1.21E+08	1.34E+07

Table 7a: Results for IFS and Von-Misses stress during 0-4 weeks with variable gap distance

S.no.	**Gap (mm)**	**Deformation in callus (m)**	**Max. IFS (%)**	**Max. Stress on Plate (Pa)**	**Max stress on bone (Pa)**
1	0	1.42E-04	2.8478	7.12E+07	1.20E+07
2	0.5	3.20E-04	6.393	1.11E+08	1.38E+07
3	1	3.38E-04	6.7626	1.14E+08	1.34E+07

Table 7b: Results for IFS and Von-Misses stress during 4-8 weeks with variable gap distance

S.no.	**Gap (mm)**	**Deformation in callus (m)**	**Max. IFS (%)**	**Max. Stress on Plate (Pa)**	**Max stress on bone (Pa)**
1	0	3.16E-04	6.3118	1.40E+08	1.66E+07
2	0.5	3.47E-04	6.944	1.09E+08	1.58E+07
3	1	3.57E-04	7.1398	1.08E+08	1.53E+07

Table 7c: Results for IFS and Von-Misses stress during 8-12 weeks with variable gap distance

S.no.	**Gap (mm)**	**Deformation in**	**Max.**	**Max. Stress**	**Max stress**

		callus (m)	IFS (%)	on Plate (Pa)	on bone (Pa)
1	0	4.34E-04	8.6866	1.85E+08	2.14E+07
2	0.5	4.74E-04	9.4866	1.42E+08	1.69E+07
3	1	5.20E-04	10.395	1.40E+08	1.63E+07

Table 7d: Results for IFS and Von-Misses stress during 12-16 weeks with variable gap distance

4. DISCUSSION

4.1 Effect of plate thickness

The effects of bone plate thickness on Inter-fragmentary Strain (IFS) in the fracture gap, and von-misses stress on the bone plate areanalysed by varying the thickness from 3 mm- 4.5 mm in increments of 0.5 mm.According to IFS theory from the above tables, it is inferred that plates witha thickness of 4 mm and 4.5 mm produce less than 2% IFS along the fracture gap during initial weeks of recovery (0-8 weeks). From these observations, we can conclude that as the plate thickness increases, the rigidity of implant increases and thereby reducing the flexibility of the bone plate which results in minor mechanical stimuli in the fracture gap. Hence, this condition is unfavourable for proper callus formation.

According to Table 5d, for the plate thickness of 3 mm, the IFS is found to be near 10% during 12-16 weeks. It indicates that smaller plate thickness have higher flexibility which is again an unfavourable condition for proper bone healing.Figure 3a and Figure 3bdepict the value of maximum stress experienced at bone and bone plate respectively. Figure 3a indicates that the maximum stress on the bone during initial stages of recovery developed when 3 mm plate used. As the thickness increases, thestressdrawn up on bone decreases resulting in higher stress shielding. These results comply with the previous studies [23] which show flexible plating reduces stress shielding effect on the bone. Both 3 mm plate and 3.5 mm plate provide better results regarding reduction in stress shielding effect but according to interfragmentary stress theory, the plate with thickness 3.5 mm is recommended as it also shows optimum behaviour (IFS between 2-10%) compared to the other plate thickness.

4.2 Effect of working length

It is evident from Table 6a and 6b, that when four screws removed (i.e., working length is 65mm), IFS exceeds 10% which isan unfavourable condition for bone healing. Fig. 5a and Fig.5b depict the value of maximum stress experienced atthe bone and the bone plate respectively when different working lengths used. Fig.5a shows that during the initial healing period, the bone plate of working length 39mm develops higher stress in the bone which helps in increasing the strength of the bone during the healing period. As the bone plates of working length 13 mm and 39 mm provide satisfactory results regarding IFS and as the bone plate with working length 39 mm has better stress shielding properties, it is recommended to choose the configuration of 3.5mm bone plate withthe removal of two innermost screws.

4.3 Effect of gap

It is evident from Table 7a that, during the later stage of healing, the IFS exceed 10% when the gap is 1 mm. Also, contact stress is developed when the gap eliminated, and it also hinders the blood supply to the bone. Hence, the difference of 0.5 mm between the bone and the bone plate is recommended for proper blood supply and optimal IFS. In addition, the validation of the results has been discussed with the statistical tests i.e. analysis of variance that is described as follows.

IFS versus Plate thickness

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	1.7071	1.7071	57.81	0.017
Residual Error	2	0.0591	0.0295		
Total	3	1.7662			

Figure 6a: Regression analysis of IFS vs Plate Thickness

IFS versus Working length

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	34.286	34.286	10928.43	0.006
Residual Error	1	0.003	0.003		
Total	2	34.289			

Figure 6b: Regression analysis of IFS vs working length

Using IFS as thedependent variable with different parameters on which the design of the plate was evaluated, regression analysis is performed to identify the significance of each factor in the design of the bone plate. From fig 6a, 6b we can observe that p-value in each case is less than 0.05 with a confidence level of more than 95%. From this, we can conclude that the results obtained from the simulation by varying the different parameters are statistically significant with the IFS where these parameters influence the growth of endosteal callus during healing.

5. CONCLUSION

The effects ofthe design of Bone Plate on healing efficiency are studied, and design modifications conducted for obtaining faster and efficient recovery of the fractured bone. The changes in design are performed by variable thickness, working length and gap distance between bone and the bone plate. The conclusions obtained are as follows:

1. Smaller thickness provides higher flexibility and helps in avoiding stress shielding effect. According to IFS theory, the plate thickness of 3.5 mm produced optimal results regarding better callus formation and less stress shielding effect.
2. The FEA of the geometric models reveals that 3.5 mm plate with working length 39 mm along with the gap distance of 0.5 mm proves to be the best configuration to provide faster and efficient bone recovery.

In future, effects ofthe bone plate on different types of bone fracture (transverse fracture, spiral fracture, anobliquefracture.) can be studied. The combined effects of all these parameters andoptimised results can be analysed through various optimisation techniques.

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