# Comparative study for Environmental Impacts of Laser Beam Welding, Friction Stir Welding and Gas Tungsten Arc Welding using Life Cycle Assessment

BY

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Dedicated to my Parents, Siblings and Teachers

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# List of Abbreviations

| | |
|---|---|
| LCA | Life Cycle Assessment |
| SETAC | Society of Environmental Toxicology and Chemistry |
| ISO | International Standards Organization |
| HAZ | Heat Affected Zone |
| GWP100a | Global Warming Potential |
| ODP | Ozone Layer Depletion Potential |
| HT | Human Toxicity Potential |
| AP | Acidification Potential |
| EP | Eutrophication Potential |
| ADP | Abiotic Depletion Potential |
| ADFFP | Abiotic Depletion Fossil Fuel Potential |
| FWEP | Fresh Water Ecotoxicity Potential |
| TEP | Terrestrial Ecotoxicity Potential |
| MAEP | Marine Aquatic Ecotoxicity Potential |
| PCOP | Photo-chemical Oxidation Potential |
| LBW | Laser Beam Welding |
| FSW | Friction Stir Welding |
| GTAW | Gas Tungsten Arc Welding |
| TRACI | Tool for Reduction and Assessment of Chemical Impacts |
| CML | Center of Environmental Science of Leiden University |

| | |
|---|---|
| AWS | American Welding Society |
| LCI | Life Cycle Inventory |
| USDA | United States Department of Agriculture |

# Abstract (English)

**Name:** **Abdul Aziz Afzal**

**Title: Comparative study for Environmental Impacts of Laser Beam Welding, Friction Stir Welding and Gas Tungsten Arc Welding using Life Cycle Assessment**

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Welding is one of the most important manufacturing processes. It is widely used in several industries like automotive, aerospace, oil and gas, etc. In this thesis, Life Cycle Assessment (LCA) method is used to investigate the environmental impacts of three welding processes Laser Beam Welding (LBW), Friction Stir Welding (FSW), and Gas Tungsten Arc Welding (GTAW). Thin sheets of AISI 304 steel were welded using these processes and data is collected for energy, material, and shielding gas consumptions.

LCA is conducted using SimaPro software package and eleven environmental impact categories are used to compare the three processes. These impact categories include global warming potential, abiotic depletion potential, acidification potential, eutrophication potential, ozone layer depletion potential, photo-chemical oxidation potential, abiotic depletion fossil fuels potential, terrestrial ecotoxicity potential, human toxicity potential, fresh water ecotoxicity potential, and marine aquatic ecotoxicity potential.

The LCA results show that for 1m weld on AISI 304 steel sheet, FSW has the highest whereas has the lowest impacts in all the eleven categories. Emissions due to energy and shielding gas consumption during welding have been the main cause of environmental impacts. The effect of increasing material sheet thickness on environmental impacts of welding is also investigated. It is observed that increasing the thickness of sheets increases the environmental impacts.

# ملخص الرسالة

**الاسم :** **عبدالعزيز افضل**

**العنوان:** **دراسة مقارنة للتأثيرات البيئية لحام شعاع الليزر ولحام ضاغطة الاحتكاك ولحام قوس تنجستن الغاز باستخدام تقييم دورة الحياة**

**التخصص:** **الهندسة الميكانيكية**

**التاريخ :** **دسمبر 2018**

اللحام هو واحد من أهم عمليات التصنيع. يستخدم على نطاق واسع في العديد من الصناعات مثل السيارات ، والفضاء ، والنفط والغاز ، وما إلى ذلك. في هذه الأطروحة ، تُستخدم طريقة تقييم دورة الحياة (LCA) لدراسة الآثار البيئية لثلاث عمليات لحام لحام شعاع الليزر (LBW) ، لحام الاحتكاك بالحرارة (FSW) ، وغاز التنغستن قوس اللحام .(GTAW)تم لحام الألواح الرقيقة من الفولاذ AISI 304 باستخدام هذه العمليات الثلاث ويتم جمع البيانات من أجل استهلاك الطاقة والمواد والوقود.

يتم إجراء تقييم دورة الحياة باستخدام حزمة برامج SimaPro وتستخدم 11 فئة من فئات التأثير البيئي لمقارنة العمليات الثلاث. تشمل هذه الفئات احتمالية الاحترار العالمي ، وإمكانية النضوب اللاأحيائي ، وإمكانية التحميض ، وإمكانية التخثُّر ، وإمكانية استنفاد طبقة الأوزون ، وإمكانية الأكسدة الكيميائية الضوئية ، وإمكانات الوقود الأحفوري للنضوب اللاأحيائي ، وإمكانية السمية الإيكولوجية الأرضية ، وإمكانية التسمم البشري للمياه العذبة ، وإمكانية التسمم الأيكولوجي للمياه العذبة ، والسمية البيئية المائية البحرية محتمل.

توضح نتائج LCA أنه بالنسبة إلى واحد متر لحام على ألواح فولاذية AISI 304 ، فإن FSW لها أكبر تأثير على البيئة ، بينما LBW تسبب أقل تأثير على البيئة. كانت الانبعاثات الناتجة عن استهلاك الطاقة وحماية الغاز أثناء اللحام السبب الرئيسي للآثار البيئية السلبية. تم دراسة تأثير زيادة سماكة الصفيحة على التأثيرات البيئية للحام. يلاحظ أن زيادة سمك الأوراق يزيد من الآثار البيئية المرتبطة بلحام هذه الأوراق.

# CHAPTER 1. INTRODUCTION

Considering the hazardous emissions emitted during manufacturing and welding processes and the importance of eco-friendly processes, sustainable manufacturing processes are being employed in the industry and efforts are undertaken to minimize their negative impacts on the environment [1]. These impacts are not only limited to global warming or the environment in general, they adversely affect the human ecosystem which consequently affects human health resulting in lower work efficiency, thus impacting both environment and the economy [2]. Therefore, sustainability analysis of industrial manufacturing process has become vital to measure and limit their adverse effects.

Welding is an important and most frequently used joining process. Construction, turbine production and automobile industries employ welding process extensively [3]. It accounts for a significant segment of resource consumption and manufacturing cost during the production process [1].

Life Cycle Assessment (LCA) is powerful tool to quantify the potential environmental impacts of a process or a product under analysis [4]. Recently with the increasing understanding of sustainability, numerous software e.g. SimaPro, GaBi etc. and databases e.g. EcoInvent, United States Department of Agriculture (USDA) etc. have been developed to facilitate the environmental impact assessment. For this thesis, SimaPro with EcoInvent database is used.

First step towards carrying-out the analysis is to specify and take into account various characteristics and procedures involved in the welding process followed by literature review to specify the methodology. Later on, four phases of LCA will be defined for the current study i.e. goal and scope definition, life cycle inventory, life cycle impact assessment and interpretation. Succeeding impact assessment; conclusions and recommendations for future assessment and analysis will be provided.

## 1.1. Introduction to Welding Processes

Welding is one of the oldest joining methods used to join two materials. Modern welding is not limited to joining metals, it is also being used to join plastics and polymers, previously considered as hard to weld materials. Depending upon the process and application, appropriate temperature and pressure are employed.

Under the application of high temperature and pressure, primary and secondary bonds are formed between the two materials and joining takes place. Bond type is dependent on the type of material e.g. metallic bond is formed when metals are joined and ionic/covalent bond is formed when ceramics are to be joined using welding [5, 6].

Similar to all other processes, welding has its own advantages and disadvantages. One of the biggest advantages is that, it creates a permanent joint between material thus preventing disassembly. Owing to its simple procedure, welding can be easily automated for industrial applications such as automobile manufacturing. Overall, welding is considered as the most simple and economical joining process.

Disadvantages of welding includes permanent joints thus preventing disassembly for further applications. High temperature involved during welding process could deteriorate base material properties and might cause residual stresses and distortion in the workpiece. Welding quality depends strongly on technician's expertise thus requiring skilled technician [5].

Welding processes can be further categorized based upon the energy source such as mechanical, chemical or electrical or based upon the phase reaction involved in the process. Figure 1 illustrates the taxonomy of welding processes.

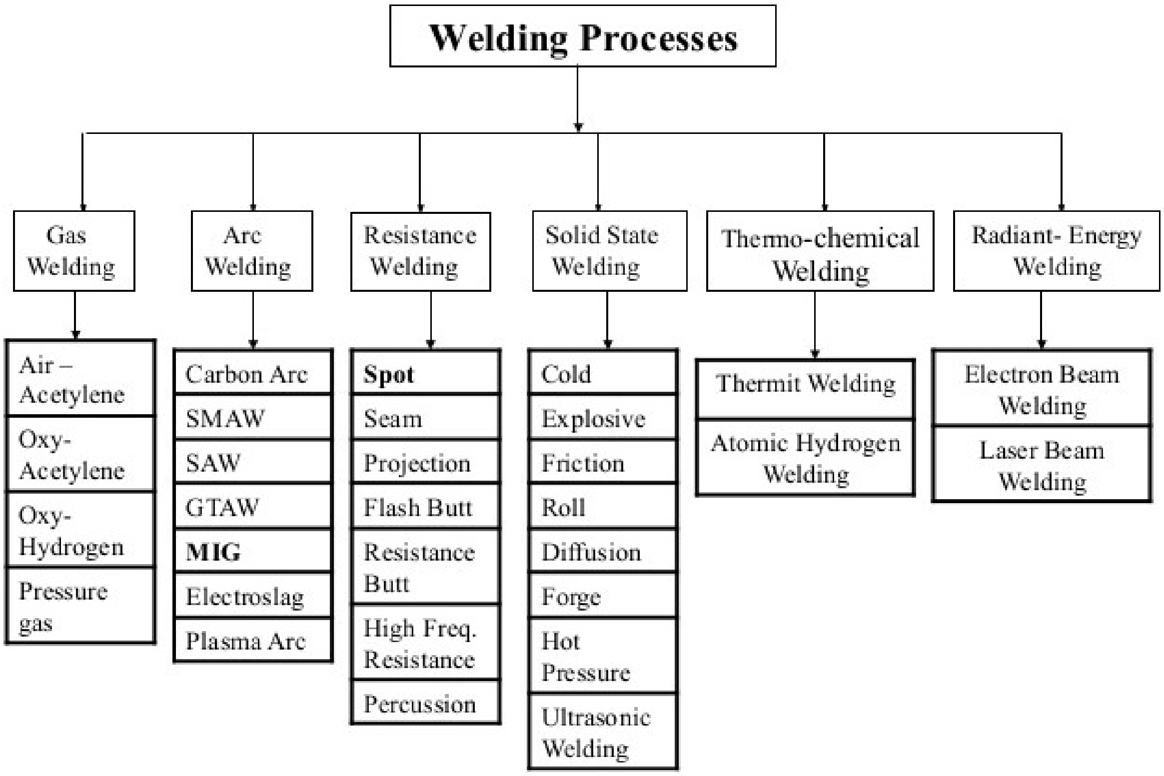


Figure 1 Classification of welding processes [5].

Fusion welding processes are extensively used in the industry. Fusion welding employs high temperature, adjoining surfaces of the samples to be joined are heated to a temperature above their melting point and are combined after solidification occurs. Fusion welding processes are further categorized into:

- Gas welding processes: Heat is provided by combustion of a fuel gas in presence of oxygen.

- Arc welding processes: Heat source is an electric arc. Electrode could be combustible or noncombustible.
- High energy beam processes: High energy beam is used as a heat source in the process.
- Resistance welding processes: Energy is provided through the electrical resistance of the parts to be joined.

Fusion welds contains a distinct heat affected zone (HAZ), partially affected zone and base material as shown in Figure 2.

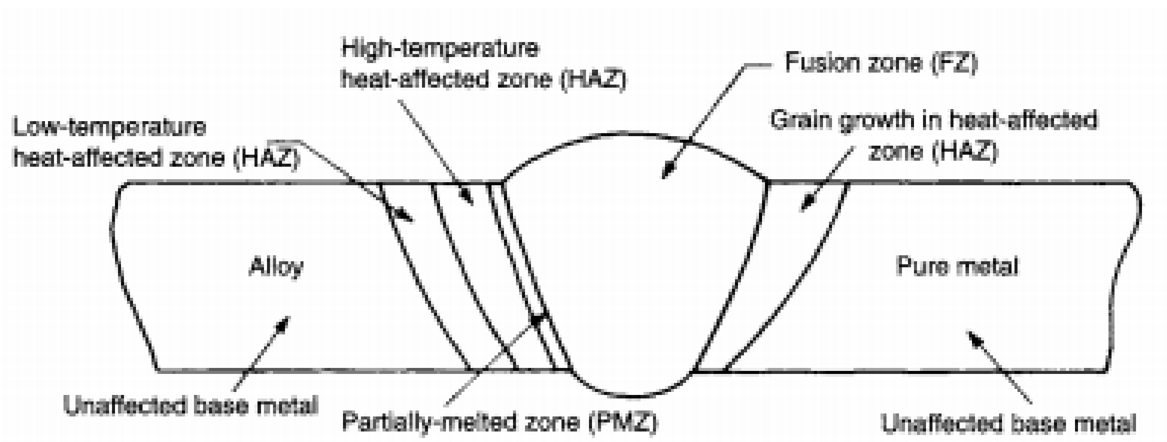


Figure 2 Fusion weld zone [5].

Since the focus of the research is on the life cycle assessment of welding processes, brief overview of concerned welding processes will be provided.

### 1.1.1. Gas Tungsten Arc Welding (GTAW)

Gas Tungsten Arc Welding is also known as Tungsten Inert Gas (TiG) welding. This process is used to melt and join metals with the help of an arc established between a tungsten electrode and the workpiece. The process is described in Figure 3.

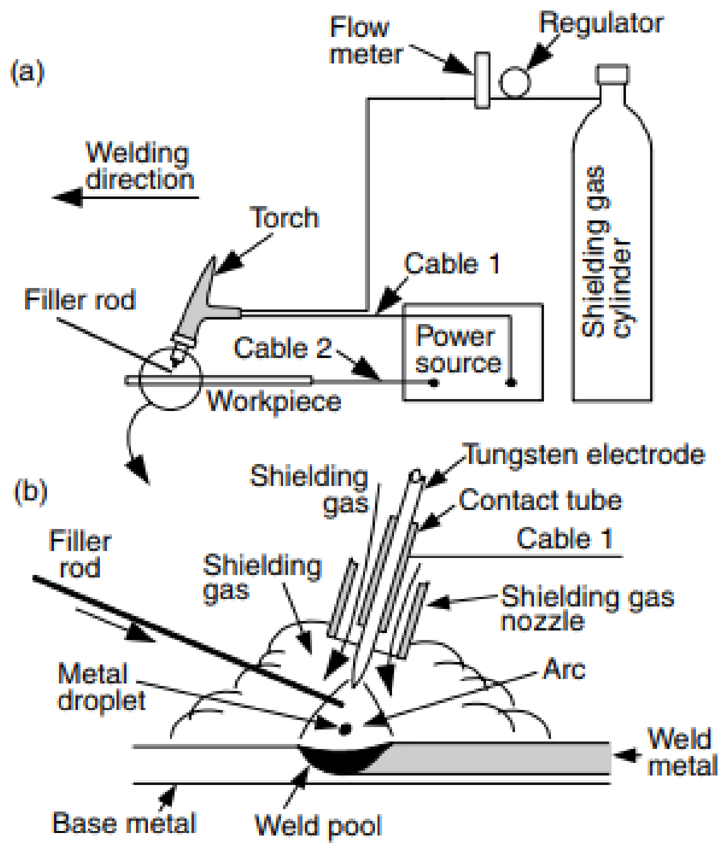


Figure 3 GTAW schematic [7].

Tungsten electrode is held in the torch which is connected to an inert shielding gas cylinder. The torch is connected to one end of the power source while the second end of the power source is connected to the workpiece completing the circuit and establishing the arc between the workpiece and the electrode [7, 8].

As shown in Figure 4, GTAW can be used in more than one variants/polarity depending upon the polarity of the electrode and current supplied each having their own advantages and disadvantages. These variants are direct current electrode negative, direct current electrode positive and alternating current

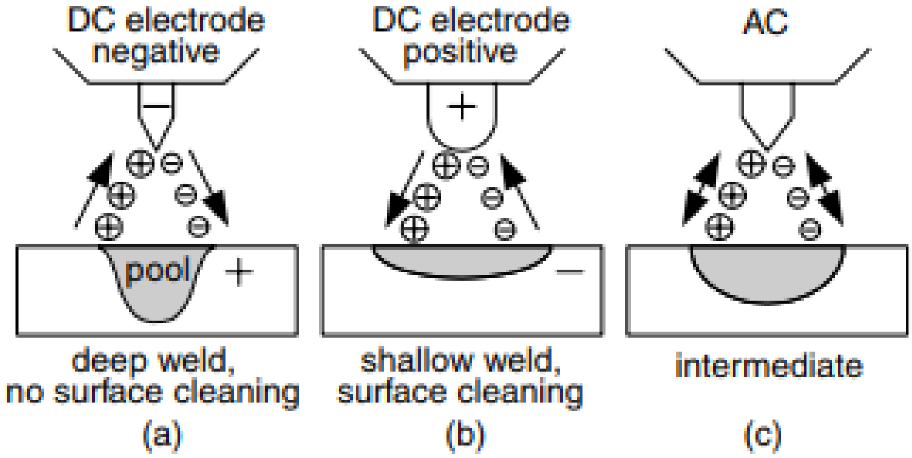


Figure 4 Various variants for performing GTAW [7].

GTAW is commonly used for joining thin sections owing to low heat output and provides more control towards dilution and energy input of the weld. GTAW can be used for buttwelding without any addition of filler metals.

Limited deposition rate and melting of tungsten electrode due to excessive welding current are some of the disadvantages of GTAW. Deposition rate, however, could be increased by using preheated filler materials [8].

### 1.1.2. Friction Stir Welding (FSW)

Friction Stir Welding is a relatively new joining process falling into the category of solid-state welding process where melting of base material does not take place during welding process. A rotating tool in contact with the surfaces to be joined is used to generate the heat required for welding based upon the friction between two surfaces. Rotating tool used in FSW is often non-consumable. However, for some applications, consumable tool is used. A schematic for FSW is shown in Figure 5.

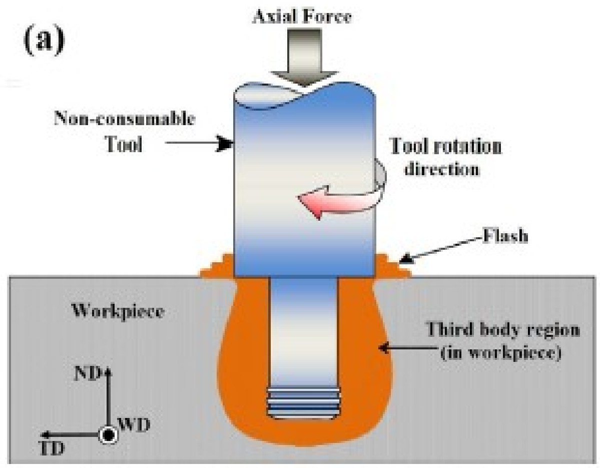


Figure 5 Schematic of FSW weld zone [9].

Rotating tool used for FSW serves more than one function i.e. they are used to generate heat and to provide material flow control. Some important process parameters to be taken care of during FSW are tool rotation speed, tool tilt angle, tool shoulder depth, tool geometry and workpiece feed speed. FSW is done in three steps plunging followed by dwelling and welding

A schematic for the three steps is shown in Figure 6.

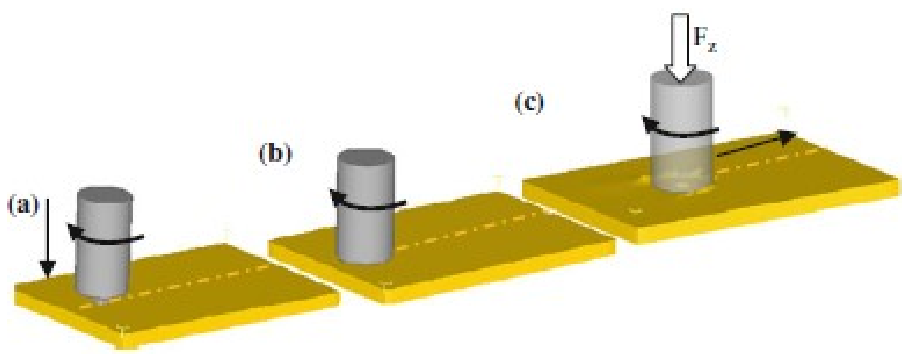


Figure 6 Steps involved in FSW [10].

As seen in Figure 6 (a), during the first stage of the process i.e. plunging, a specifically designed pin made of non-consumable material attached to a rotating tool is plunged to the edges of the workpiece. Rotation of the tool and the pin generates heat which raises the workpiece temperature and consequently softens the workpiece. This step is analogous to drilling.

Plunging is then followed by dwelling as described in Figure 6 (b), where the tool starts to rotate/stir at a specified speed which causes a steep increase in the temperature which consequently turn the material surrounding the pin into a viscous material.

Third stage is when the tool moves along the desired weld area increasing the temperature of weld area and mixing the materials among the weld line as depicted in Figure 6 (c).

A non-consumable tool is required for heat generation in the weld area and for inducing plastic deformation among the weld line. FSW provides excellent results when joining dissimilar materials and has certain advantages over conventional fusion welding processes. Defects occurring during fusion welding such as blow holes and porosity are eliminated completely as this process is a solid-state joining process [8, 10].

Moreover, no additional filler material is required which keeps the workpiece free from any sort of contamination. However, at the end of the welding process, since an exit hole is required for FSW some loss of material is expected [10]. Some of the companies using FSW for their products are Honda [11], Apple [12] and Boeing [13]

### 1.1.3. Laser Beam Welding (LBW)

Laser beam welding is being widely used in sophisticated applications owing to its high energy density, high precision, better sample penetration and ease of automation. An extremely high-power density reaching up to 103 W/mm$^2$ can be produced by properly focusing the laser beam which is then used to fuse two or more materials to form a joint. LBW is performed in two modes i.e. direct heating and transmission welding.

Direct heating involves melting of the workpiece materials to form a joint. $CO_2$ lasers are a prime example for direct heating. Transmission welding is used for processing of plastics, polymers and diode lasers are employed for the process [9]. A schematic for LBW is shown in Figure 7.

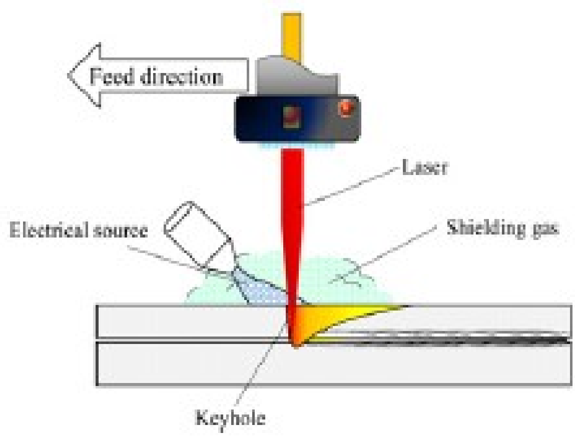


Figure 7 LBW schematic [14].

LBW is considered as a stable low energy input process. Requirement of low power results in employing low cost laser beam. Stable welding conditions results in reduced processing time, simple material separation, high temperature strength and good bead appearance. Two important processing parameters for LBW are material properties and beam characteristics.

Pre-treatment of materials to be joined is required to remove moisture and contaminants on the surface and to smooth out any surface defects that may result in weld imperfections.

Melting temperature and the absorptivity of both base and filler materials play an important role in process efficiency [14, 15].

Beam properties such as beam power, beam size and the joint geometry are important for important for processing time and weld quality. Low power input results in predictable distortion of the weld region which consequently reduces reworking and material consumption.

LBW is particularly effective in industrial applications involving large number of identical parts such as computer hard drive components, catheters and dental prostheses [14]. Figure 8 shows LBW of pressure vessels.

Figure 8 LBW of pressure vessels. [16]

Some of the important process parameters for LBW are energy density, shielding gas, beam wavelength, focal position, welding speed and spot size. Laser beam welding is being extensively used since recent past especially in the automotive industry due to its high quality and precise welds. [17]

Some disadvantages of traditional welding on LBW are:

- Inert gas consumption increases manufacturing cost
- Requires dexterity of worker
- Significant amount of heat is required
- Susceptibility to contaminants

## 1.2. Life Cycle Assessment (LCA)

With the advancement in technology and recent development of novel manufacturing techniques, production of various products has increased exponentially, and the manufacturing time has reduced significantly. Consequently, an increase in consumption and depletion of natural resources has been observed. Hence, manufacturing industries have switched their focus towards sustainable, energy and material efficient design with low impact on environment. LCA is an important tool for measuring the environmental impacts of certain product or process. This assessment could be either cradle to grave, cradle to gate, gate to gate or gate to grave depending upon the availability of required manufacturing data [18, 19, 20].

Start of the life cycle stage of a process/product is known as cradle while end of life cycle stage is known as grave. Gate is described as any life cycle stage in between cradle and grave. Cradle to grave study involves the complete assessment of the product from raw material extraction for its production to the end of life cycle stage where the product is either recycled or dumped. Cradle to gate study involves assessment of the product from the raw material extraction stage to a certain point in its life cycle before the end of life stage while gate to grave study involves assessment from a certain point after the raw material extraction to the end of life stage.

LCA is a method to analyze the environmental impacts a product, service or process could have by examining the full range of processes related to the life cycle of a certain process or product from manufacturing till disposal. In general, a product life cycle is summarized as follows in Figure 9:

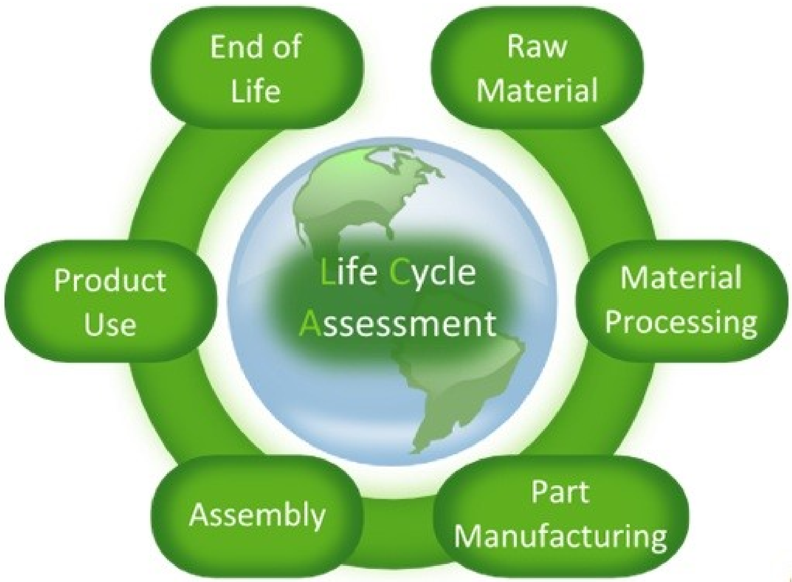


Figure 9 Product Life Cycle [18].

Product life cycle starts with the extraction of raw materials followed by the manufacturing phase, distribution, consumer utilization and end of life where it is either recycled or disposed of.

LCA evaluates the environmental impacts during the active life of a product including the inputs and outputs to nature and technosphere during each life cycle stage. Inputs and outputs to and from technosphere are defined as the man-made inputs and outputs. Figure 10 shows a schematic of a product life cycle.

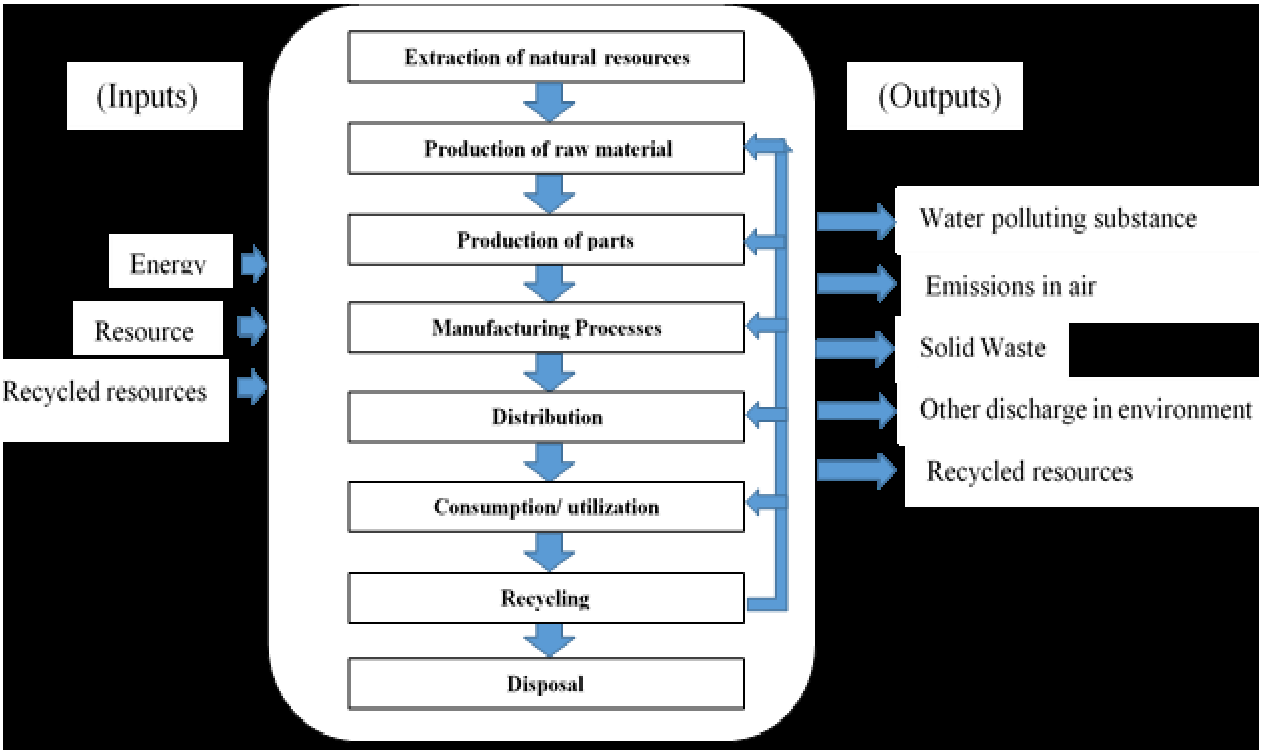


Figure 10 Detailed Schematic of Product Life Cycle [18].

Since LCA takes into account all the life cycle processes involved starting from extraction of raw materials to the disposal of the product as a waste, it provides a complete and comprehensive assessment of the product and risks associated with each individual life cycle stage [21].

### 1.2.1. Development of LCA

We will discuss briefly the history and development of LCA. LCA has gone through three major transformations since its application in 1960s. These transformations can be categorized into the time period they occurred i.e. 1960-1990, 1990-2000 and from 2000 onwards. First period is known for conceptualization of LCA, where researchers started to realize the severity of depletion of natural resources.

In 1960s, depleting raw materials and energy resources forced researchers towards establishing an account for resources consumption and to project the resources available for future consumption. In 1963, Harold Smith calculated the energy requirement for chemical production providing a starting step towards LCA analysis [22]. However, in 1969, Coca-Cola Company performed the first LCA analysis comparing containers for beverage storage to determine the optimum container design having least impact on the environment and natural resources [23].

However, major step towards development of LCA took place during the 2$^{nd}$ period when Society of Environmental Toxicology and Chemistry (SETAC) defined LCA for the first time in 1994. In the year 1996, SETAC released a report which was then used as a basis for LCA framework defined by ISO i.e. ISO 14040. During the 3$^{rd}$ period ISO 14044:2006 was published and replaced the previously used framework for LCA.

### 1.2.2. Advantages and Applications of LCA

LCA is a strong tool to analyze the sustainability in terms of environmental impacts of a product or a process. Certain advantages linked with LCA are:

- Analysis of the system can be done depending on researchers' interest and availability of data i.e. cradle to grave or gate to gate or gate to cradle.
- LCA analyzes multiple attributes of the product at once.
- Provides comparison between alternative solutions and their advantages and disadvantages.

In general, LCA is a systematic evaluation of environmental impacts related to the product or process under observation and can provide a comparison between the product and its alternative providing a strong base for selection of environment friendly products, thus LCA plays a major role in decision making.

This has helped industries to focus towards sustainable design and manufacturing. Unilever, a Dutch company, has performed LCA of more than 1600 products and realized that for its product 68% of carbon footprint is contributed when the product is in use by the consumers [23].

Similarly, Philips has employed LCA to produce energy efficient lighting bulbs containing less mercury. Dyson, a renowned appliances manufacturer compared different hand-dryers using LCA and concluded that Dyson hand-dryer is more environment friendly [24].

### 1.2.3. Phases of LCA

The general methodology for performing LCA is defined in ISO 14040. Performing LCA consists of four phases mentioned below:

- Goal and scope definition: Establishing aims and limitations of the study is done during the first phase.
- Life Cycle Inventory: After defining the life cycle of the system during first phase, necessary data for energy and resource consumption during the defined life cycle of the product is collected and defined in the 2$^{nd}$ phase.
- Life Cycle Impact Assessment: Using the data collected during the 2$^{nd}$ phase, environmental impacts resulting from the energy and resource consumption are evaluated and classified.
- Interpretation: This is the last step in any LCA study where the results obtained are analyzed and interpreted based upon the objectives defined in the 1$^{st}$ phase.

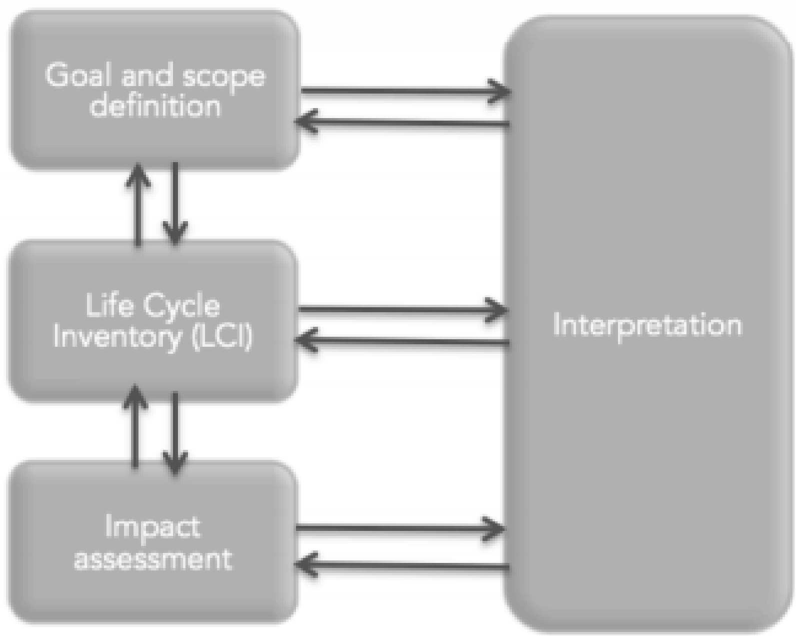


Figure 11 Phases of LCA as defined by ISO standards [19, 20].

Figure 11 shows that the methodology of LCA is iterative in nature and all the phases are interconnected. If the hypothesis and objectives defined during 1st phase are changed in the later stages of the study, the rest of the phases of LCA will also have to be redefined [19, 20].

#### 1.2.3.1. Goal and Scope Definition

Defining the purpose and aims of the study is first step of any analysis. Depending upon intended objective of the study, the methodology of the study changes. Hence, in guidance of ISO 14044, clearly defined and consistent goal and scope of LCA should be established.

While establishing the goals of the study, few preliminary things should be well defined:

- Purpose
- Intended application
- Methodology

- Intended audience

Methodology of the study is heavily dependent upon the goals of the study i.e. whether comparison is done among the products or different processes are to be compared. [20]

While defining scope of the analysis, following aspects should be well defined:

- System function: Defining the main aspects of the system under observation is very important. A system could have more than one function which further complicates the comparison. Special care should be taken when comparing systems with more than one function as it would not be feasible to compare welding process taking place in car manufacturing unit and in construction industry thus, to compare the processes, identical framework should be followed.
- Functional unit: It is a reference unit that is used to quantify the inputs and outputs of a given system depending upon the type of study. For an instance, functional unit for a welding process could be to weld a specific length of metal sheet under specified environmental conditions. Similarly, for comparison of grocery bags, potential functional unit could be the volume of groceries that could be carried by the bag. Hence, to compare different products or processes, one should define same functional unit to each process/product.
- System and system boundary: System is defined as the complete set of processes included in the product under analysis. These processes could be in terms of energy or material consumed during the manufacture of the product. While, system boundary defines the extent to which the study will analyze the system. If the system is to be analyzed completely from raw material extraction to end of life, it

is known as cradle to grave study while studying a system from a certain stage of life cycle till its disposal is known as gate to cradle study.

- Impact evaluation: Selection of evaluation method depends upon the types of impact categories study is intended for. Various methods for impact evaluation are TRACI, CML, ReCiPe and Eco-Indicator. The difference between these methods are the impact assessment categories. TRACI and CML deals with midpoint approach i.e. assessing the impact on global warming potential, ozone layer depletion potential, etc., while Eco-Indicator deals with endpoint approach i.e. direct impact on human health and environment is analyzed. ReCiPe method combines both the approaches and provide an assessment in midpoint categories and endpoint categories. Figure 12 shows the difference between midpoint and endpoint categories.

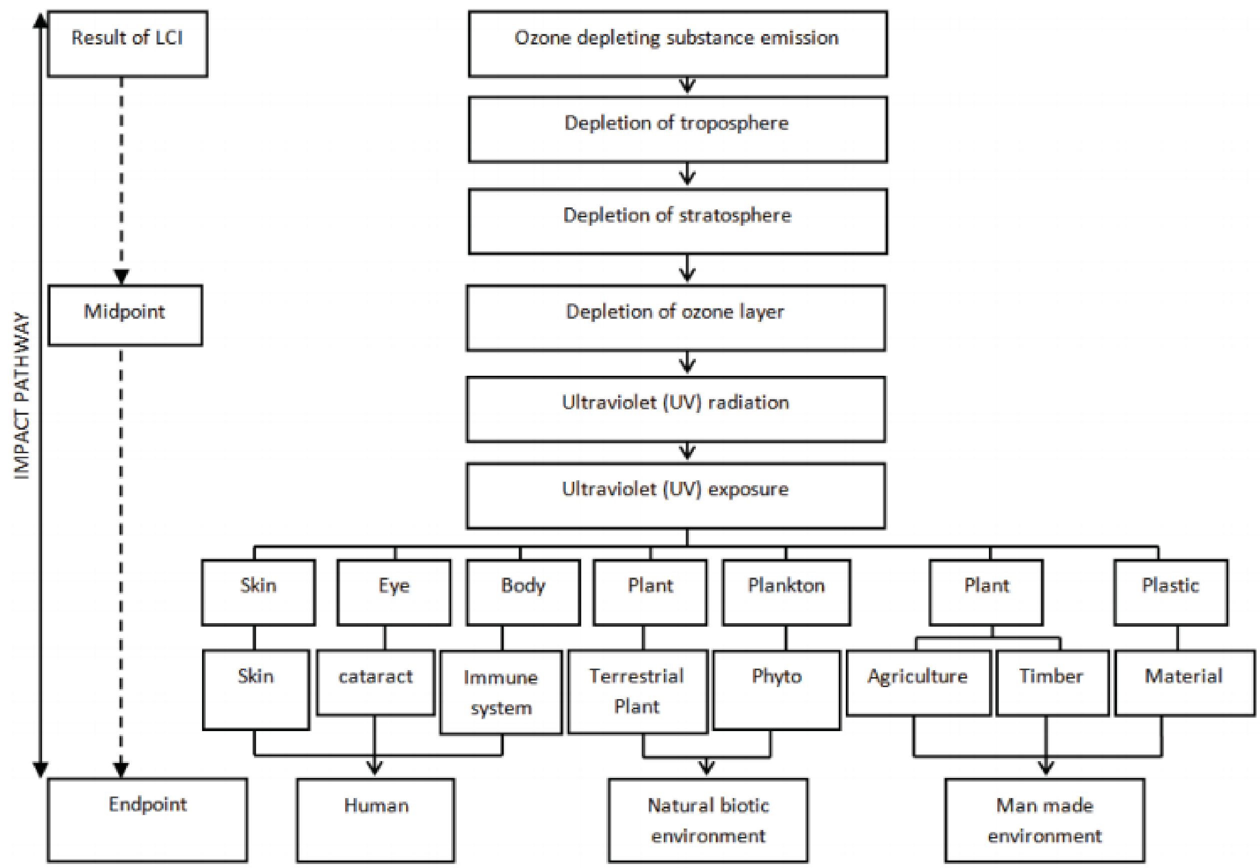


Figure 12 Difference between endpoint and midpoint approach [25].

Goals of LCA study determines the scope of the study and how the analysis will be carried out as well as defining the depth of analysis.

### *1.2.3.2. Life Cycle Inventory:*

Second phase in LCA analysis is life cycle inventory. This step includes collection of data and quantifying inputs and outputs related to each unit processes. Various stages of product life cycle are modelled as unit processes.

Smallest possible portion of a process system for which data can be collected and obtained to perform LCA is known as unit process and shown in Figure 13 [19, 23].

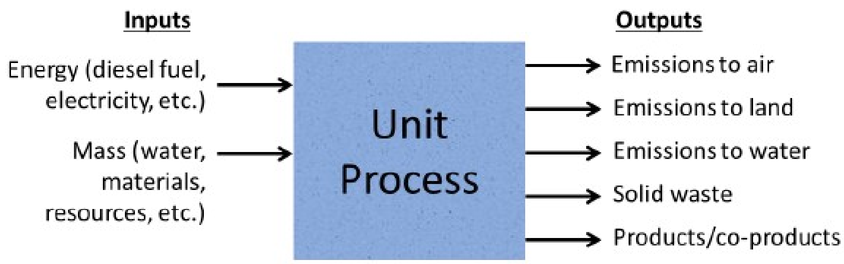


Figure 13 Schematic of a Unit process [20].

Each unit process comprises of inputs from nature such as raw material, water or from techno sphere such as electricity which are then processed to produce output to nature or techno sphere in form of emission and products respectively. These unit processes when combined results in complete product life cycle [19, 20].

Once enough data is obtained to carry out the analysis, dedicated software packages for LCA analysis e.g. SimaPro and Gabi are then used to facilitate in performing the analysis.

#### 1.2.3.3. *Life Cycle Impact Assessment*

Third phase in LCA analysis is to assess and quantify the magnitude of environmental impacts related to the product which are defined during the first phase of the analysis. ISO 14040 defines the steps involved in impact assessment:

- Proper impact category selection (1$^{st}$ phase)
- Classifying the data obtained during inventory analysis to the selected impact categories
- Impact characterization in each category
- If analysis is done for comparison, further steps of normalization and weighting should be performed to facilitate in direct comparison of the products.

ISO 14044 has defined life cycle impact categories as “class representing environmental issues to which life cycle inventory result may be assigned”. Various impact assessment methods available for analysis depending upon the approach of the analysis [20].

As defined earlier in Goal and Scope Definition, if the analysis is problem oriented i.e. midpoint approach, impacts are translated to environmental effects e.g. global warming, acidification or eutrophication. On the other hand, if the analysis is damage oriented i.e. end-point approach, impacts are translated to depletion of natural resources and concerns to ecosystem.

For this thesis, we will make use of CML impact assessment method. It was developed in 2002 by a group of researchers in center of environmental science of Leiden University [26]. This method uses problem-oriented approach i.e. mid-point approach for analysis. Various impact categories that are included in this approach are global warming potential, acidification potential, eutrophication potential, and abiotic depletion potential etc.

#### *1.2.3.4. Interpretation*

This is the fourth and final stage of LCA analysis. Results obtained during LCA analysis are assembled and assessed to provide useful conclusions and recommendations for the process analyzed. Results should be interpreted in compliance with the previously defined goals and scope of the study. Interpretation includes three basic components:

- Identification of hotspot in the product system
- Verification and validation of obtained results
- Providing valuable and concise conclusion and recommendations

### 1.2.4. LCA Software

LCA relies heavily on the software and databases, as manual collection of data for life cycle inventory and its translation to environmental impacts is a tedious task [9]. For this research, SimaPro is used. SimaPro is a commonly used software package that follows the guidelines for conducting LCA provided in ISO 14040. SimaPro relies on databases for calculating environmental impacts, one of the most comprehensive database is Eco-invent. Eco-invent contains more than 14,700 life cycle inventory datasets encompassing majority of the processes used in industry [27]. SimaPro simplifies the analysis by computing impacts related to multiple processes in a single calculation while classifying each impact categories separately.

## 1.3. Research Scope

With recent advancement in material development and manufacturing technologies, laser based manufacturing processes have gained manufacturers attraction owing to greater efficiency and shorter machining time. Development of several materials with hard to machine characteristics such as ceramics, Ti and its alloys also requires development of new manufacturing processes.

As these novel manufacturing processes are finding their way in the manufacturing industry, need to evaluate their environmental performance in terms of their environmental impacts e.g. global warming potential, ozone layer depletion potential and their contribution towards resource depletion and their comparison with conventional machining processes arises which is done through LCA.

Welding is an extensively used and one of the oldest known joining processes since first ever welding was done in India in the year 310 AD [28]. Welding could be done either in indoor or outdoor environments. However, emissions and pollutants gases are released to the environment ultimately.

Welding is one of the manufacturing processes that is undergoing the transformation from traditional methods such as GTAW to novel methods such as LBW. LBW is finding its application in the industry owing to low heat dispersion, shorter processing time, less deteriorating effect on workpiece material and ease of automation [29].

LBW provides huge benefits over traditional welding processes in terms of increased productivity [30]. Higher weld speeds and productivity is achieved while allowing decreased resource consumption owing to reduced number of work passes and low weld volume [1].

With depletion of natural resources along with various technical and economic concerns, environmental impact assessment of novel joining processes has become necessary to provide a possible solution to the concerns related to economy and natural resource depletion. Therefore, in this thesis, LCA methodology is used to perform comparative environmental impact assessment of LBW, FSW and GTAW as LCA is a method for assessing environmental impact associated with industrial products and processes.

Comparative impact assessment will facilitate in determining which process is environment friendly by analyzing the environmental impact in following categories: global warming potential, acidification potential, eutrophication potential, ozone layer depletion potential, photochemical ozone creation potential, abiotic depletion potential, abiotic depletion fossil fuel potential, terrestrial ecotoxicity potential, fresh water ecotoxicity potential, marine aquatic ecotoxicity potential and human toxicity potential.

Although LCA analysis of several welding processes has been investigated previously, detailed comparative analysis including LBW and the effect of energy, material and shielding gas consumption for thin metal sheets is not performed.

Therefore, the objectives of this thesis can be listed as follows:

- To construct an LCA model for three metal joining processes: LBW, GTAW and FSW.
- To establish life cycle inventory of each welding process.
- To conduct LCA of each welding process.
- To identify environmental issues related to each welding process.
- To provide meaningful recommendations towards proper selection of welding process.

# CHAPTER 2. LITERATURE REVIEW

LCA is an important and powerful tool for comparing different processes and products in terms of their sustainability. Several studies have already been conducted to compare different processes. In this chapter, a review of the studies conducted on LCA of manufacturing processes and specifically welding processes will be presented.

To begin with, review of LCA of manufacturing processes will be presented in general which will be then narrowed down to studies related to LCA of welding processes including but not limited to LBW, FSW and GTAW.

## 2.1. LCA of Manufacturing Processes

Serres et.al [31] compared the environmental impacts of a novel laser-based machining process MESO-CLAD (additive laser manufacturing) and the traditional machining process employing LCA. Effect of consumption of resources in CLAD is relatively higher as compared to other machining process as machining time for CLAD is higher than the conventional process. It was also observed from the analysis that CLAD process is less energy efficient due to longer operation time [31]. It was concluded from the research that CLAD process was relatively more environment friendly than conventional process with certain impact categories such as Eco-System quality and human health have almost negligible effect.

Zhao et.al [32] compared the environmental impact assessment of laser shock peening and laser assisted turning to their conventional counterparts. Material under assessment was Aluminum Alloy 7075-T7351. It was determined that both laser-based processes were environment friendly as compared to their conventional counterpart and had 45%-50% less impact of the most impact categories. However, both the processes had high impact on eutrophication and ozone depletion categories. This is reportedly due to the paint used during laser-based processes. Employing Nd:YAG laser system will render the use of paint resulting in much better overall environmental performance [32].

Kellens et.al [33] performed thorough environmental impact modelling of selective laser sintering process and energy and resource consumption were quantified. Figure 14 shows the contribution of various parameters on the environment. It can be observed that waste material has significant contribution towards environment deterioration.

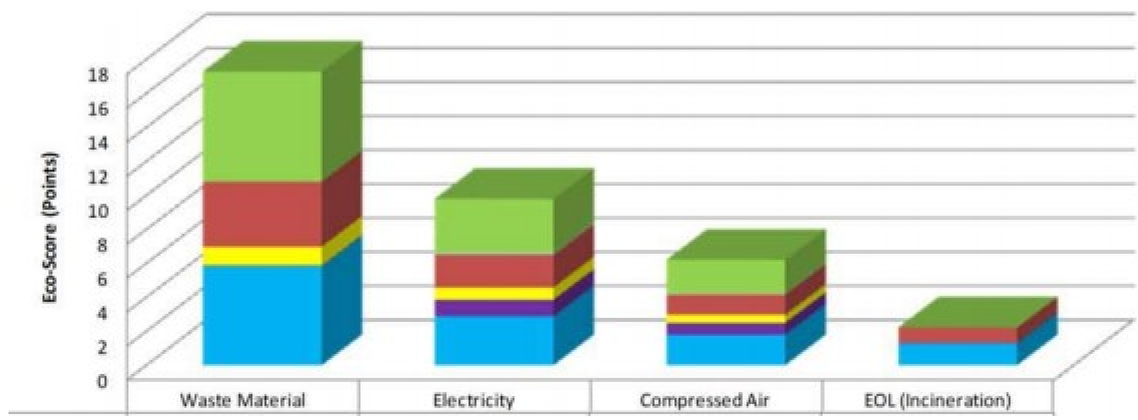


Figure 14 Impact Assessment of Selective Laser Sintering [33].

It is also inferred from Figure 14 that to optimize and improve the environmental performance of laser sintering process, efforts should be made towards reducing the waste material as it is the hotspot for the process [33].

Kellens et.al [15] analyzed the environmental impacts of Additive manufacturing process using ReCiPe method and concluded that reducing the waste material will significantly improve the environmental performance of additive manufacturing as seen from Figure 15 [15].

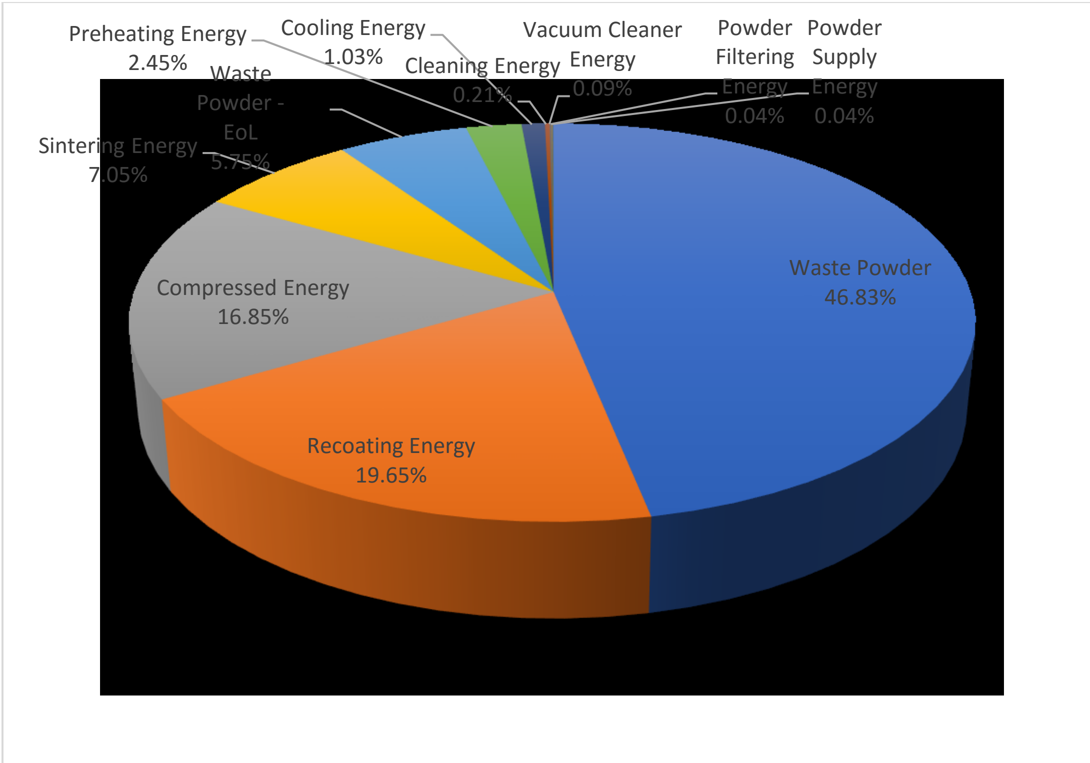


Figure 15 Impact contribution of Additive Manufacturing Process Parameters [15].

Liu, et al [34] studied the environmental benefits of remanufacturing of cylinder heads using laser cladding by quantifying the energy consumption and emissions during complete lifecycle of newly manufactured cylinder head and remanufactured cylinder heads.

Six impact categories were assessed; global warming potential, acidification potential, eutrophication potential, ozone layer depletion potential, photochemical ozone creation potential and abiotic depletion potential. It was concluded that cylinder head remanufacturing will reduce the overall environmental impacts by 40% [34].

Yilbas et.al [35] performed kerf width size analysis of laser cutting of Ti-6Al-4V alloy, Nickel based Inconel 625 and AISI 304. $CO_2$ laser with the intensity of 2000kW were used on the workpiece surface in form of high frequency pulses with nitrogen acting as an assisting gas to prevent oxidation at significantly high temperature.

It was observed that as the laser output power was increased, percentage kerf width size increased as well. On the contrary, percentage kerf width size decreased as cutting speed was increased. Yilbas et.al also concluded that material selection in laser cutting has significant impact on determining the environmental impacts with Inconel 625 contributing the most towards environmental degradation. Effect of waste from the cutting sites is easily mitigated through recycling [35].

Kellens et.al [36] provided an overview of energy consumption during processes involving laser cutting. It was concluded that $CO_2$ lasers requires 50% more energy as compared to the alternative lasers. Kellens et.al proposed a three-step model for reduction of resources consumption: proper process, proper tool selection and optimized tool design [36].

Alexopoulos et.al [37] compared laser beam welding with traditional joining process for manufacture of light weight aircraft. The study concluded that employing laser beam welding resulted in reduced weight, low production time and decreased energy consumption resulting in up to 53% reduction $CO_2$ emissions [37].

Bekker & Verlinden [38] analyzed and compared casting, milling and additive manufacturing for production of metal parts. They concluded that environmental performance of each process is dependent on product shape, materials and process parameters.

Comparing the overall performance of each process, milling process had the most environmental impacts owing to its high resource consumptions and emission affecting human health. On the other hand, additive manufacturing and casting had low environmental impact due to near net shape product and low resource consumption [38].

Zhong et.al [39] proposed a selection framework for appropriate selection of process parameters for turning process. Selection of optimum process parameters results in reduction in energy consumption during the turning process thus reducing environmental impacts [39].

Walachowicz et al [40] performed life cycle assessment of industrial repair process for gas turbine burners using machining processes and additive manufacturing. It was shown that the energy consumption and greenhouse gas emissions can be reduced for additive manufacturing if the right manufacturing approach is used. It is established that primary energy demand for conventional repair process i.e. machining is significantly higher as compared to additive manufacturing. Figure 16 shows the energy consumption during various life cycle stages of both repair processes.

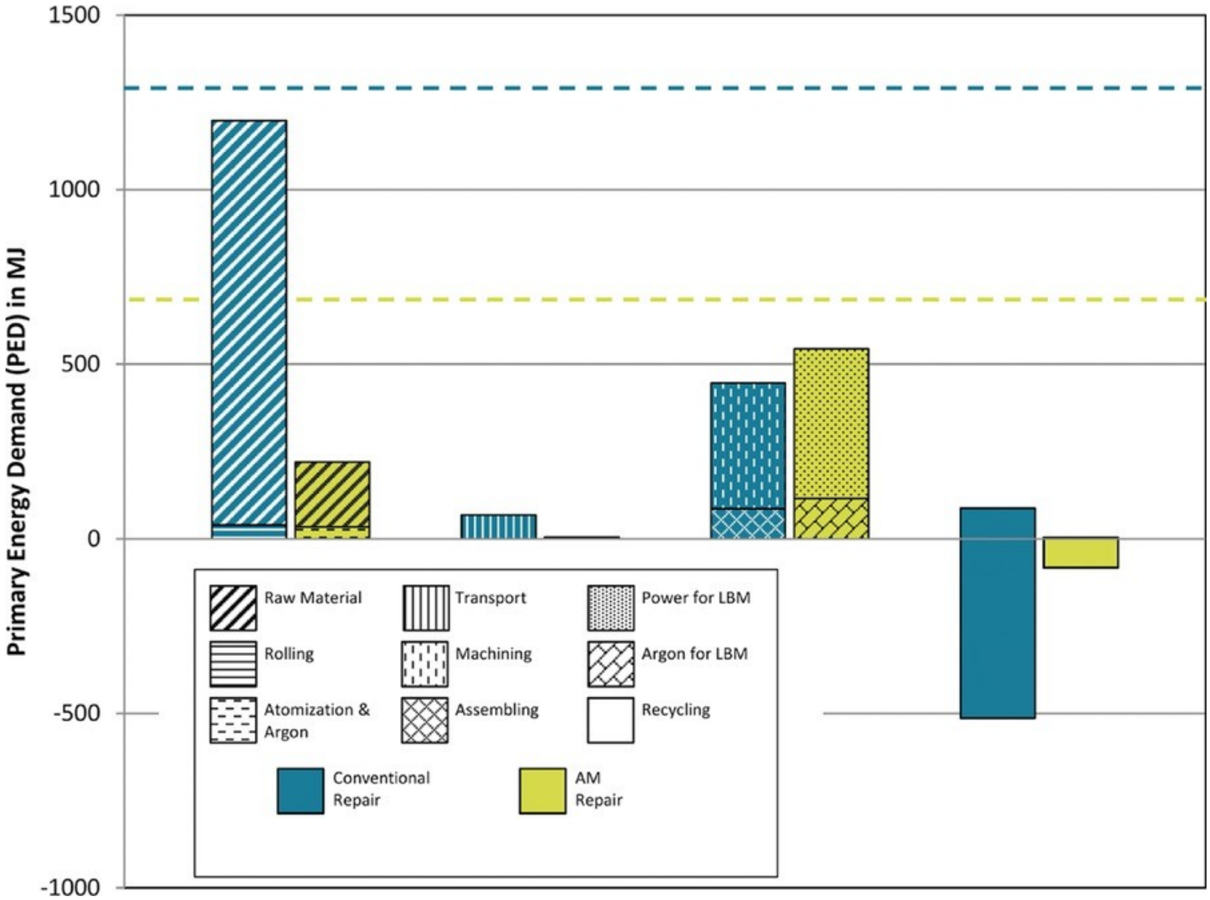


Figure 16 Energy Consumption during life cycle stages of conventional and AM repair process [40].

Environmental impacts during additive manufacturing occurs due to high electricity consumption during the process while for conventional repair process, environmental impacts contributions are significant on upstream carbon-based process [40].

Liu et.al [41] analyzed the energy and emissions consumption for production of aircraft components using additive manufacturing (AM) and conventional manufacturing (CM) process. Figure 17 shows the energy consumption during production of various aircraft components.

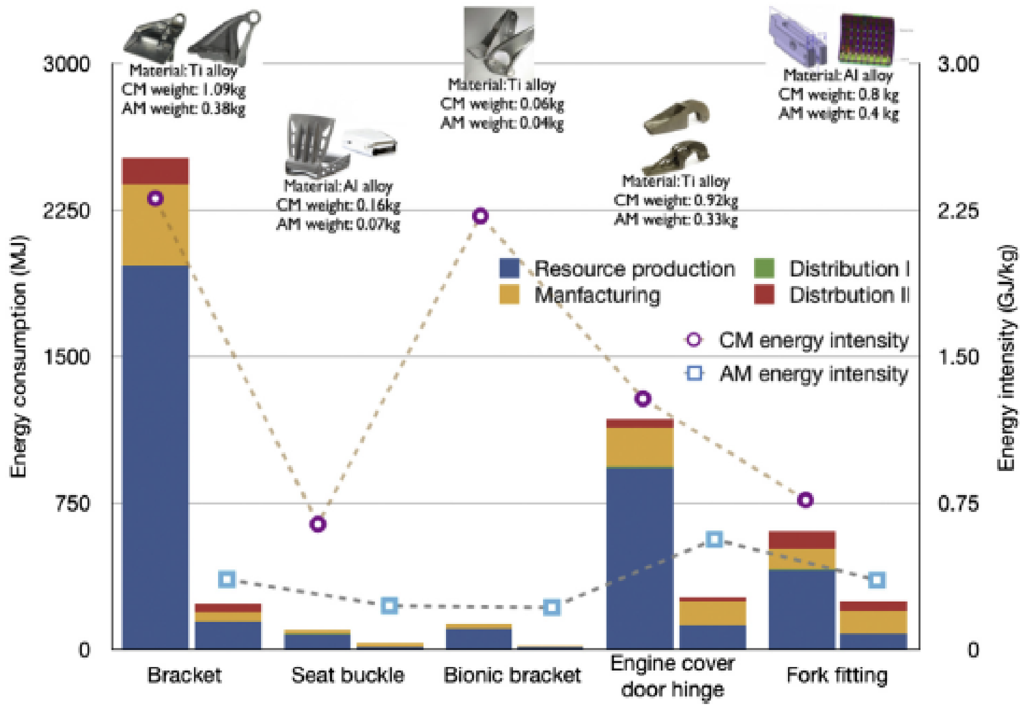


Figure 17 Energy consumption during production of various aircraft components [41].

It can be seen that energy consumption reduces significantly when additive manufacturing is used for production. This reduction in energy consumption is attributed to overall reduction in fuel consumption during flight owing to light weight components produced through additive manufacturing.

Most of this reduction happens during the use phase of aircraft. Estimated reduction in energy consumption during manufacturing of different aircraft parts is shown in Figure 18.

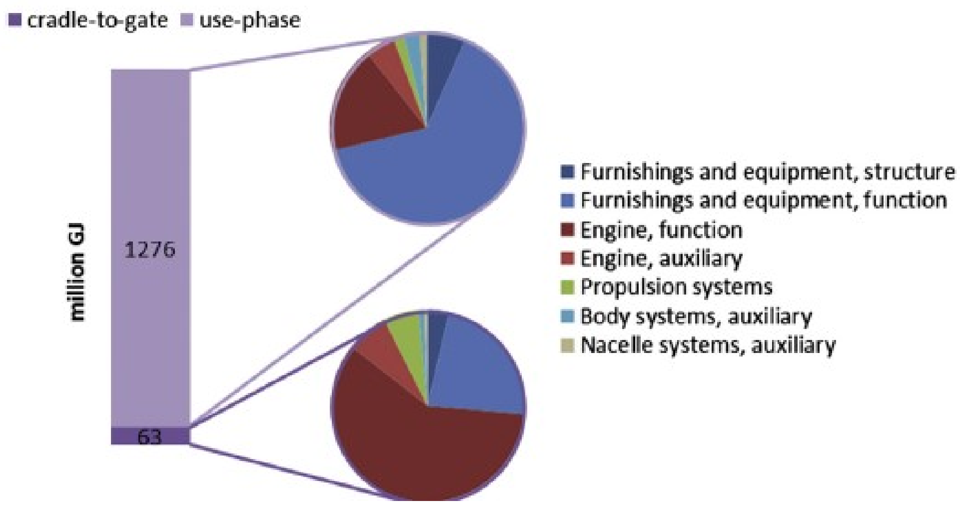


Figure 18 Estimated reduction in energy consumption by 2050 [41].

Figure 18 shows the estimated reduction in energy consumption that could be potentially achieved by 2050 by employing additive manufacturing for production of aircraft components [41].

Vimal et.al [42] proposed process parameter optimization using full factorial design for Submerged Metal Arc Welding (SMAW) for reduction of environmental impacts associated with SMAW. They proposed optimization of current, voltage and welding speed. It was found out that acidification and ecotoxicity are significantly impacted by SMAW.

It was observed that the environmental impacts are significantly reduced when optimized process parameters are used as compared to existing process parameters. They concluded based upon environmental impact assessment, 10% improvement in overall environmental performance was observed when optimized process parameters were used [42].

Caneghem et.al [43] studied the reduction in environmental impacts associated with Steel production industry. Reduction in environmental impacts was observed due to switch from ingot casting production method to continuous casting. Moreover, reduction in material losses during various production steps and good housekeeping practices were attributed towards reduction in environmental impacts. Figure 19 shows the steel production in tons and evolution of acidifying emissions per annum.

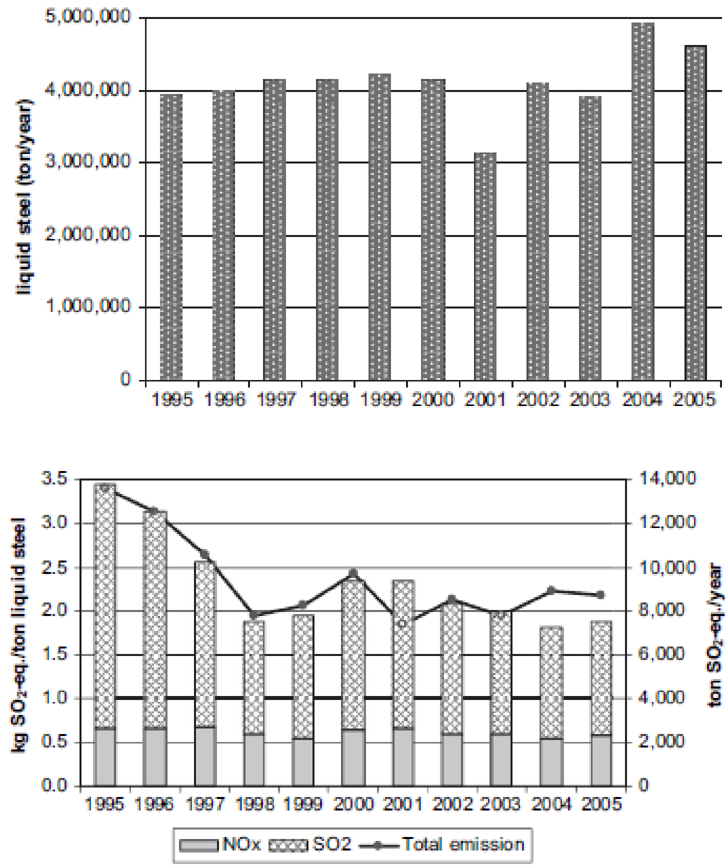


Figure 19 Evolution of Steel production and acidifying emissions over the period of time [43].

It was found out that almost 45% improvement in acidification potential was observed due to overall improvement in production efficiency and taking various process integrated measures. Figure 20 shows the eco-efficiency for all impact categories.

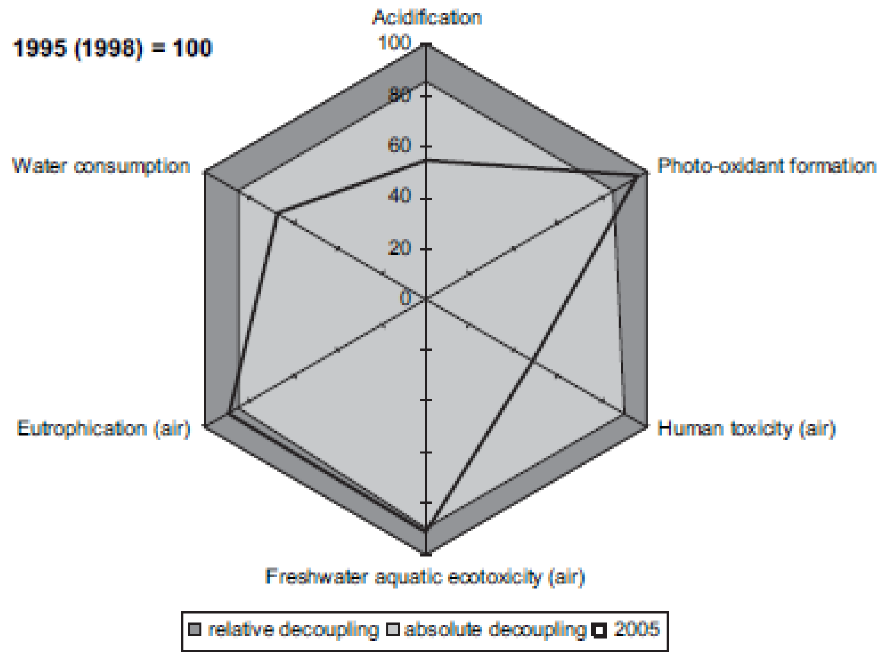


Figure 20 Eco-efficiency for steel production [43].

It was concluded that an overall improvement of eco-efficiency for all impact categories was achieved by employing new production method and introducing certain process-integrated changes [43].

Le et.al [44] performed LCA of CNC machining and an innovative manufacturing strategy involving additive and subtractive manufacturing. It was concluded that the innovative manufacturing strategy had reduced environmental impacts in both scenarios whether existing part material is reused, or new part is manufactured.

Moreover, it was found out that the environmental competition among two processes were significant during powder production and electron beam melting (EBM). It was concluded that the innovative strategy has almost 50% reduced impact on the environment as compared to conventional CNC machining owing to reduced material consumption [44].

Ingarao et.al [45] performed environmental modelling of additive manufacturing, machining and forming for production of aluminum components. They performed the comparative assessment on three different shapes of component production while for additive manufacturing, reduction in material consumption is also incorporated.

As observed in Figure 21, Figure 22 and incorporating potential reduction in component weight during additive manufacturing, it can be concluded that additive manufacturing is currently not suitable for production of aluminum components owing to its high energy consumption.

This significantly high energy consumption is associated with melting of aluminum powder layers. This high energy consumption is attributed to high reflectivity and high thermal conductivity of aluminum.

However, they concluded that if the component is to be used for long distance aircraft, additive manufacturing should be employed while for road vehicles, component production through conventional processing methods would be environment friendly [45].

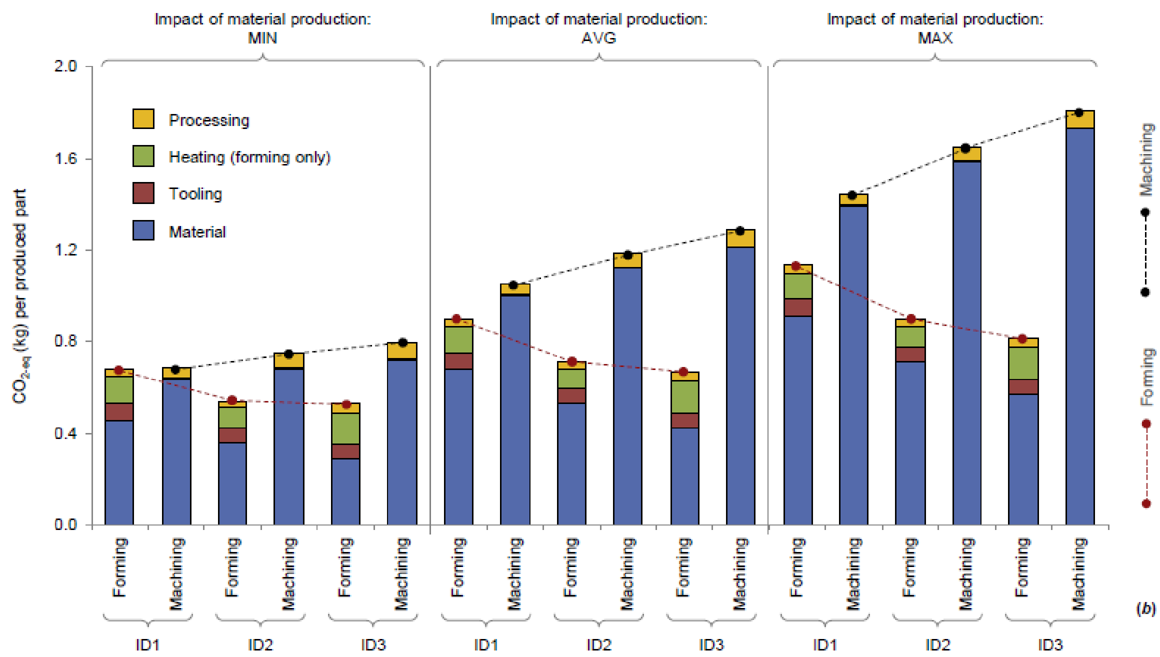


Figure 21 $CO_2$ emissions for forming and machining processes [45].

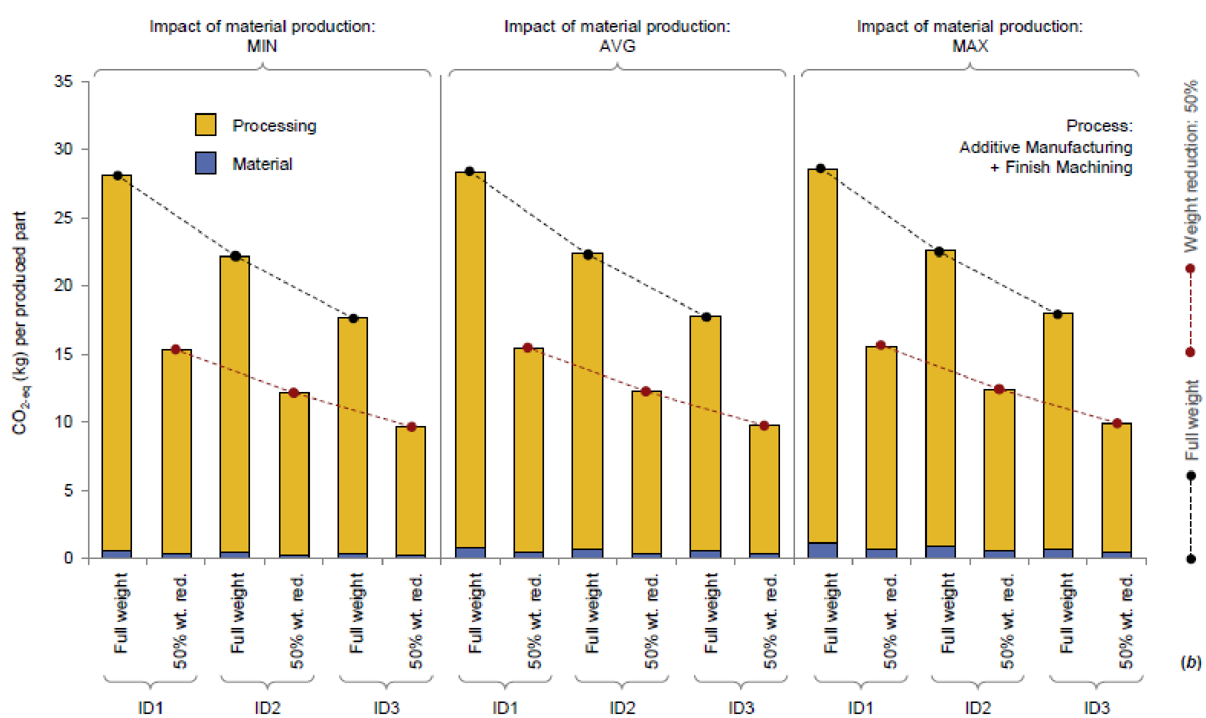


Figure 22 $CO_2$ emissions for additive manufacturing process [45].

Bours et.al [46] developed a framework to analyze the direct hazardous impacts of additive manufacturing on human health and the environment using LCA. According to Bours et.al additive manufacturing is carried out in six different stages as shown in Figure 23.

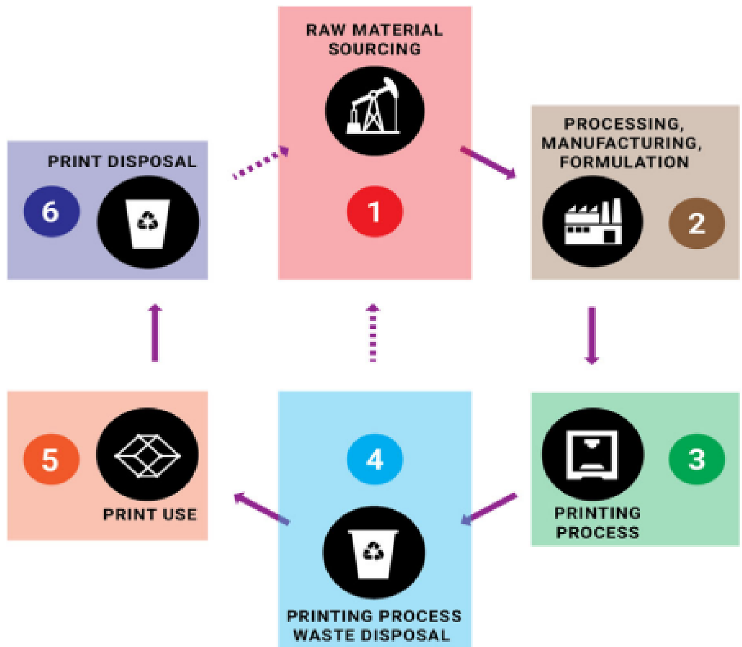


Figure 23 Life Cycle Stages of Additive Manufacturing [46].

They established that during the printing process of additive manufacturing i.e. stage 3, additive manufacturing has direct and most conspicuous impact on human health i.e. to the operator and the immediate surroundings. These hazards include dermal, physical and environmental hazards in form of particulate and volatile compound emissions [46].

Pineda-Henson & Culaba [47] proposed a methodology integrating LCA and Analytic Hierarchy Process(AHP) to assess green productivity(GP) of a manufacturing process. Green productivity is a novel model used to enhance environmental performance and productivity of a manufacturing process using waste reduction and resource management strategy.

Using streamlined LCA and HRP, they concluded that for a manufacturing process; terrestrial ecotoxicity, human toxicity, water resource depletion and energy resource depletion has a significant impact on determining GP of the process [47].

Dias et.al [48] performed a comparative LCA analysis to determine the environmental impacts of newly manufactured and remanufactured diesel engine. A comparative LCA is shown in Figure 24.

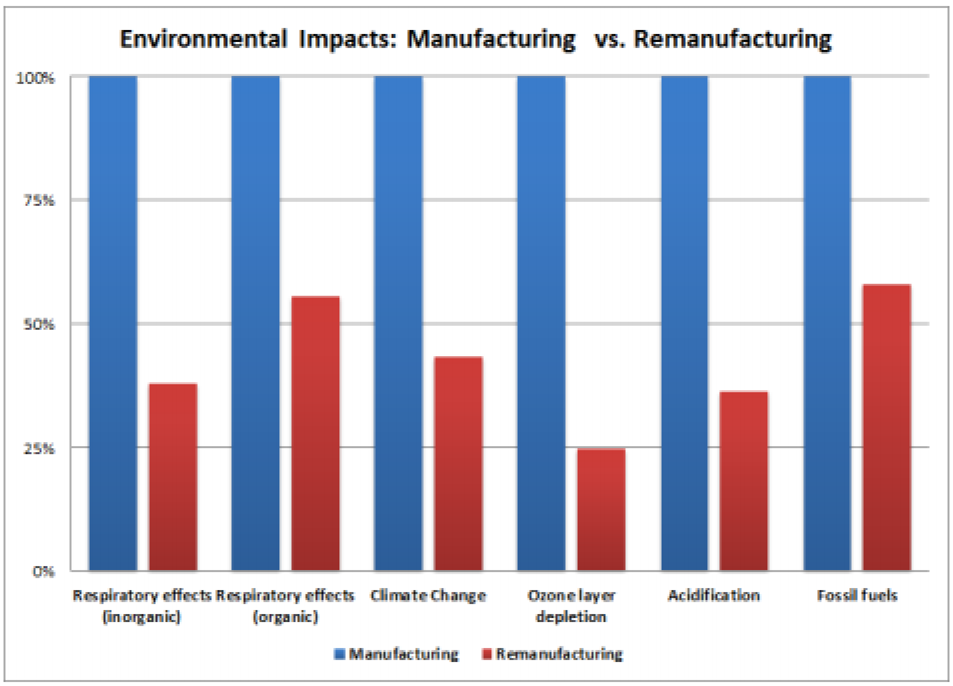


Figure 24 Comparative environmental impact assessment of new and remanufactured diesel engine [48].

It was concluded from the research that the remanufacturing process had significantly less impact on the environment as compared to the newly manufactured diesel engine owing to significant reduction in energy consumed during the process. Moreover, it is evident from Figure 24 that remanufacturing a diesel engine has significantly reduced overall impact on the environment [48].

Kafara et.al [49] performed a comparative cradle to grave LCA using ReCiPe midpoint H method for production of mold cores using low alloy melting, milling and additive manufacturing from high impact polystyrene and powder material.

Additive manufacturing is found out to be more environment friendly as compared to conventional mold core manufacturing processes. This can be attributed to reduction of environmental impacts during the production of core material as the material of mold core contributes significantly towards determining the environmental behavior of production of mold core [49].

Faludi et.al [50] compared the environmental impacts associated with additive manufacturing and conventional computer numerical control(CNC) milling process using LCA and ReCiPe H methodology. Comparative LCA was made among FDM 3-D printing, inkjet 3-D printing and conventional CNC milling. They concluded that the environmental performance of each process cannot be generalized as it depends on the usage profile and the machine itself.

It is concluded that FDM printing can significantly reduce the environmental impacts both in maximum utilization and minimum utilization state of production. Moreover, they concluded that when comparing sustainability performance of different processes, a complete analysis must be done to reach a viable decision about the sustainability of the process e.g. if only energy consumption was considered during the said LCA, CNC would have performed better. On the other hand, if only material consumption is considered, CNC machining would have performed the worst [50].

Hirogaki et al [51] performed a comparative life cycle impact assessment of desktop-sized five-axis CNC machine(D5MC) and regular five-axis CNC machine(5MC) for small scale part manufacturing. They concluded that downsizing the CNC results in significantly reduced global warming potential associated with CNC machining [51].

Liu et al [52] performed life cycle impact assessment of amorphous alloy strip production using rapid solidification technique using CML method and the results are shown in Figure 25.

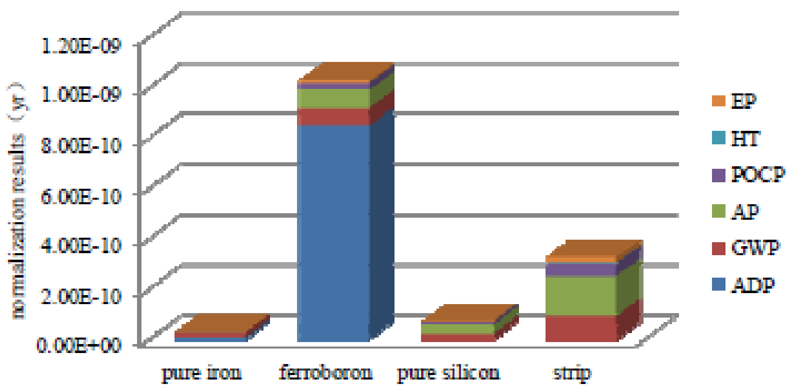


Figure 25 Life cycle impact assessment for production of amorphous alloy strip [52].

It can be seen from Figure 25 that during production of amorphous alloy strip, pre-production of ferroboron accounts for approximately 70% of the total environmental impact while the production of strip from processed materials accounts to 22% of the total environmental impact. They proposed that environmental impact associated with production of ferroboron can be reduced by increasing the boric acid consumed during production process [52].

Norgate & Jahanshahi [53] proposed a solution to reduce the greenhouse gas footprint associated with metal production processes. They concluded that major contribution towards greenhouse gas footprint is by the metal extraction stage in particular for aluminum and steel production. They found out that employing biomass as a source of fuel can significantly reduce the greenhouse gas footprint associated with metal production industry. Moreover, employing energy efficient methods for comminution of ores can potentially facilitate in reducing greenhouse gas footprint [53].

Faludi et.al [54] analyzed the environmental impacts of production of aluminum workpiece using selective laser melting(SLM). They concluded that energy consumed during the process had significant influence on the environmental impacts associated with SLM while the contribution of powder material on the environmental impacts was insignificant [54].

## 2.2. LCA of Welding Processes

Welding processes are the most commonly used joining processes currently being employed in the industry and are a major source of energy and gas consumption [55]. It is necessary to perform LCA analysis to study the effects on the environment and to compare different welding processes and rank them according to their environmental performance. Some studies will be presented below to understand the environmental performance of welding processes.

Sangwan et.al [56] found out that impact to the environment is significant during the raw material extraction phase due to copper and mild steel being used for equipment manufacture followed by the use phase owing to electricity consumption and fume generation during welding processes arriving to the conclusion that arc welding processes have significant deteriorating effects towards the environment due to high consumption of electricity, shielding gas and fume generation [56].

Sproesser et.al [57] performed LCA for joining of thick metal plates using welding techniques and compared them. The study concluded that laser assisted hybrid arc welding had the least impact on the environment while Manual Metal Arc Welding (MMAW) had the most impact on the environment as observed from Figure 26.

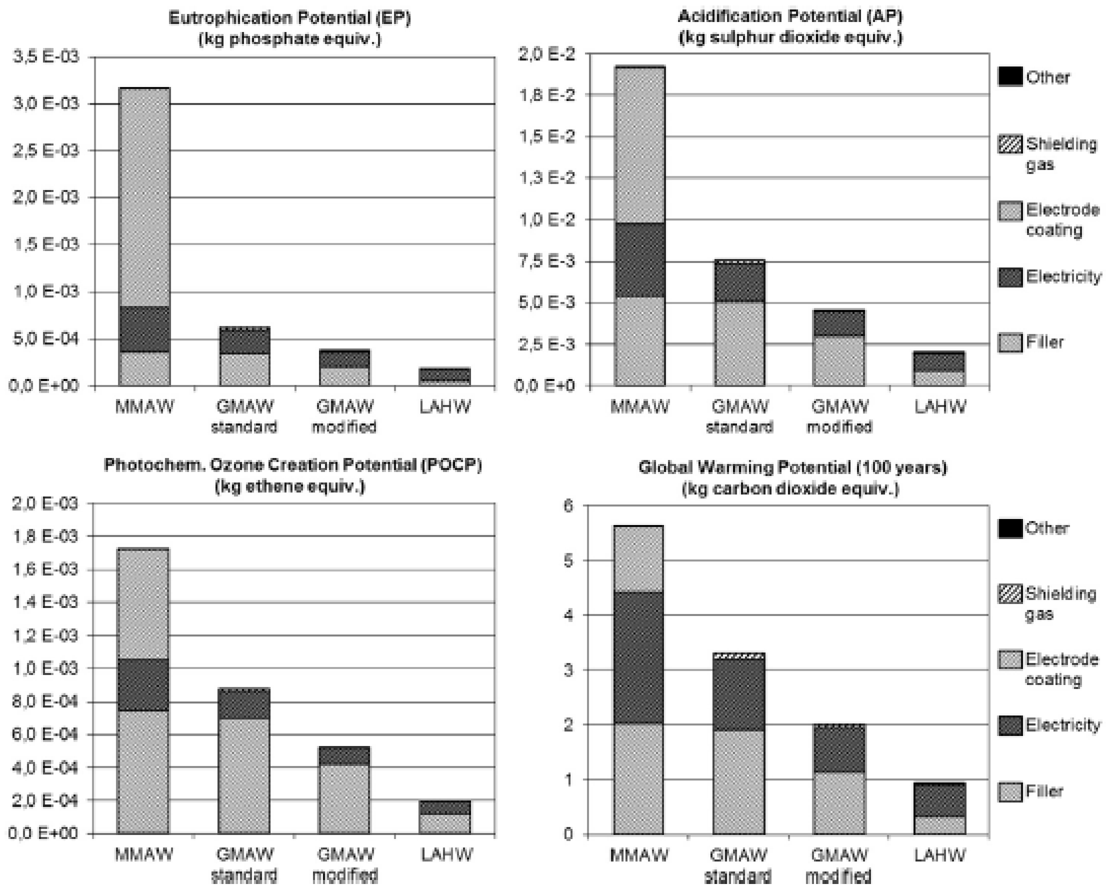


Figure 26 Comparison of various welding processes [57].

It was observed that due to high power density in laser welding, weld was performed with both least number of welding passes and weld volume. High welding speed played an important role in low consumption of energy resources. While, MMAW performed the worst owing to low deposition rate and welding speed, thus consuming relatively more energy resources [57].

Sproesser et.al [58] compared environmental performance of Single Wire Arc Welding (SGMAW) and High Power Arc Welding (TGMAW) and concluded that using high power arc welding (TGMAW) can reduce environmental impacts by 11% [58].

Comparison between friction stir welding (FSW) and gas metal arc welding (GMAW) was made by Shrivastava et.al [59] for joining aluminum sheets. FSW was found to be 42% more energy efficient than GMAW while consuming 10% less material for the same weld [59].

Bevilacqua et.al [60] analyzed the sustainability of FSW of Aluminum sheets and concluded that the environmental performance of FSW depends strongly upon selection of optimal welding parameters [60].

A framework for selection of suitable and energy efficient welding process was proposed by Yeo & Neo [61] as they compared Metal Inert Gas welding (MIG) with Manual Metal Arc welding (MMA) and concluded based upon environmental impact alone, MIG should be avoided.

Yeo & Neo also addressed the importance of selection of appropriate welding process based upon their environmental performance and stated that 1% of consumables used in Arc welding processes are converted to emissions [61].

Chang et al [1] provided a detailed comparison of different state of the art welding techniques i.e. Laser arc hybrid welding, automatic gas metal arc welding, manual gas metal arc welding and manual metal arc welding as seen in Figure 27.

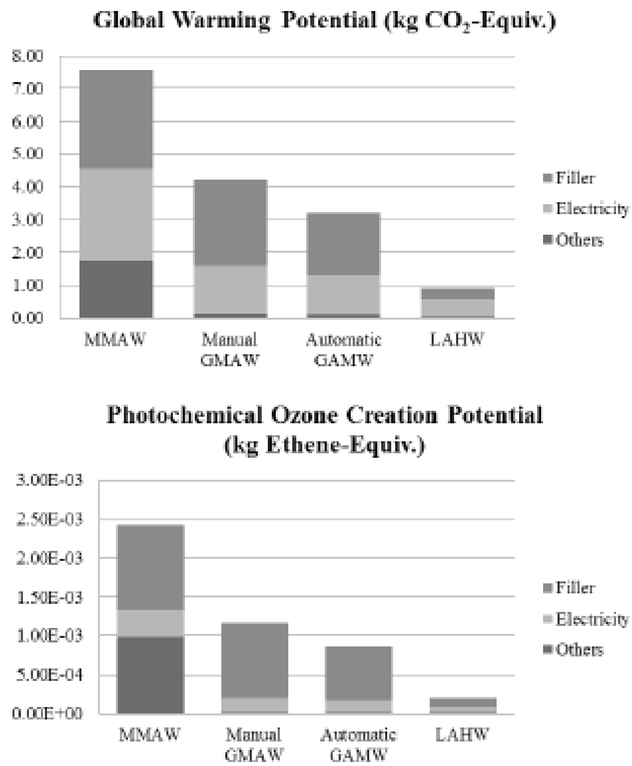


Figure 27 Comparative LCA of different welding processes [1].

Due to high resources consumption during Manual Metal Arc Welding (MMAW), it ranked the least among the process while laser assisted hybrid arc welding performed exceptionally well in term of sustainability [1].

Wei et.al [62] performed an in-depth analysis of laser welding for improved efficiency [62]. Drakopoulos et.al [63] modelled and compared various cutting and welding processes with the help of SimaPro. Comparison was made among Flux Core Arc Welding (FCAW), Submerged Arc Welding (SAW) and Shielded Metal Arc Welding (SMAW). FCAW had a significant overall impact on the environment while SAW had the least overall impact among the three [63].

Dahmen et.al [64] compared the ecological footprint of laser beam welding and various arc welding processes for production of T-beams. Comparison between energy consumption of MAG and laser welding showed that the energy consumption of laser welding is very close to MAG even though MAG has high efficiency as seen from Figure 28. Moreover, it can be seen that hazardous emissions, post processing, preparation and material consumption have been significantly reduced in laser welding as compared to arc welding process.

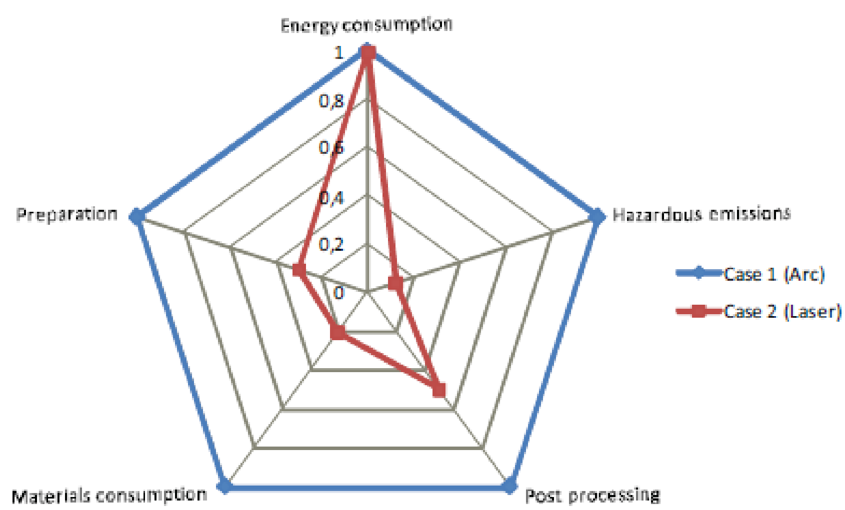


Figure 28 Environmental performance comparsion of Arc and Laser welding [64].

Moreover, comparison of laser welding and arc welding for manufacture of flanges reveals that laser welding is eco-friendly as energy consumption is reduced from 1.19 MJ/m to 0.743 MJ/m while reducing material consumption drastically as shown in Figure 29 [64].

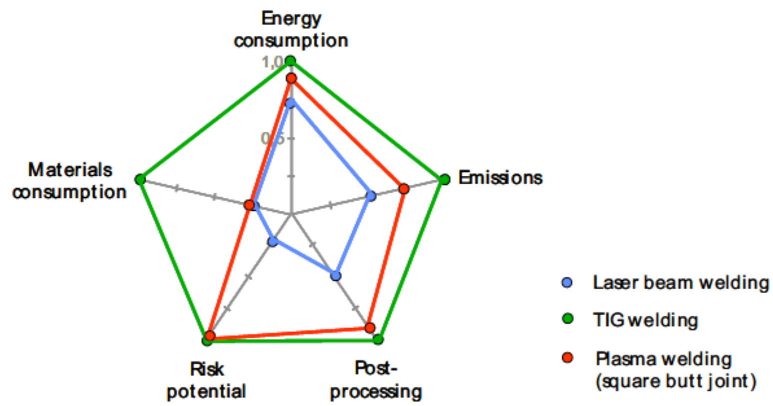


Figure 29 Environmental Performance comparison of laser, TiG and Plasma welding [64].

Um & Stroud [65] estimated the energy consumption of conventional robotic laser welding and remote laser welding process. It was found out that processing time and laser power plays an important role in determining energy consumption during the process. It was concluded that remote laser welding consumed less energy while the processing time was significantly reduced as shown in Figure 30 [65].

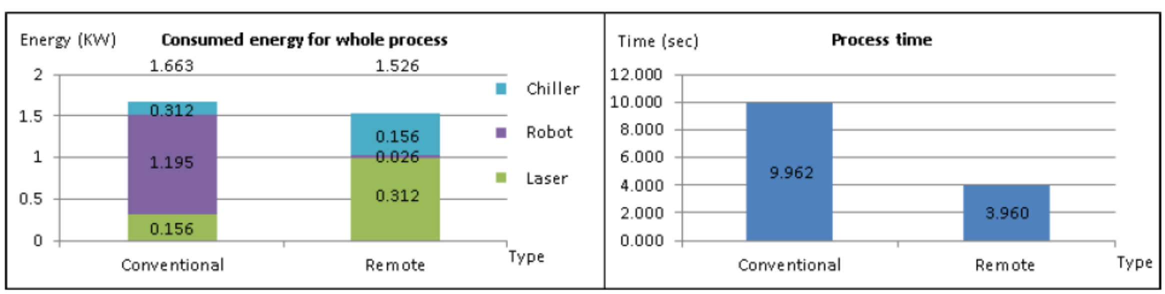


Figure 30 Energy Comparsion of Robotic and Remote laser welding [65].

Gialos et al [66] investigated the carbon footprint of joining of various aeronautical subscale components using laser beam welding and riveting. They found out that the weight of various components decreased by roughly 20% when laser beam welding is used.

Figure 31 shows the comparison between weight of component joined, process duration and carbon footprint using two different methods.

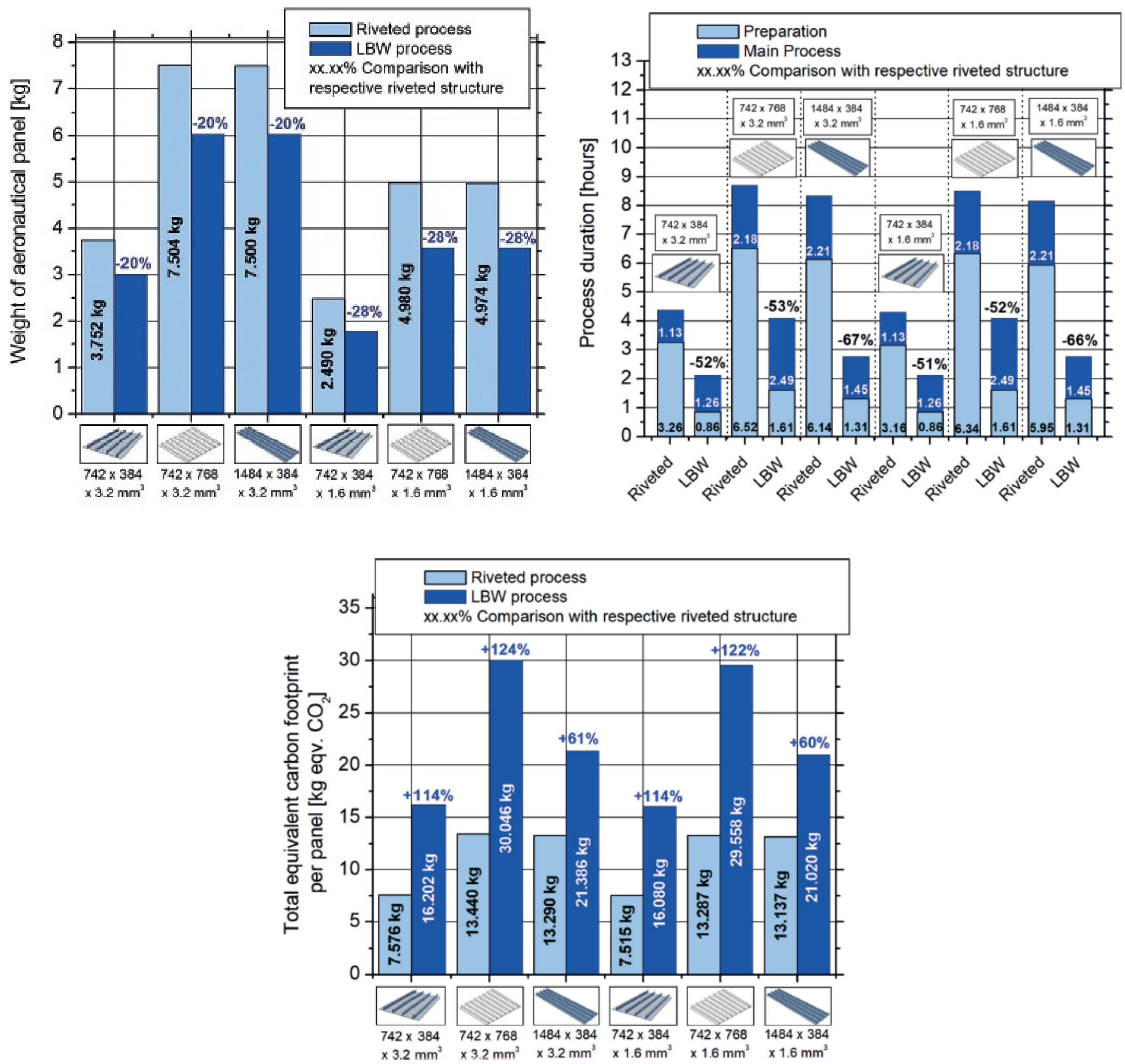


Figure 31 Component weight, Process duration and Carbon footprint of both production process [66].

As seen from Figure 31, processing time is also significantly reduced when laser beam welding is employed. However, the carbon footprint associated with laser beam welding is significantly higher than riveting process due to high energy consumption of laser beam welding. Nevertheless, laser beam welding emits more $CO_2$ emission during processing but when complete life cycle of aircrafts is considered, laser beam welding could essentially reduce the $CO_2$ emissions and the effect of increased $CO_2$ emission during processing could be neglected. Moreover, they also found out that the total manufacturing cost for laser beam welded large components is 40% reduced as compared to riveted components [66]. Vimal et.al [67] proposed reduction of environmental impacts of SMAW by insisting on waste minimization and introducing new disposal scenario [67].

Zukauskaite et.al [68] analyzed the sustainability of welding technologies and their effect on human health and environment [68]. Improved thermal efficiency of gas tungsten arc welding (GTAW) can increase the environmental efficiency of the process.

Magalhaes et.al [69] used temperature moving sensor to improve thermal efficiency up to 59%.

Alkahla & Pervaiz [70] performed sustainability analysis in terms of social and environmental aspects of shielded metal arc welding(SMAW) using LCA and concluded that the health hazards associated with SMAW can be reduced by using optimum process design as health hazards are mostly due to fume inhalation by the operator [70].

To conclude the section, in line with the above-discussed studies [31-72], it is clearly demonstrated that performing LCA analysis provides estimation and quantification of the environmental impacts related to the manufacturing processes such as welding. Furthermore, the impact of the three concerned welding processes on the environment has been made clear with the help of studies cited above [56-72].

Several studies have been carried out to establish the environmental performance of fusion welding and solid-state welding of thick metal sheets in terms of the impact categories discussed in Research Scope.

However, environmental impacts associated with welding of thin metal sheet has not been done. This provided the motivation to carry out the current study and to close the gap towards determining and quantifying the environmental impacts of LBW, FSW and GTAW of thin metal sheets in order to establish the environmental performance of LBW in comparison with other two processes.

# CHAPTER 3. RESEARCH METHODOLOGY

This project investigates the environmental impact of welding of thin metal sheets using LBW, FSW and GTAW. LCA analysis was carried out in accordance with the guidelines provided in ISO 140400 and ISO 140440 while keeping the scope of study wide enough to allow comparisons with any future study done on welding processes. This research is also intended to facilitate towards selection of welding processes for the concerned materials based entirely upon their environmental performance.

This chapter will introduce the experimental procedure for LBW, FSW and GTAW, collection of life cycle data and generation of life cycle inventory (LCI) for the three welding processes.

## 3.1. Welding Processes

Numerous welding and joining techniques are available and used in manufacturing industry. Selection of appropriate welding processes is an essential step and requires special consideration. Selection of the joining process depends strongly upon the application, dimensions and shape of the joint, workpiece material, precision and equipment availability.

For this study, environmental impacts associated with LBW, FSW and GTAW of AISI 304 Steel are studied. The workpiece dimensions used for the experiments are given in Table 1:

Table 1 Dimensions for AISI 304 sample under assessment

| Sample Type | Thickness (mm) | Length (mm) | Width (mm) |
|---|---|---|---|
| Sample 1 | 1.5 | 200 | 55 |
| Sample 2 | 2.0 | 200 | 55 |
| Sample 3 | 2.5 | 200 | 55 |

### 3.1.1. Gas Tungsten Arc Welding

For GTAW, Miller Syncrowave 351 machine was used. A non-consumable tungsten electrode is used while Argon gas was used to prevent the oxidation of weld area. Gas consumed during the process was measured through the gas flow meter reading. 308L filler material was used for joining purposes.

Energy consumption is calculated using output voltage and current. Material consumption was calculated by measuring the weight of the workpiece before and after the welding process and amount of electrode consumed during welding. The equipment used for GTAW is shown in Figure 32.


Figure 32 Syncrowave Miller Welding Equipment.

Post weld image of AISI 304 steel workpiece is shown in Figure 33.

Figure 33 GTAW welded sample of AISI 304 Steel.

### 3.1.2. Friction Stir Welding

For FSW, MTI-RM1 equipment is used to weld AISI 304 Steel samples. The input parameters for welding are shown in Table 2.

Table 2 FSW Processing Parameters

| Input Parameter | Magnitude |
|---|---|
| Tool Speed (RPM) | 950 |
| Welding Speed (mm/min) | 65 |
| Tilt Angle(degrees) | 1.5 |

Argon gas is used to avoid oxidation at the flow rate of 40 CFH. Inventory analysis for FSW is provided in section Life Cycle Inventory. The equipment used for FSW is shown in Figure 34.

Figure 34 MTI-RM 1 FSW Equipment.

Post weld image of AISI 304 Steel is shown in Figure 35

Figure 35 FSW welded sample of AISI 304 Steel.

## 3.2. LCA of LBW, FSW and GTAW

In this section we will explain and define the formal steps of LCA required for this study in accordance with ISO 140400 guidelines i.e. defining goal and scope, functional unit, data collection and impact categories.

### 3.2.1. Goal of the Study

The aim of this study is to compare and quantify the environmental impacts associated with the three welding techniques in manufacturing industry. While the intended application of this study is to identify and recommend the most sustainable joining technique. This study is targeted towards industrial experts and academic researchers.

### 3.2.2. Scope of the Study

A cradle to gate LCA analysis is performed for comparison of the three welding processes including the raw material extraction for the workpiece till the joining of the workpiece. System boundaries for the analysis are shown in Figure 36, Figure 37 and Figure 38.

LBW was performed in Turkey while the experiment involving the rest of joining processes were carried out in Saudi Arabia as the focus of the study is on Saudi Arabia. For simplicity of the analysis, length of the weld line is considered as functional unit. Experiments were performed under controlled environment in the lab to ensure data quality.

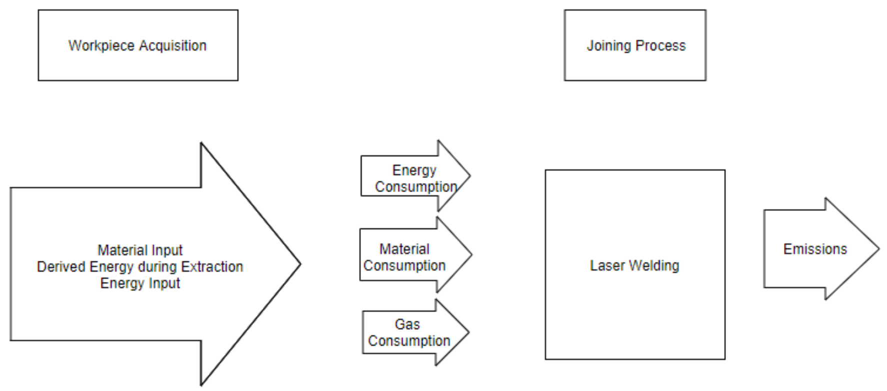


Figure 36 System Boundary for LBW

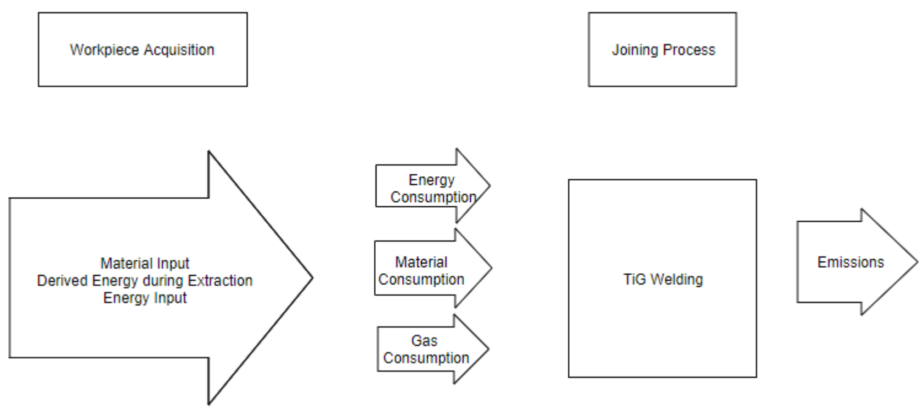


Figure 37 System Boundary for GTAW.

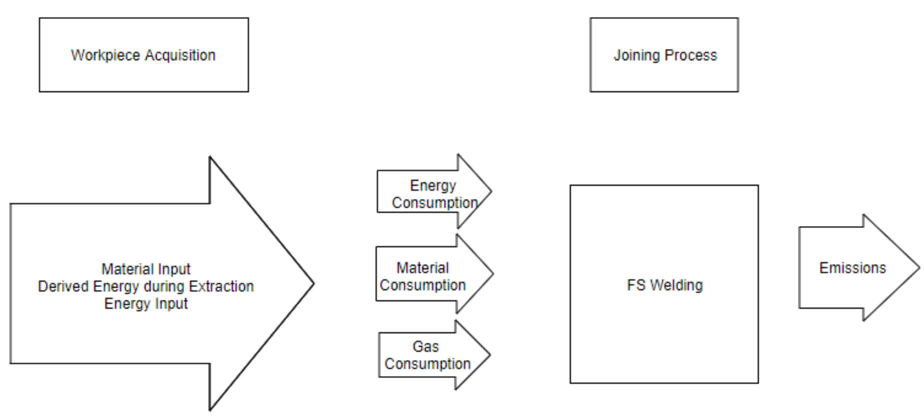


Figure 38 System Boundary for FSW.

### 3.2.3. Life Cycle Inventory

Welding experiments were performed in the lab and inventory data was measured and recorded accordingly.

- LBW is performed in Turkey due to equipment limitation. As the focus of the study is on the environmental impacts, LBW was carried out on three different samples having different composition and thicknesses to make a comparison among them and to rank them according to their sustainability. $1^{st}$ sample was made of Ti-6Al-4V while second sample was made of AISI 304 Steel and third sample was made of Inconel 625.
- FSW is performed locally on AISI 304 Steel samples for comparison with LBW and GTAW and energy and material consumption during the process were recorded.
- GTAW is also performed locally on AISI 304 Steel samples for comparison with LBW and FSW. Energy, material and shielding gas consumption during welding process were recorded in lab with the help of output voltage, output current, gas consumed, material evaporated, and electrode consumed during the process.

### 3.2.4. Life Cycle Impact Assessment

Once life cycle inventory is completed, SimaPro was used for inventory analysis and environmental impacts were calculated using CML method. Following impact categories were analyzed during the analysis:

#### 3.2.4.1. Global Warming Potential (GWP100a)

Global warming potential is the effect of emission of greenhouse gases over 100 years. Global warming potential is expressed in kg $CO_2$/kg emissions.

#### 3.2.4.2. Abiotic Depletion Potential (ADP)

Abiotic depletion potential is concerned with extraction of raw materials. Abiotic depletion potential is expressed in kg Sb eq/ kg of extraction.

#### 3.2.4.3. Ozone Layer Depletion Potential (ODP)

Ozone layer depletion potential is a measure ozone layer depletion. Ozone layer depletion potential is expressed in kg CFC-11 eq./kg emissions.

#### 3.2.4.4. Photo-Chemical Oxidation Potential (PCOP)

Photo-chemical oxidation potential is the development of reactive substance in earth's atmosphere due to emissions. Photochemical oxidation potential is measured in kg ethylene eq./kg of emissions.

#### 3.2.4.5. Acidification Potential (AP)

Acidification Potential is defined as the rate of deposition of acidic substance in atmosphere. Acidification potential is measured in kg $SO_2$ eq./kg of emissions.

#### 3.2.4.6. Eutrophication Potential (EP)

Eutrophication potential is the measure of total impact due to macro nutrients caused by the emissions to air. Eutrophication potential is expressed in kg $PO_4$ eq./kg of emissions.

#### 3.2.4.7. Human Toxicity Potential (HTP)

Human toxicity potential is the measure of impact of emission of toxic substances on human ecosystem. Human toxicity potential is expressed in kg 1,4 dichlorobenzene eq./kg emissions.

#### 3.2.4.8. Marine Aquatic Ecotoxicity Potential (MAEP)

Marine aquatic ecotoxicity potential is the measure of impact of emissions on marine ecosystem. Marine aquatic ecotoxicity potential is expressed in kg 1,4 dichlorobenzene eq./kg emissions.

#### 3.2.4.9. Freshwater Ecotoxicity Potential (FWEP)

Freshwater ecotoxicity potential is the measure of impact of emissions on the freshwater ecosystem. Fresh water ecotoxicity potential is expressed in kg 1,4 dichlorobenzene eq./kg emissions.

#### 3.2.4.10. Terrestrial Ecotoxicity Potential (TEP)

Terrestrial ecotoxicity potential is the measure of impact of emissions on terrestrial ecosystem. Terrestrial ecotoxicity potential is expressed in kg 1,4 dichlorobenzene eq./kg emissions.

#### 3.2.4.11. Abiotic Depletion Fossil Fuel (ADFFP)

Abiotic depletion fossil fuel is concerned with the depletion in natural fossil fuels resources. It is expressed in MJ.

To conclude the section, process parameters used during welding experiments were defined and the methodology to carry out LCA analysis, primary data collection and life cycle inventory was generated for three welding processes. Based upon the life cycle inventory, life cycle impact assessment was performed, and the results obtained are presented and discussed in next chapter.

# CHAPTER 4. RESULTS AND DISCUSSION

Once life cycle inventory was completed, SimaPro was used for inventory analysis and environmental impacts were calculated using CML method. CML method is problem oriented i.e. it uses midpoint approach for analysis. Following impact categories were of interest during the research: global warming potential, abiotic depletion potential, ozone layer depletion potential, photochemical oxidation potential, acidification potential, human toxicity potential, freshwater ecotoxicity potential, marine aquatic ecotoxicity potential, terrestrial ecotoxicity, abiotic depletion fossil fuel potential and eutrophication potential.

In this chapter, environmental impacts associated with the concerned welding processes are discussed. Contribution of each life cycle inventory component i.e. energy, gas and material consumption towards the above-mentioned environmental impact categories for each welding process were analyzed.

This chapter is further divided into: Environmental impact assessment of welding of AISI 304 steel sheet of thickness of 2.5mm using three different welding processes, effect of workpiece thickness on environmental impact associated with each welding process and environmental impact assessment of LBW of AISI 304 Steel, Inconel 625 and Ti-6Al-4V.

## 4.1. Life Cycle Inventory

### 4.1.1. Primary Data for Welding of AISI 304

Life cycle inventory data for the process was measured and tabulated in Table 3:

Table 3 Inventory Analysis for welding of AISI 304 Steel

| | LBW | | | GTAW | | | FSW | | |
|---|---|---|---|---|---|---|---|---|---|
| Thickness Mm | Energy (J) | Gas (g) | Material (g) | Energy (J) | Gas (g) | Material (g) | Energy (J) | Gas (g) | Material (g) |
| 1.5 | 280000 | 600 | 4 | 646144 | 225 | 30 | 2729479 | 609 | 3.67 |
| 2.0 | 420000 | 600 | 8 | 772278 | 234 | 34 | 3223441 | 637 | 8.5 |
| 2.5 | 640000 | 600 | 11 | 859155 | 243 | 37 | 3717404 | 665 | 13.3 |

Life cycle data was modeled with the help of SimaPro and process layout for each welding process can be seen in Figure 39, Figure 40, and Figure 41.

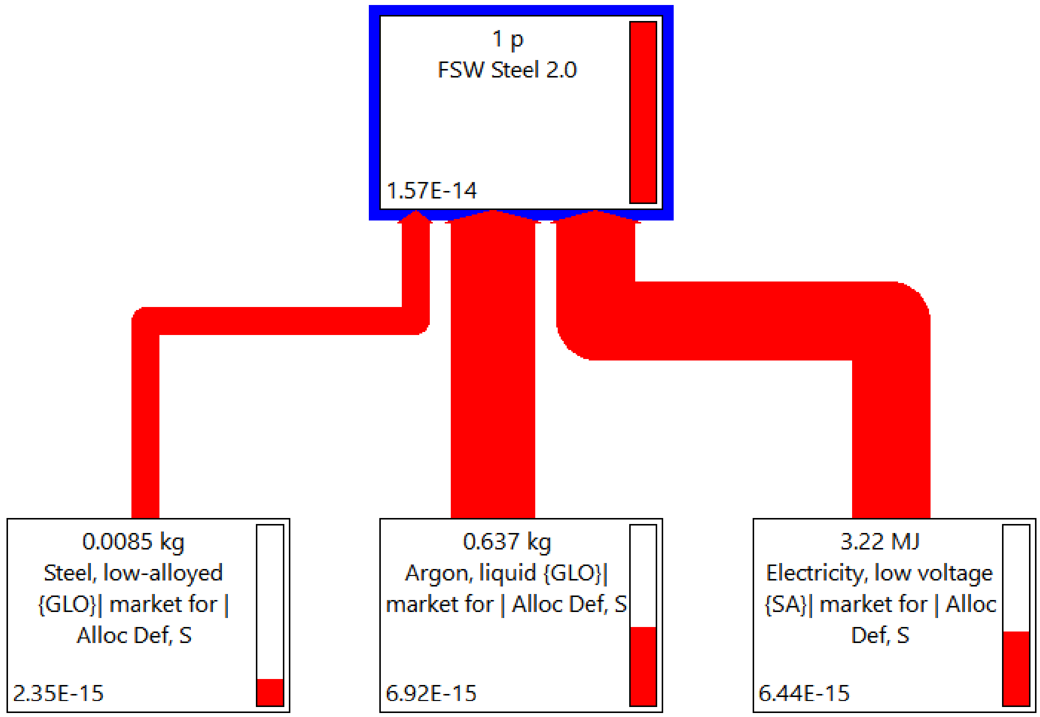


Figure 39 FSW contribution layout.

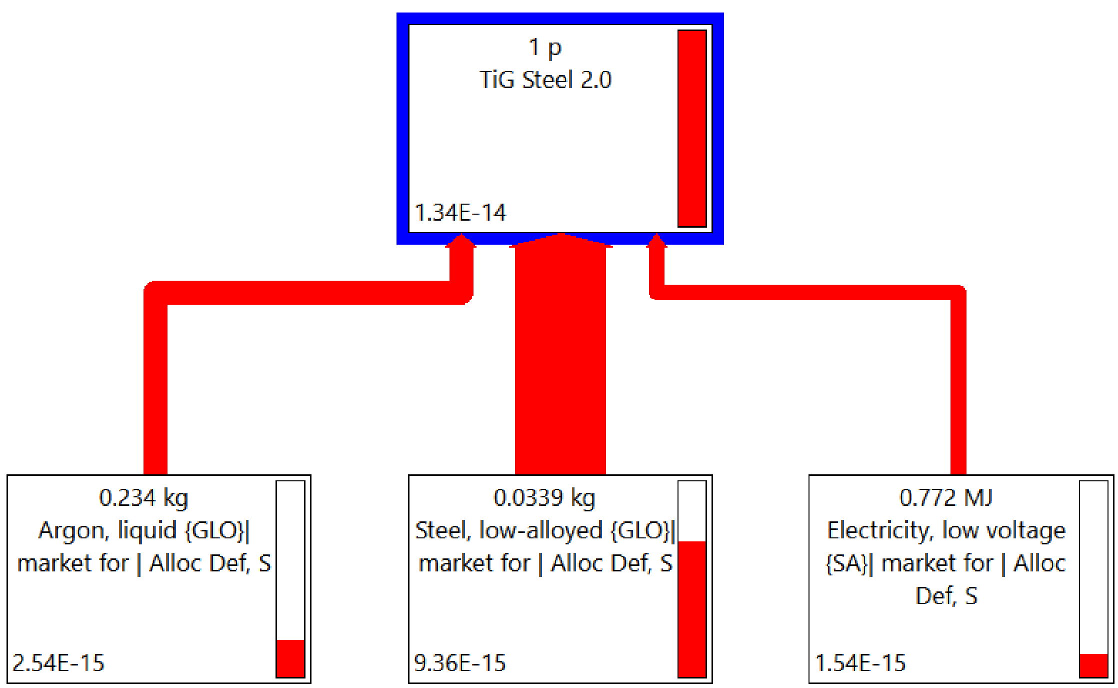


Figure 40 GTAW welding contribution layout.

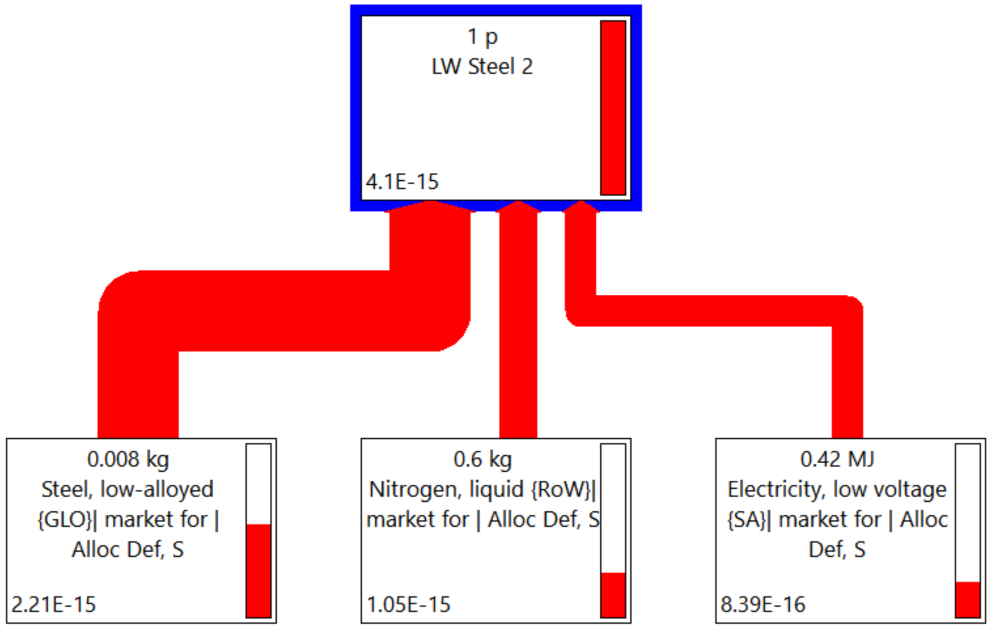


Figure 41 LBW contribution layout.

### 4.1.2. Gas Tungsten Arc Welding

GTAW is the most commonly used welding process. Gas consumption was recorded using gas flow meter while energy consumed during the process was calculated based upon the power consumption data which is given in Table 4. Weld was completed in 364 s.

Table 4 Welding output data for GTAW.

| Output Data | Magnitude |
|---|---|
| Output Current (A) | 90 |
| Output Voltage (V) | 12.3 |
| Filler Length (mm) | 140 |
| Gas Flow Meter (CFH) | 35 |

Energy consumed during the process is measured from output voltage and current while gas consumption was recorded directly from the gas flow meter and material consumption was measured by recording the weight before and after welding and by measuring the amount of filler material consumed

### 4.1.3. Friction Stir Welding

FSW is a relatively new joining process which employs solid state joining of the workpiece materials. Welding was completed in 1175 seconds. Inventory data measured during the experiment is shown in Table 5:

Table 5 Welding output data for FSW.

| Output Data | Magnitude |
|---|---|
| Tool Speed (RPM) | 950 |
| Gas Flow meter (CFH) | 40 |
| Weld Speed (mm/min) | 65 |
| Tool Angle (degrees) | 1.5 |

Energy consumption was measured from the torque generated by the equipment while gas consumption was recorded from the gas flow meter and material consumption was measured by recording workpiece weight before and after welding.

### 4.1.4. Laser Beam Welding

LCA of LBW of various materials of varying thickness was also performed and life cycle inventory was obtained and tabulated in Table 6.

Table 6 Primary Data for LBW

| | AISI 304 Steel (Consumption) | | | Ti-6Al-4V (Consumption) | | | Inconel 625 (Consumption) | | |
|---|---|---|---|---|---|---|---|---|---|
| Thickness (mm) | Energy (J) | Gas (g) | Material (g) | Energy (J) | Gas (g) | Material (g) | Energy (J) | Gas (g) | Material (g) |
| 1.5 | 280000 | 600 | 4 | 640000 | 900 | 0.6 | 360000 | 600 | 2 |
| 2.0 | 420000 | 600 | 8 | 820000 | 900 | 4 | 700000 | 600 | 5 |
| 2.5 | 640000 | 600 | 11 | 1120000 | 900 | 8 | 820000 | 600 | 8 |

## 4.2. Results & Discussion

### 4.2.1. Life Cycle Impact Assessment of AISI 304 Stainless Steel using three Welding Processes

Comparison of environmental impacts of AISI 304 Stainless Steel of 2.5mm thickness welded using 3 different welding processes will be discussed in this section.

#### *4.2.1.1. Global Warming Potential*

Global warming potential associated with welding of AISI 304 Stainless Steel and the individual contributions of waste material, gas consumption and energy consumption are depicted in Figure 42.

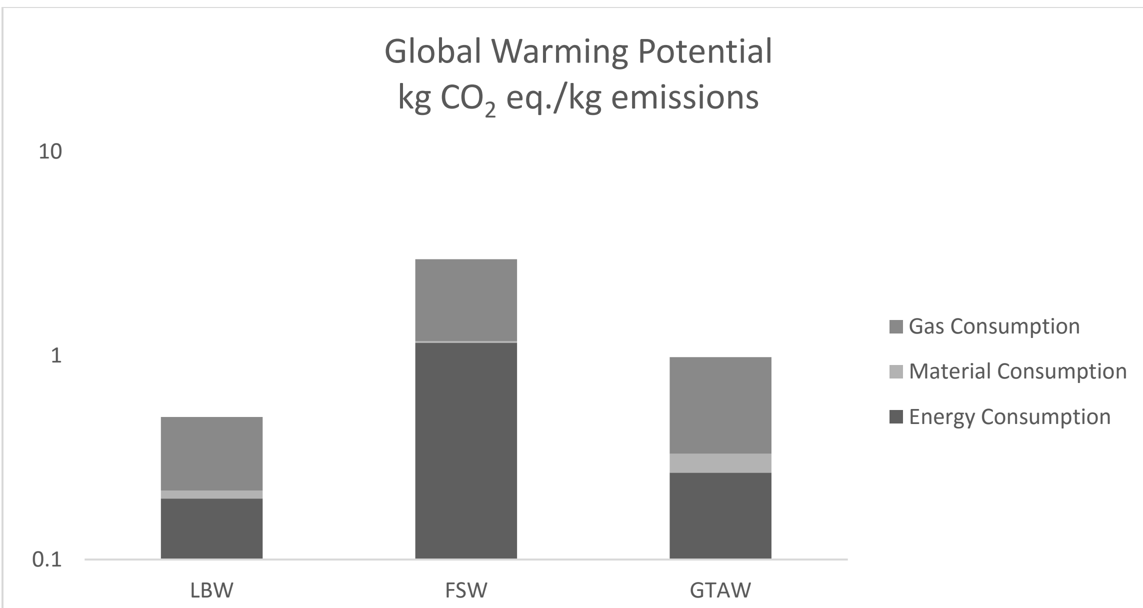


Figure 42 GWP100a comparison of AISI 304 Steel.

It can be observed from Figure 42 that FSW contributes significantly towards global warming potential owing to high shielding gas consumption and energy consumption during the process. While LBW was most sustainable and eco-friendly among the three welding processes. Gas consumed during welding process had the most significant contribution on global warming potential while the impact of material consumption was negligible.

#### 4.2.1.2. Eutrophication Potential

Eutrophication potential associated with welding of AISI 304 Stainless Steel using three welding processes was obtained from the analysis and the results are illustrated in Figure 43.

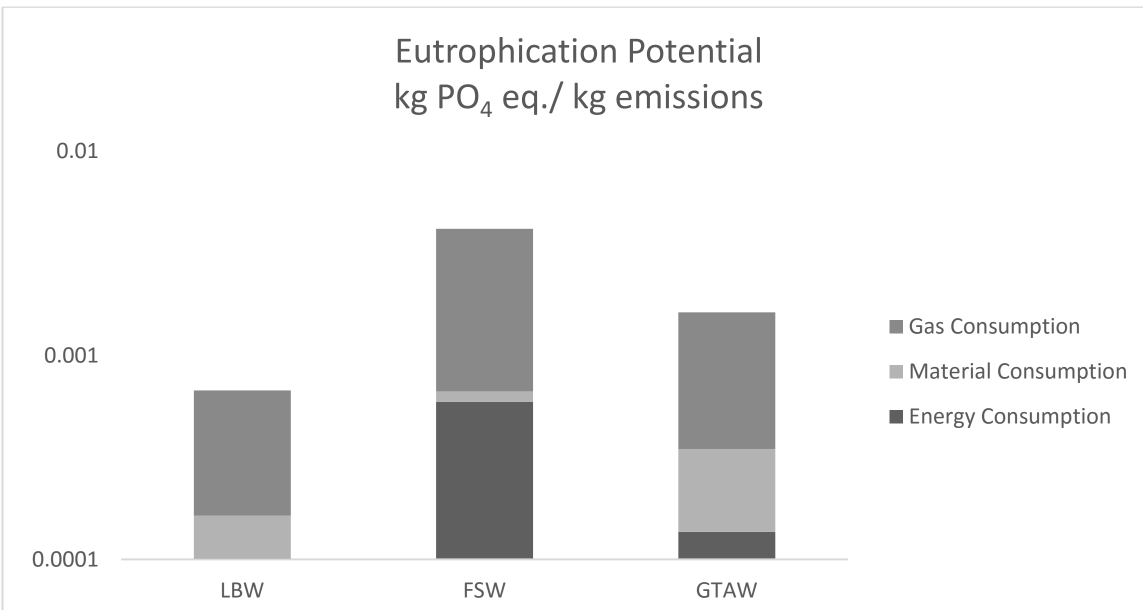


Figure 43 EP comparison of AISI 304 Steel.

FSW had the highest contribution towards eutrophication potential due to its high gas and material consumption while LBW was found out to be the most sustainable and eco-friendly. Gas consumption during welding process had significant impact on the respective impact category while impact of energy consumption was negligible.

### *4.2.1.3. Acidification Potential*

Comparative assessment for acidification potential of welding of AISI 304 Stainless Steel was carried out and contribution of each welding process towards acidification potential is shown in Figure 44.

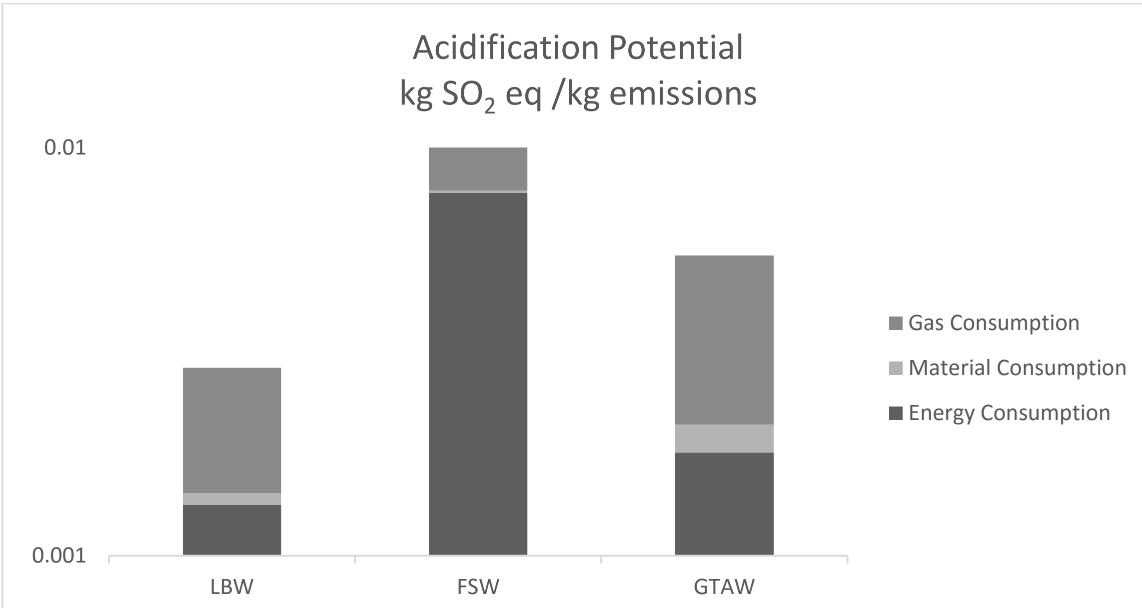


Figure 44 AP comparison of AISI 304 Steel.

Overall FSW had significant contribution towards acidification potential owing to its high gas and energy consumption during the process while LBW was found out to be the most sustainable and eco-friendly welding process. Gas consumed during welding process had the most significant contribution on acidification potential while the impact of material consumption was negligible.

### *4.2.1.4. Photo-Chemical Oxidation Potential*

Comparative assessment of photo-chemical oxidation potential associated with welding of AISI 304 Stainless Steel was carried out and contribution of each welding process towards photo-chemical oxidation potential is shown in Figure 45.

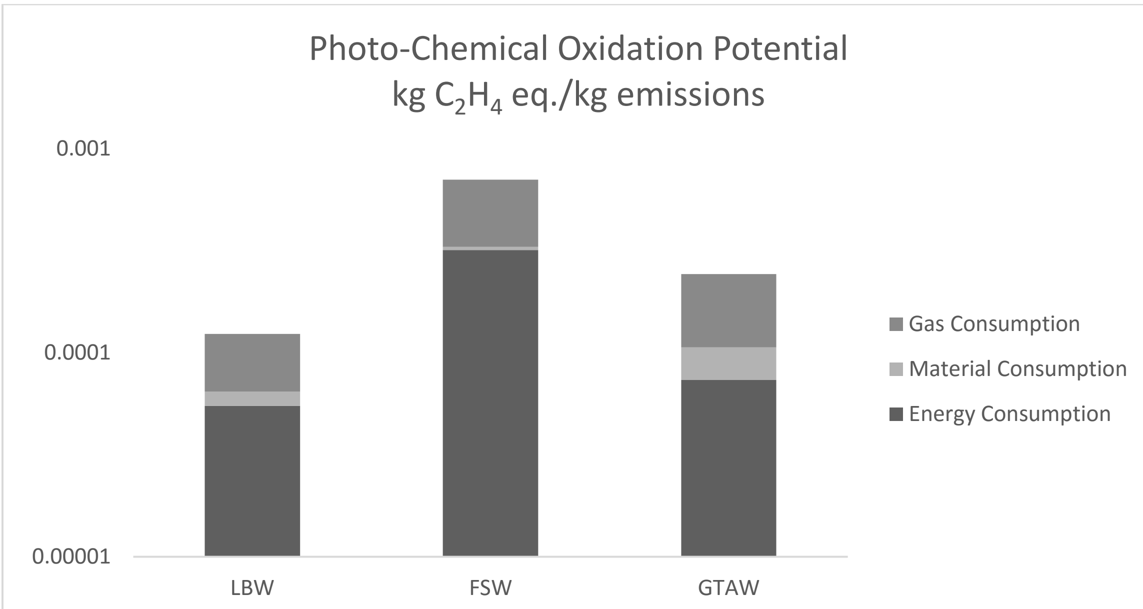


Figure 45 PCOP comparison of AISI 304 Steel

As seen from Figure 45, Photo-chemical oxidation potential associated with FSW is the highest among the three processes high shielding gas consumption and energy consumption during the process while LBW had the least PCOP among the three welding processes. Gas consumption is found out to be the significant contributor while the impact of material consumption was negligible.

### 4.2.1.5. Ozone Layer Depletion Potential

Comparative assessment of ozone layer depletion potential was carried out for welding of AISI 304 Stainless Steel and contribution of each welding process towards ODP is shown in Figure 46.

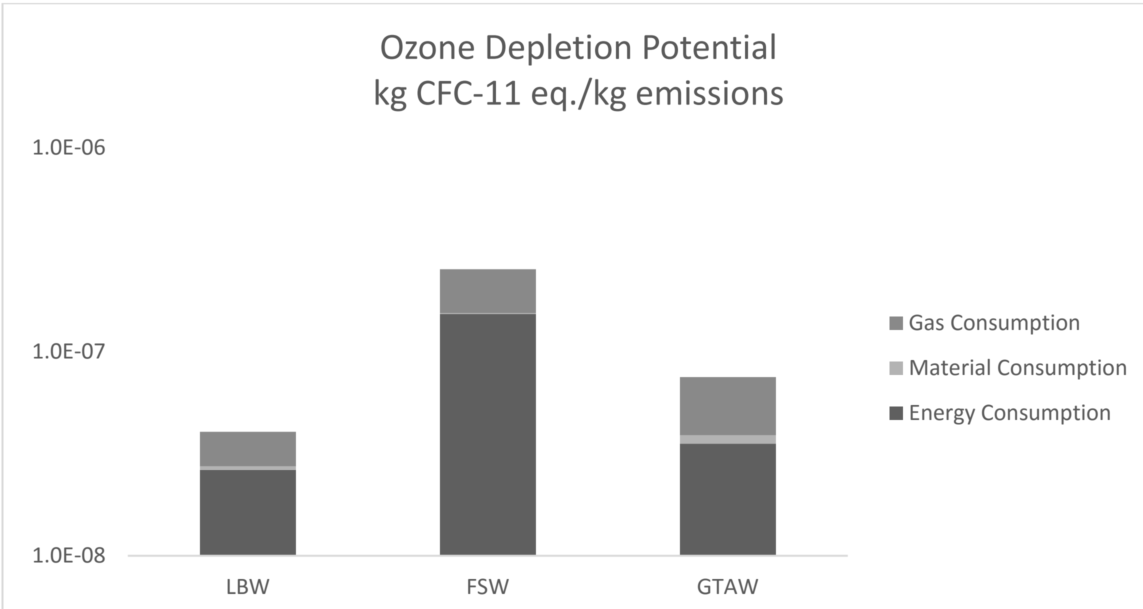


Figure 46 ODP comparison of AISI 304 Steel.

It can be observed from Figure 46 that FSW had significant contribution towards ozone layer depletion potential owing to its high shielding gas and energy consumption. While LBW was found out to be the most sustainable and eco-friendly process among the three welding processes. Gas consumed during welding process had the most significant contribution on ozone layer depletion potential while the impact of material consumption was negligible.

#### 4.2.1.6. *Abiotic Depletion Potential*

Comparative assessment of abiotic depletion potential was carried out and contribution of each welding process towards abiotic depletion potential is shown in Figure 47.

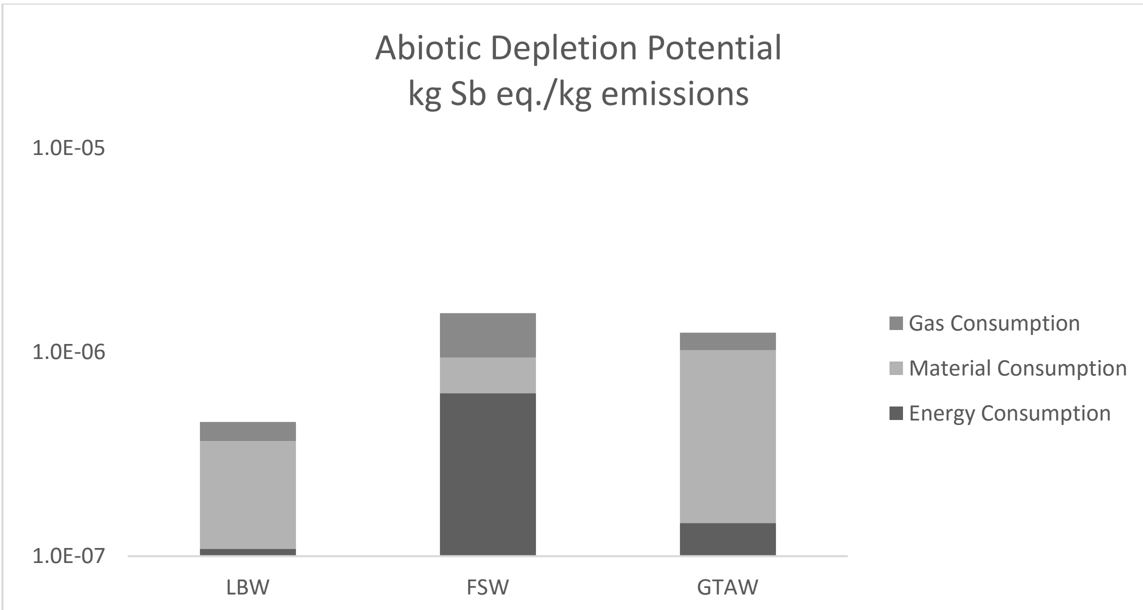


Figure 47 ADP comparison of AISI 304 Steel.

FSW contributes significantly towards abiotic depletion potential owing to its high shielding gas consumption and energy consumption. While LBW had the least contribution among the three welding processes. Gas consumed during a welding process had the most significant contribution on abiotic depletion potential while the impact of material consumption was negligible.

#### 4.2.1.7. *Human Toxicity Potential*

Human toxicity potential associated with welding of AISI 304 Stainless Steel was assessed and contribution of each welding process towards human toxicity potential is shown in Figure 48.

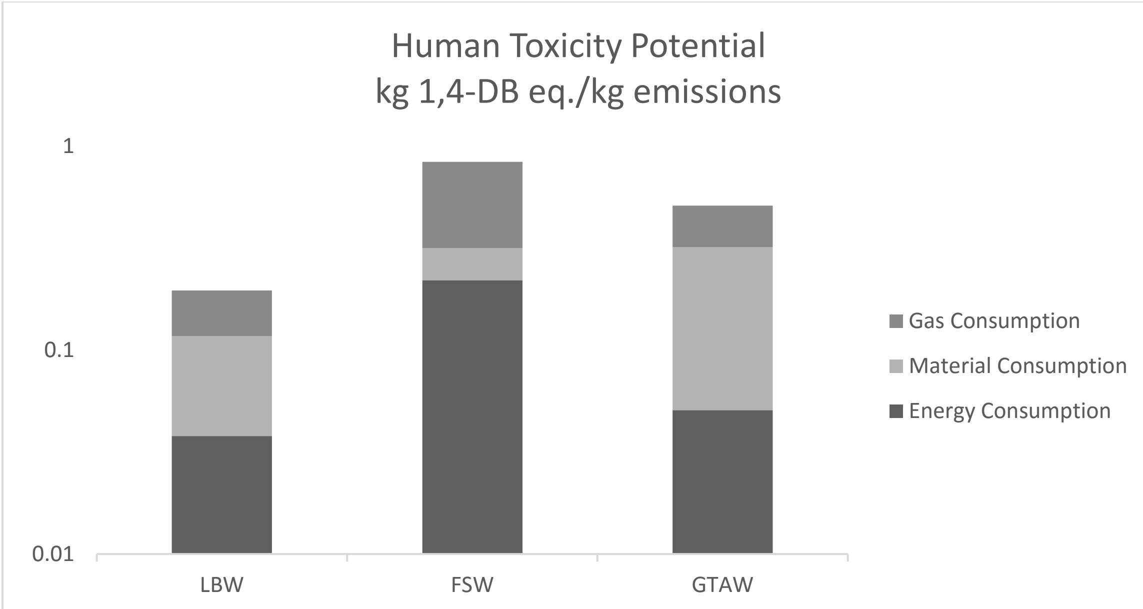


Figure 48 HTP comparison of AISI 304 Steel

FSW contributes significantly towards human toxicity potential owing to its high shielding gas consumption and energy consumption. While LBW was found out to be the most sustainable and eco-friendly among the three welding processes. Gas consumed during welding process had the most significant contribution on human toxicity potential while the impact of material consumption was negligible.

#### *4.2.1.8. Terrestrial Ecotoxicity Potential*

Terrestrial ecotoxicity potential of welding of AISI 304 Stainless Steel was assessed and contribution of each welding process towards terrestrial ecotoxicity potential is shown in Figure 49.

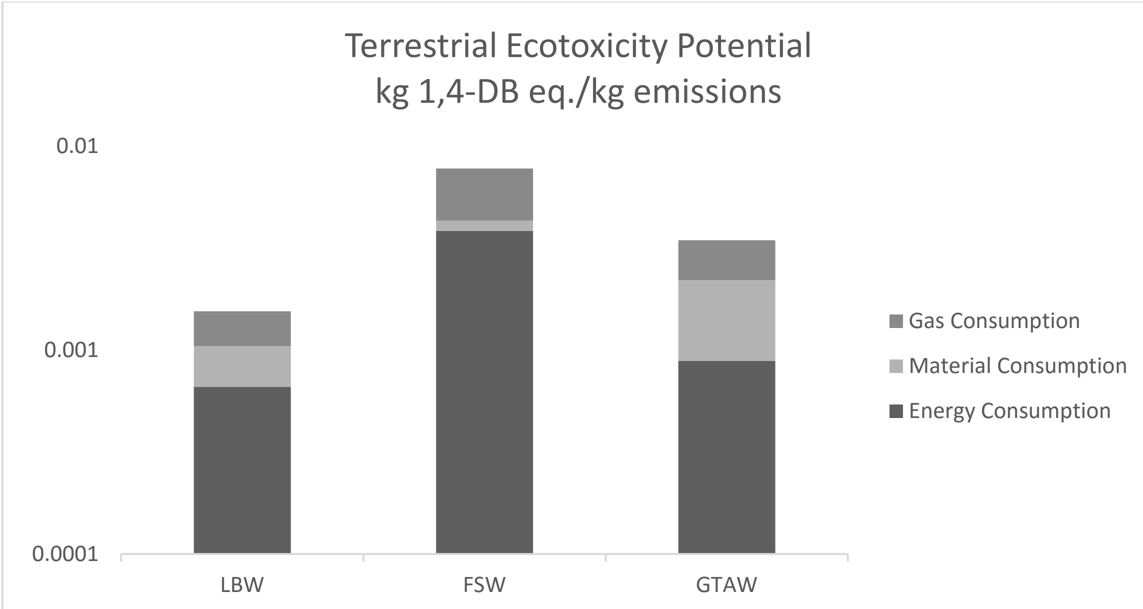


Figure 49 TEP comparison of AISI 304 Steel.

Figure 49 depicts that FSW contributes significantly towards terrestrial ecotoxicity potential owing to high shielding gas consumption and energy consumption during the process. While LBW was found out to be the most sustainable and eco-friendly process among the three welding processes. Gas consumed during welding process had the most significant contribution on terrestrial ecotoxicity potential while the impact of material consumption was negligible.

#### *4.2.1.9. Marine Aquatic Ecotoxicity Potential*

Comparative assessment of marine aquatic ecotoxicity potential associated with welding of AISI 304 Stainless Steel was carried out and contributions of each welding process towards marine aquatic ecotoxicity potential is shown in Figure 50.

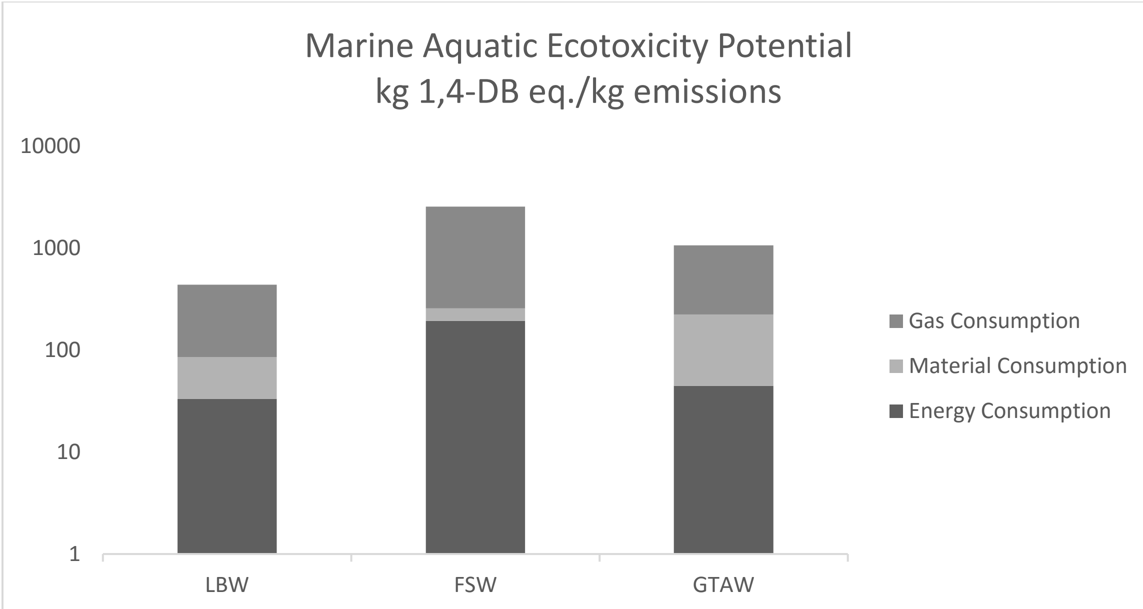


Figure 50 MAEP comparison of AISI 304 Steel.

It can be seen from Figure 50 that FSW had the highest contribution towards marine aquatic ecotoxicity potential owing to its high shielding gas consumption and energy consumption. While LBW was found out to be the most sustainable and eco-friendly process among the three welding processes. Gas consumption during welding process had the most significant contribution on marine aquatic ecotoxicity potential while material consumption had the least impact.

#### *4.2.1.10. Fresh Water Ecotoxicity Potential*

Fresh water ecotoxicity potential associated with welding of AISI 304 Stainless Steel was assessed and contribution of each welding process towards freshwater ecotoxicity potential is shown in Figure 51.

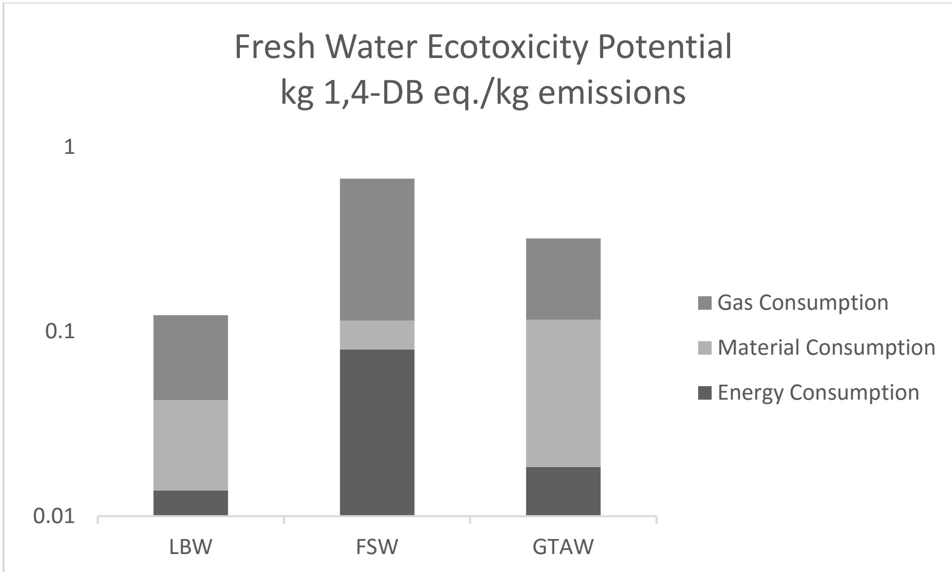


Figure 51 FWEP comparison of AISI 304 Steel.

It can be observed from Figure 51 that FSW contributes significantly towards freshwater ecotoxicity potential owing to its high shielding gas consumption and energy consumption while LBW was found out to be the most sustainable and eco-friendly among the three welding processes. Gas consumed during welding process had the most significant contribution on freshwater ecotoxicity potential while the impact of material consumption was negligible.

#### *4.2.1.11. Abiotic Depletion Fossil Fuel Potential*

Comparative assessment of abiotic depletion fossil fuel potential associated with welding of AISI 304 Stainless Steel was carried out and contribution of each welding process towards abiotic depletion fossil fuel potential is shown in Figure 52.

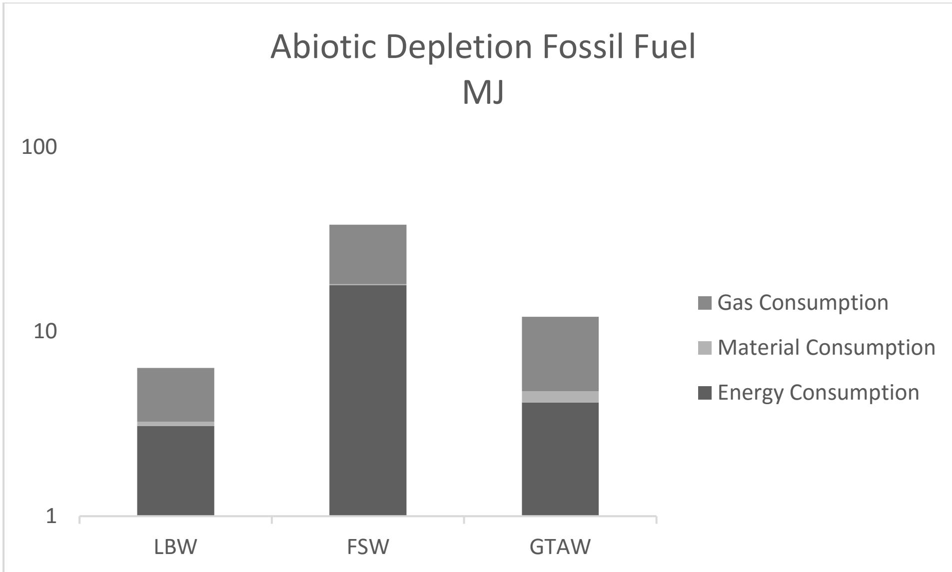


Figure 52 ADFFP comparison of AISI 304 Steel.

It can be observed from Figure 52 that FSW contributes significantly towards abiotic depletion fossil fuel potential owing to high shielding gas consumption and energy consumption during the process. While LBW was most sustainable and eco-friendly among the three welding processes. Gas consumed during welding process had the most significant contribution on abiotic depletion fossil fuel potential while the impact of material consumption was negligible.

### 4.2.2. Effect of Sample Thickness on Environmental Impacts of AISI 304 Welding using Three Welding Processes

In this section, comparison is made between welding of stainless steel AISI 304 workpiece of varying thickness using LBW, FSW and GTAW and their relationship with environmental impacts are analyzed.

#### *4.2.2.1. Global Warming Potential*

A comparison of variation on the overall impact of global warming potential associated with three welding processes by varying workpiece thickness is shown in Figure 53. It can be seen that the relation between global warming potential and workpiece thickness is nearly linear. As the workpiece thickness is increased, global warming potential is also increased.

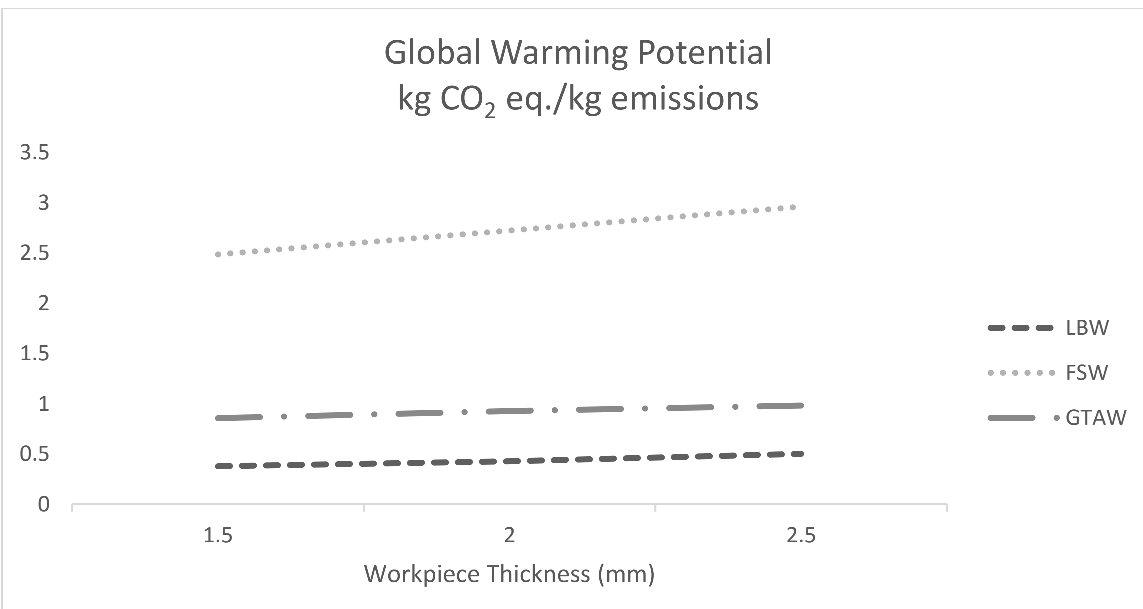


Figure 53 Effect of workpiece thickness on GWP100a.

### 4.2.2.2. *Eutrophication Potential*

A comparison of variation on the overall impact of eutrophication potential associated with three welding processes by varying workpiece thickness is shown in Figure 54. It can be seen that the relation between eutrophication potential and workpiece thickness is nearly linear. As the workpiece thickness is increased, eutrophication potential is also increased. However, it is observed that eutrophication potential associated with FSW increases more rapidly as compared to the other two welding processes which is attributed to high energy and shielding gas consumption.

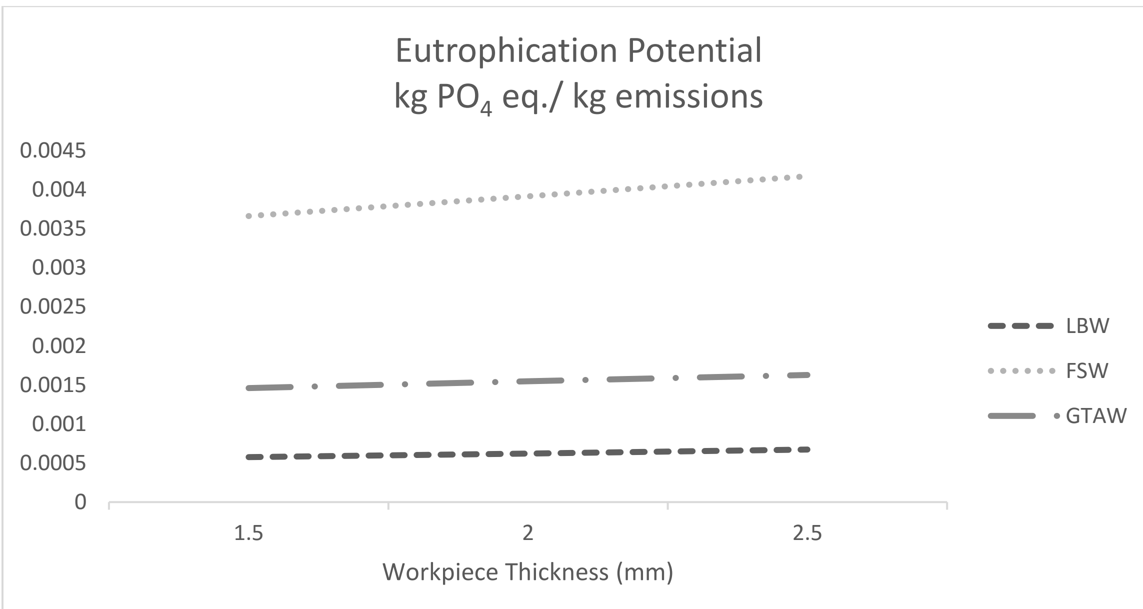


Figure 54 Effect of workpiece thickness on EP.

### 4.2.2.3. *Acidification Potential*

A comparison of variation on the overall impact of acidification potential associated with three welding processes by varying workpiece thickness is shown in Figure 55. It can be seen that the relation between acidification potential and workpiece thickness is nearly linear. As the workpiece thickness is increased, acidification potential is also increased.

Moreover, it can also be observed that acidification potential of FSW increases more rapidly with the increase in thickness, this is due to high energy and shielding gas consumption.

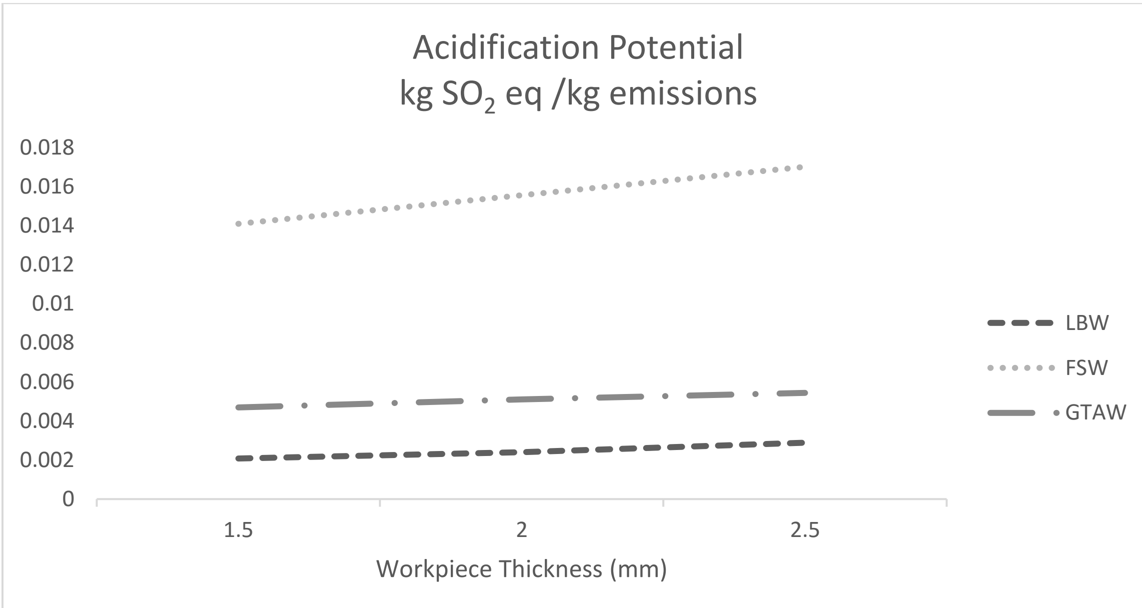


Figure 55 Effect of workpiece thickness on AP.

### *4.2.2.4. Photo-Chemical Oxidation Potential*

A comparison of variation on the overall impact of photo-chemical oxidation potential associated with three welding processes by varying workpiece thickness is shown in Figure 56. It can be observed that the relation between photo-chemical oxidation potential and workpiece thickness is nearly linear. As the workpiece thickness is increased, photo-chemical oxidation potential is also increased. It was also observed that photo-chemical oxidation potential of FSW increases rapidly when workpiece thickness is increased owing to high consumption of energy and shielding gas during the process.

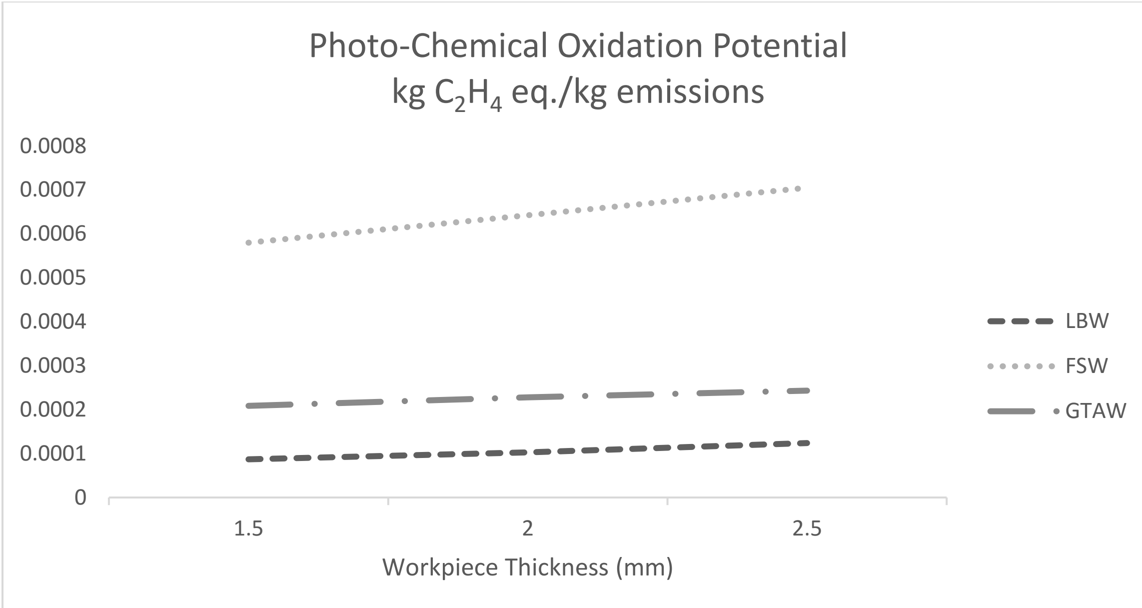


Figure 56 Effect of workpiece thickness on PCOP.

#### *4.2.2.5. Ozone Layer Depletion Potential*

A comparison of variation on the overall impact of ozone layer depletion potential associated with three welding processes by varying workpiece thickness is shown in Figure 57. It can be seen that the relation between ozone layer depletion potential and workpiece thickness is nearly linear. As the workpiece thickness is increased, ozone layer depletion potential is also increased. It was also found out that ozone layer depletion for FSW increases rapidly with the increase in thickness due to high consumption of shielding gas and energy during the process.

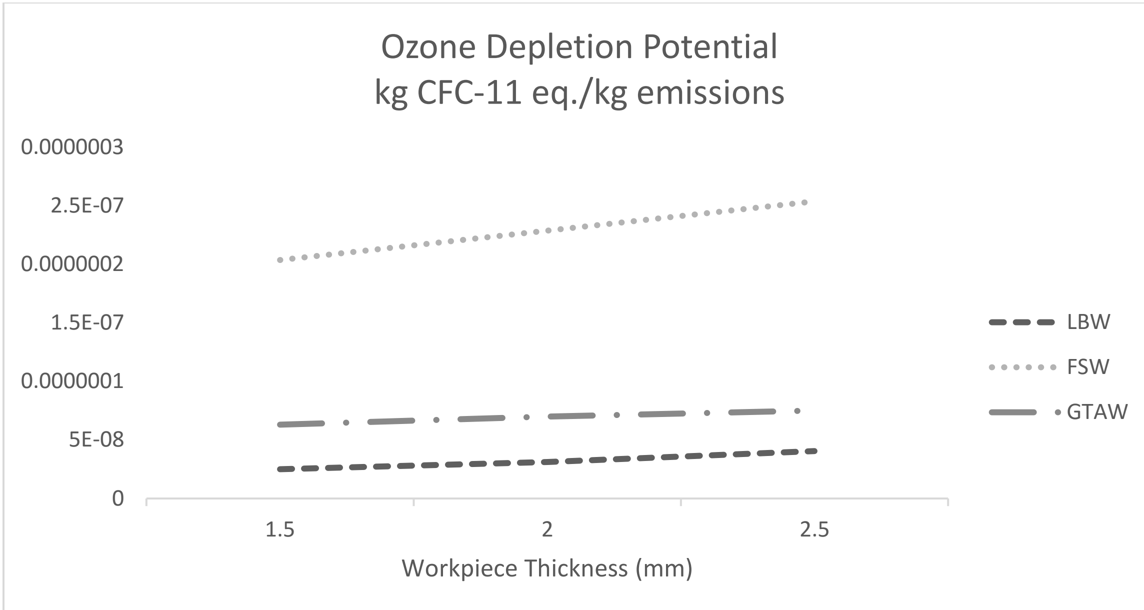


Figure 57 Effect of workpiece thickness on ODP.

#### *4.2.2.6. Abiotic Depletion Potential*

A comparison of variation on the overall impact of abiotic depletion potential associated with three welding processes by varying workpiece thickness is shown in Figure 58. It can be seen that the relation between abiotic depletion potential and workpiece thickness is nearly linear. As the workpiece thickness is increased, abiotic depletion potential also increases.

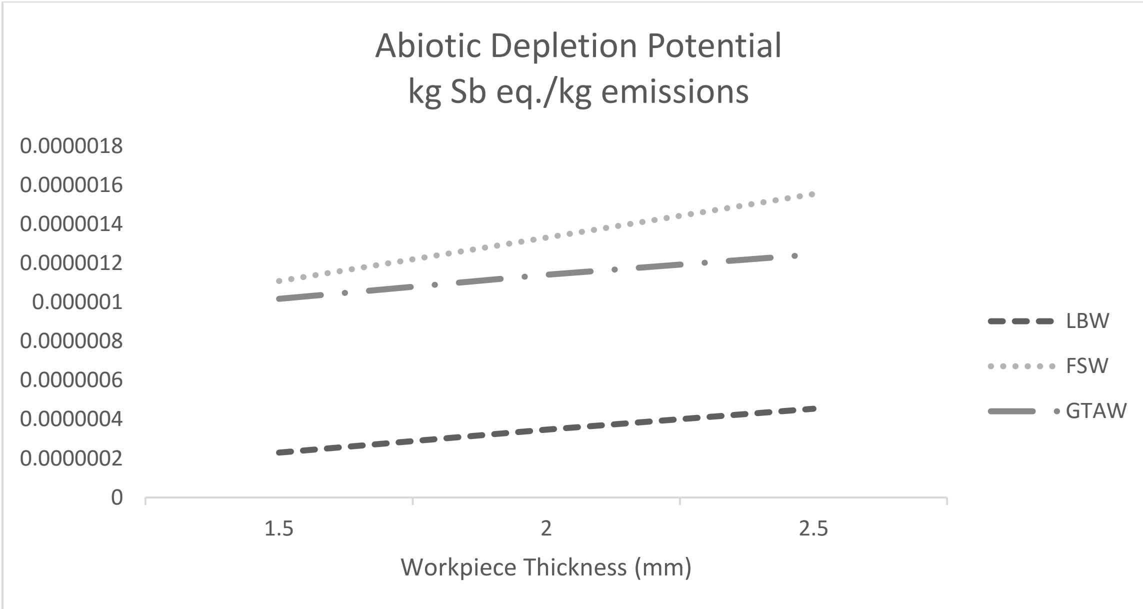


Figure 58 Effect of workpiece thickness on ADP.

#### *4.2.2.7. Human Toxicity Potential*

A comparison of variation on the overall impact of human toxicity potential associated with three welding processes by varying workpiece thickness is shown in Figure 59. It can be seen that the relation between human toxicity potential and workpiece thickness is nearly linear. As the workpiece thickness is increased, human toxicity potential also increases. Moreover, it was also observed that human toxicity potential of FSW increases rapidly with the increase in the workpiece thickness owing to high energy and shielding gas consumption during the process.

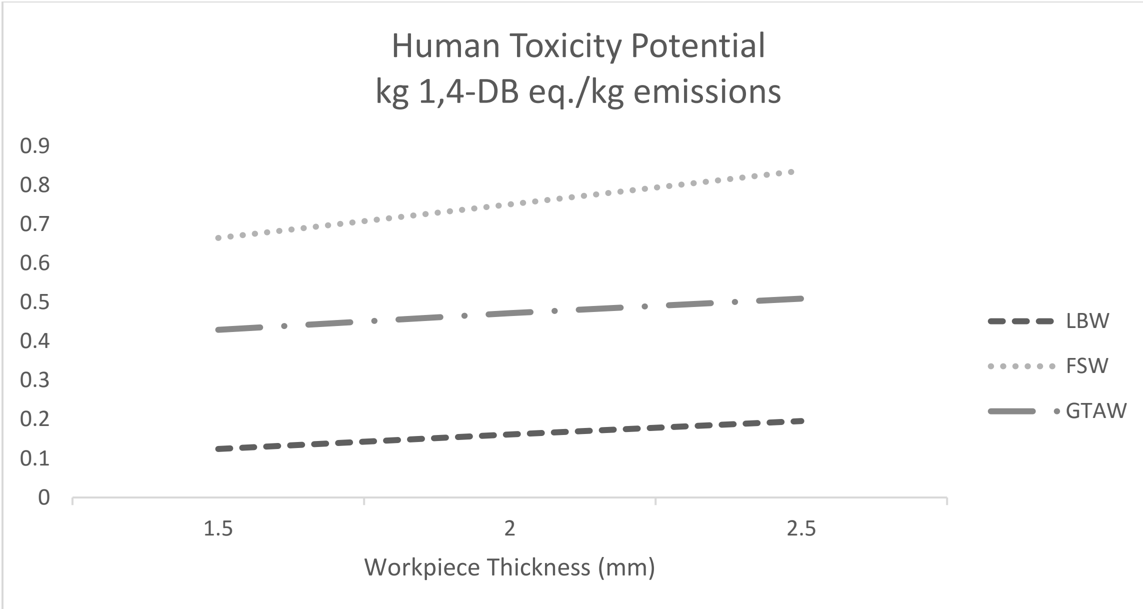


Figure 59 Effect of workpiece thickness on HTP.

#### *4.2.2.8. Terrestrial Ecotoxicity Potential*

A comparison of variation on the overall impact of terrestrial ecotoxicity potential associated with three welding processes by varying workpiece thickness is shown in Figure 60. It can be observed that the relation between terrestrial ecotoxicity potential and workpiece thickness is nearly linear. As the workpiece thickness is increased, terrestrial ecotoxicity potential also increases. However, it was observed that terrestrial ecotoxicity potential associated with FSW increases more rapidly attributing to high energy and shielding gas consumption.

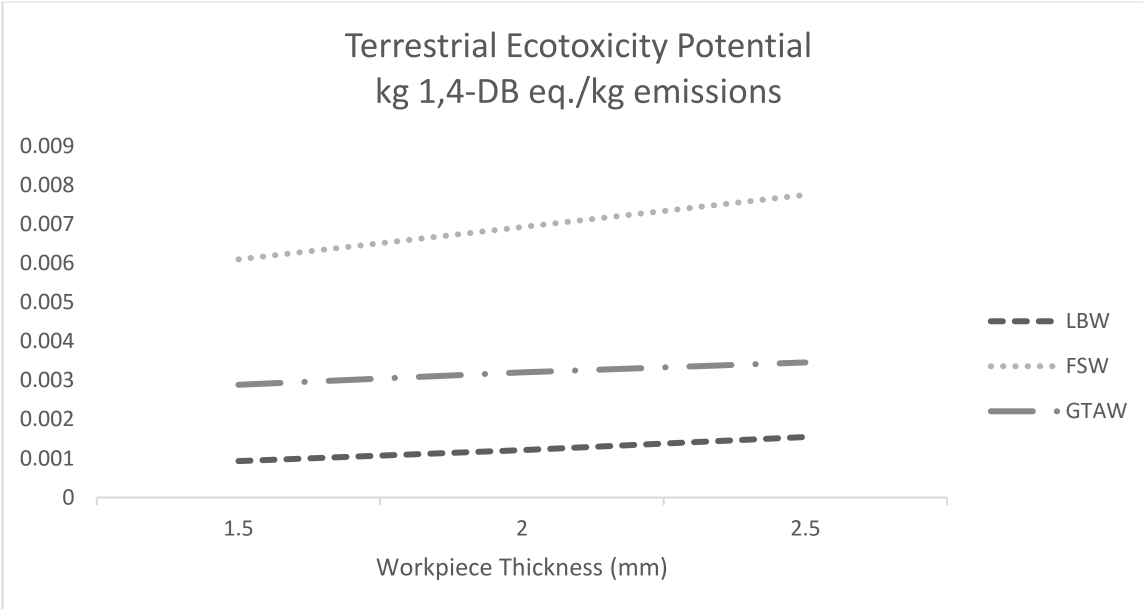


Figure 60 Effect of workpiece thickness on TEP.

#### *4.2.2.9. Marine Aquatic Ecotoxicity Potential*

Figure 61 shows the relationship between marine aquatic ecotoxicity potential associated with a welding process and the workpiece thickness. It can be observed that the relation between marine aquatic ecotoxicity potential and workpiece thickness is nearly linear. As the workpiece thickness is increased, marine aquatic ecotoxicity potential also increases. However, it is observed that marine aquatic ecotoxicity potential associated with FSW increases more rapidly which is attributed to high energy and shielding gas consumption.

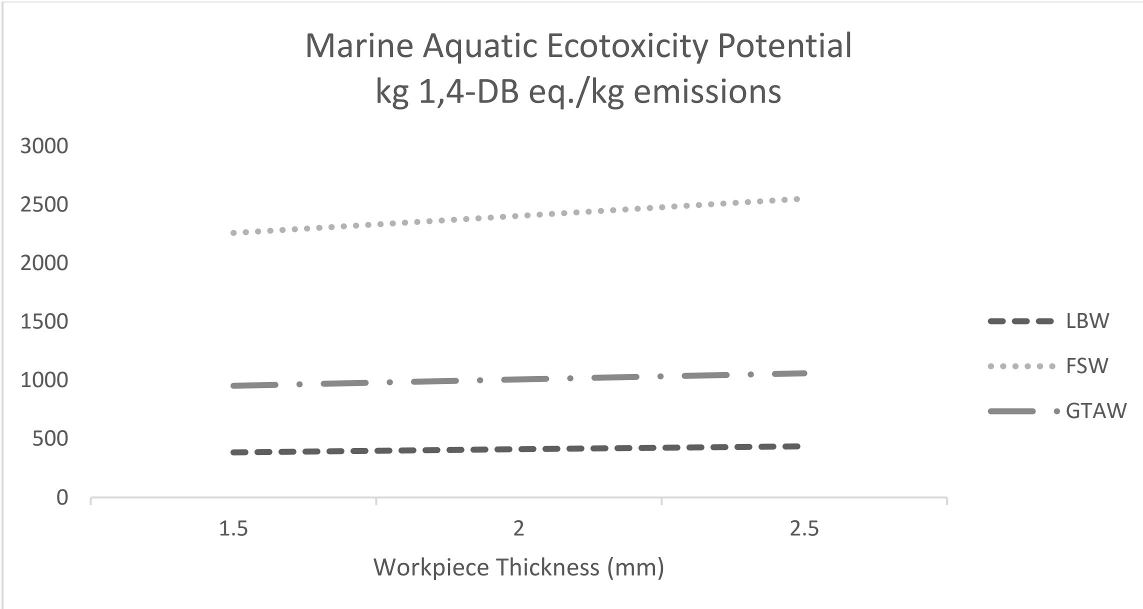


Figure 61 Effect of workpiece thickness on MAEP.

#### 4.2.2.10. Fresh Water Ecotoxicity Potential

A comparison of variation on the overall impact of fresh water ecotoxicity potential associated with three welding processes by varying workpiece thickness is shown in Figure 62. It can be observed that the relationship between fresh water ecotoxicity potential and workpiece thickness is almost linear. As the workpiece thickness is increased, fresh water ecotoxicity potential also increases. Moreover, it was also observed that fresh water ecotoxicity potential associated with FSW increases more rapidly attributing to high energy and shielding gas consumption.

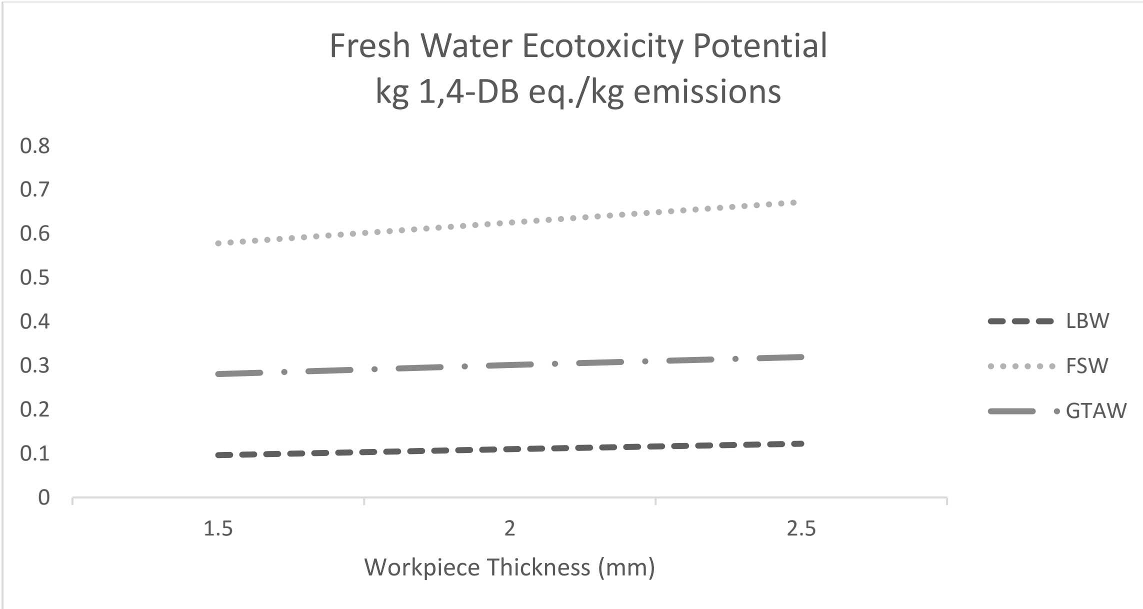


Figure 62 Effect of workpiece thickness on FWEP.

#### *4.2.2.11. Abiotic Depletion Fossil Fuel Potential*

Figure 63 shows the relationship between abiotic depletion fossil fuel potential and workpiece thickness. It can be observed that the relationship between abiotic depletion fossil fuel potential and workpiece thickness is nearly linear. As the workpiece thickness is increased, abiotic depletion fossil fuel potential also increases. However, it was observed that abiotic depletion fossil fuel potential associated with FSW increases more rapidly which is attributed to high energy and shielding gas consumption.

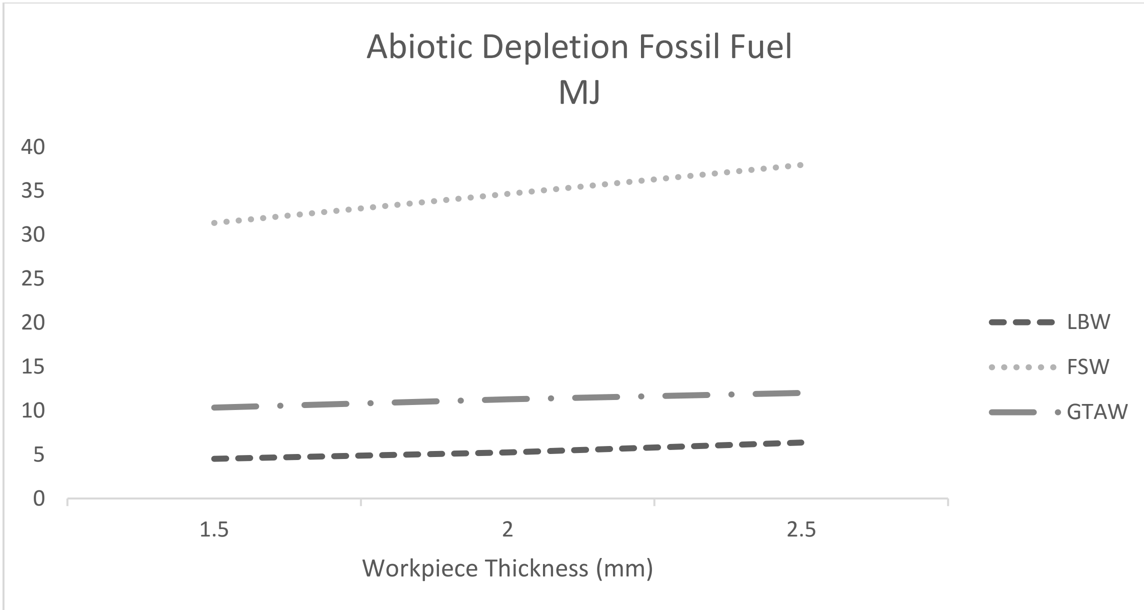


Figure 63 Effect of workpiece thickness on ADFFP.

### 4.2.3. Life Cycle Impact Assessment of LBW of Different Materials

In this section, comparison is made between LBW of workpiece made of stainless steel AISI 304, Inconel 625 and Ti-6Al-4V and their environmental impacts are analyzed.

#### 4.2.3.1. *Global Warming Potential*

A comparative plot of global warming potential of LBW of different materials is shown in Figure 64. Individual contributions of waste material, gas consumption and energy consumption are also depicted in Figure 64. It was observed that gas consumption plays a significant role in global warming potential of LBW. LBW of Ti-6Al-4V had the highest overall impact on global warming potential among the three materials.

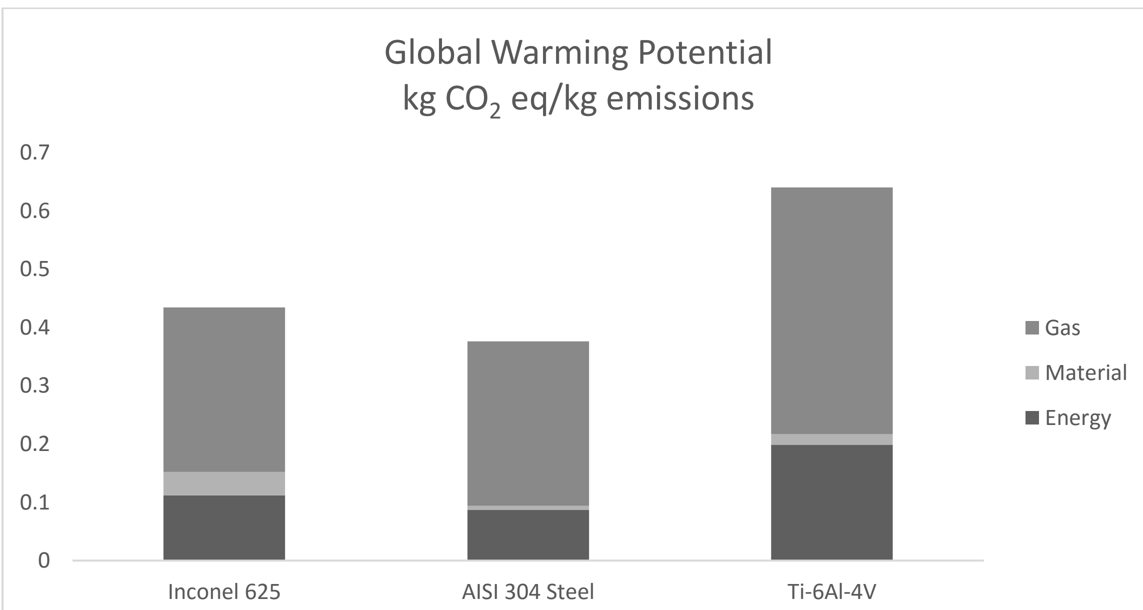


Figure 64 GWP100a comparison of LBW of three different materials.

#### 4.2.3.2. *Eutrophication Potential*

Comparative analysis was made for LBW of three materials and the results are illustrated in Figure 65. It can be seen that gas consumption plays a significant role in eutrophication potential of LBW. LBW of Inconel 625 had the highest overall impact on eutrophication potential among the three materials attributing to the material composition of Inconel 625.

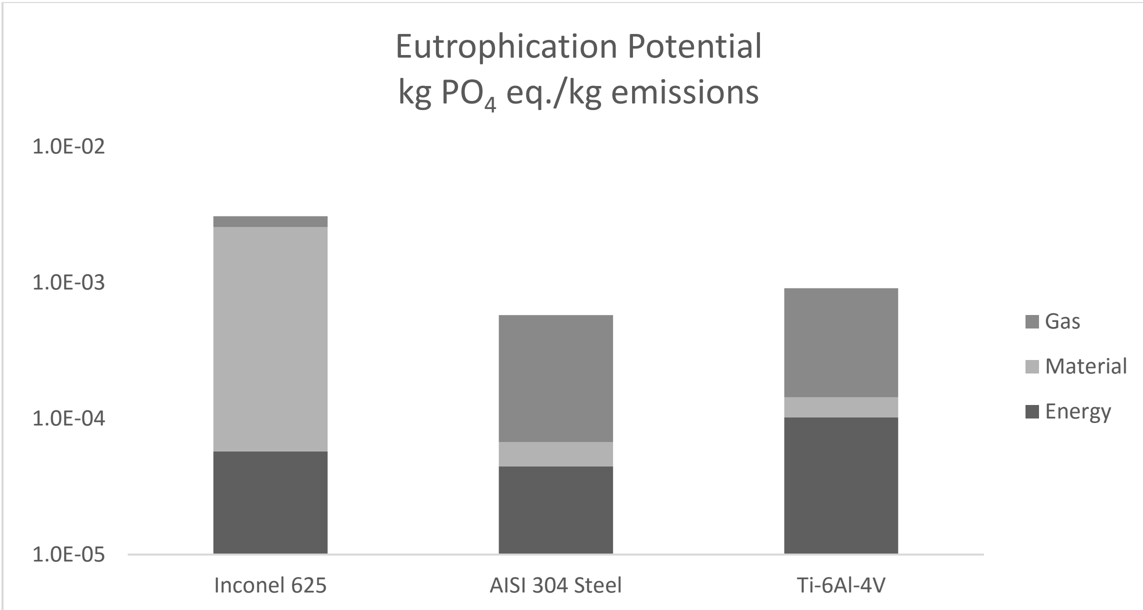


Figure 65 EP comparison of LBW of three different materials.

#### 4.2.3.3. *Acidification Potential*

Contributions of LBW of each material towards acidification potential is shown in Figure 66. It can be seen that gas consumption plays a significant role in acidification potential of LBW. Gas consumption had the highest contribution towards acidification potential among the material, gas and energy consumption. LBW of Inconel 625 had the highest overall impact on acidification potential among the three materials attributing to the material composition of Inconel 625.

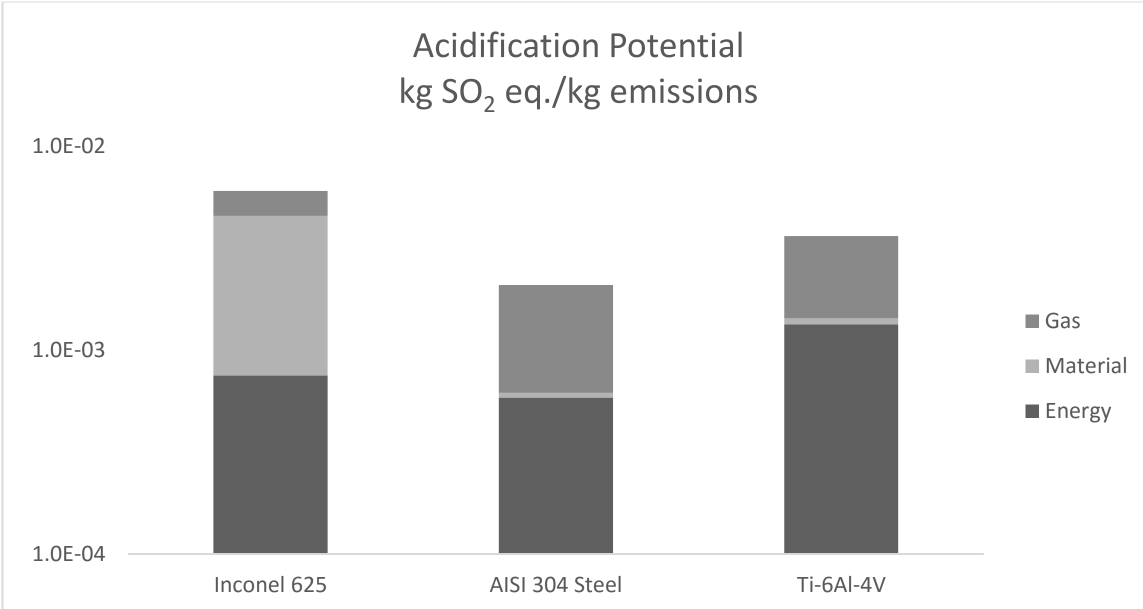


Figure 66 AP comparison of LBW of three different materials.

#### *4.2.3.4. Photo-Chemical Oxidation Potential*

Photo-chemical oxidation potential refers to ability of emissions to form reactive substance in the atmosphere. It is expressed in kg $C_2H_4$ eq/kg emissions. Contributions of LBW of each material towards photo-chemical oxidation potential is shown in Figure 67. It was observed that for LBW of AISI 304 Steel and Ti-6Al-4V, gas consumption plays a significant role in photo-chemical oxidation potential of LBW of respective materials. However, for LBW of Inconel 625, material consumption played an important role owing to the impact of material composition of Inconel 625 on photo-chemical oxidation potential. LBW of Inconel 625 had the highest overall impact on photo-chemical oxidation potential among the three materials attributing to the material composition of Inconel 625.

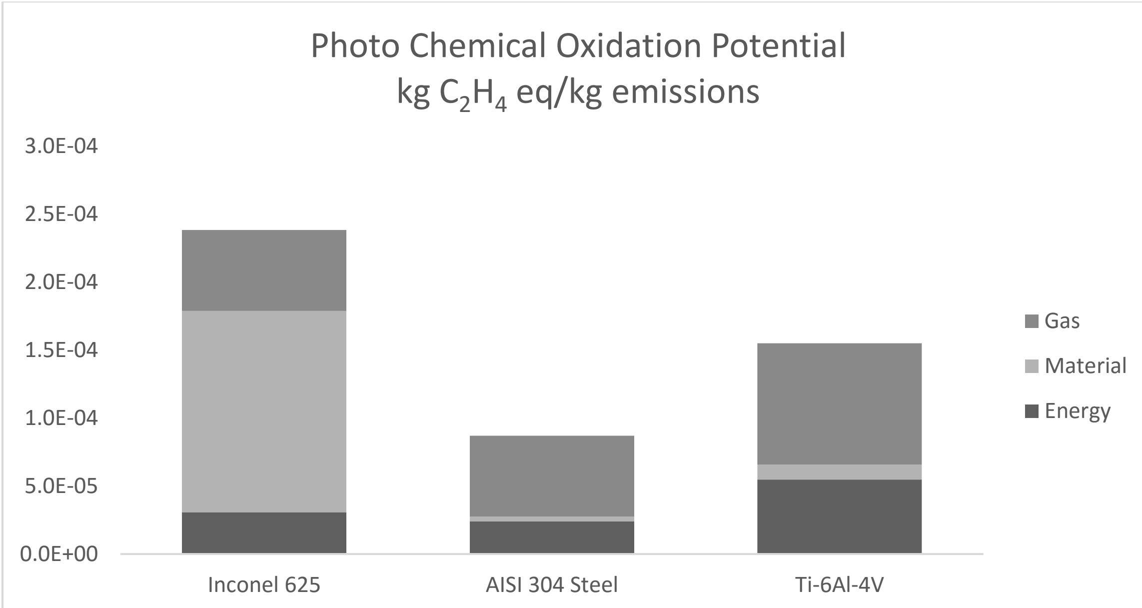


Figure 67 PCOP comparison of LBW of three different materials.

#### *4.2.3.5. Ozone Layer Depletion Potential*

Contributions of LBW of each material towards ozone layer depletion potential is shown in Figure 68. It can be seen that gas consumption plays a significant role in ozone layer depletion potential of LBW. LBW of Ti-6Al-4V had the highest overall impact on ozone layer depletion potential among the three materials.

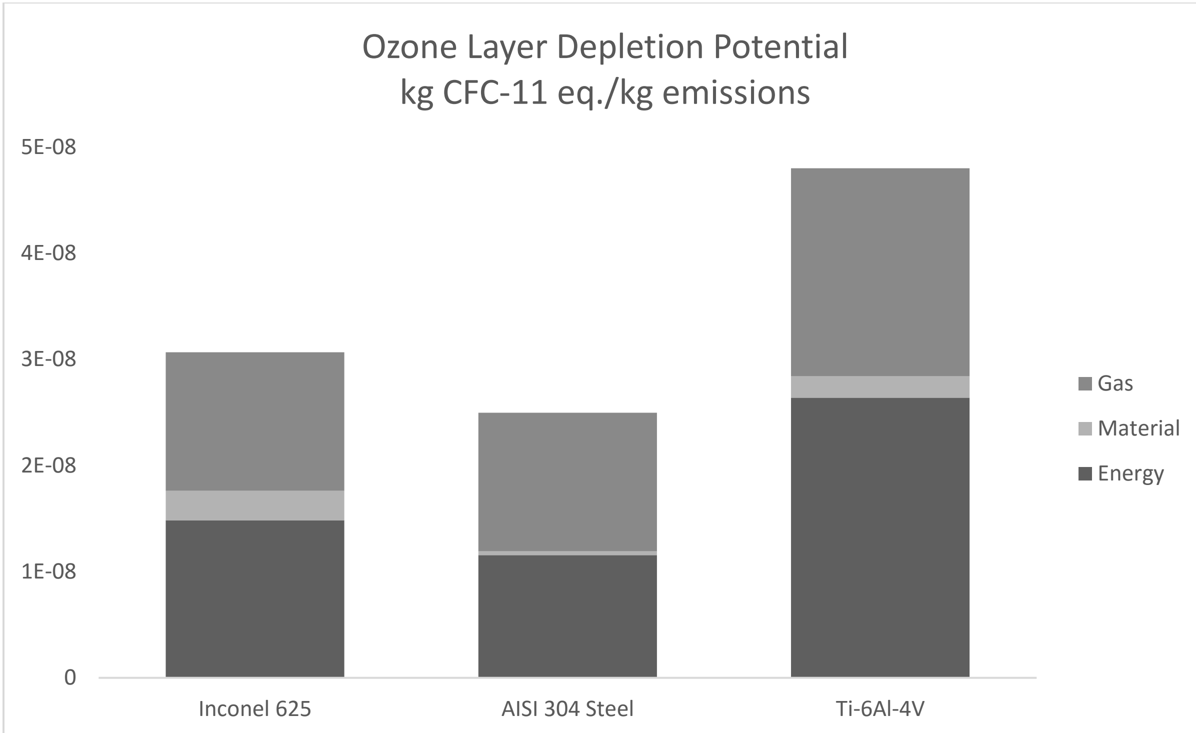


Figure 68 ODP comparison of LBW of three different materials.

#### 4.2.3.6. *Abiotic Depletion Potential*

A comparative plot of abiotic depletion potential associated with each material is shown in Figure 69. It can be seen that for LBW of AISI 304 Steel and Ti-6Al-4V, gas consumption plays a significant role in abiotic depletion potential of LBW of respective materials. However, for LBW of Inconel 625, material consumption played an important role owing to the impact of material composition of Inconel 625 on abiotic depletion potential. LBW of Inconel 625 had the highest overall impact on abiotic depletion potential among the three materials attributing to the material composition of Inconel 625.

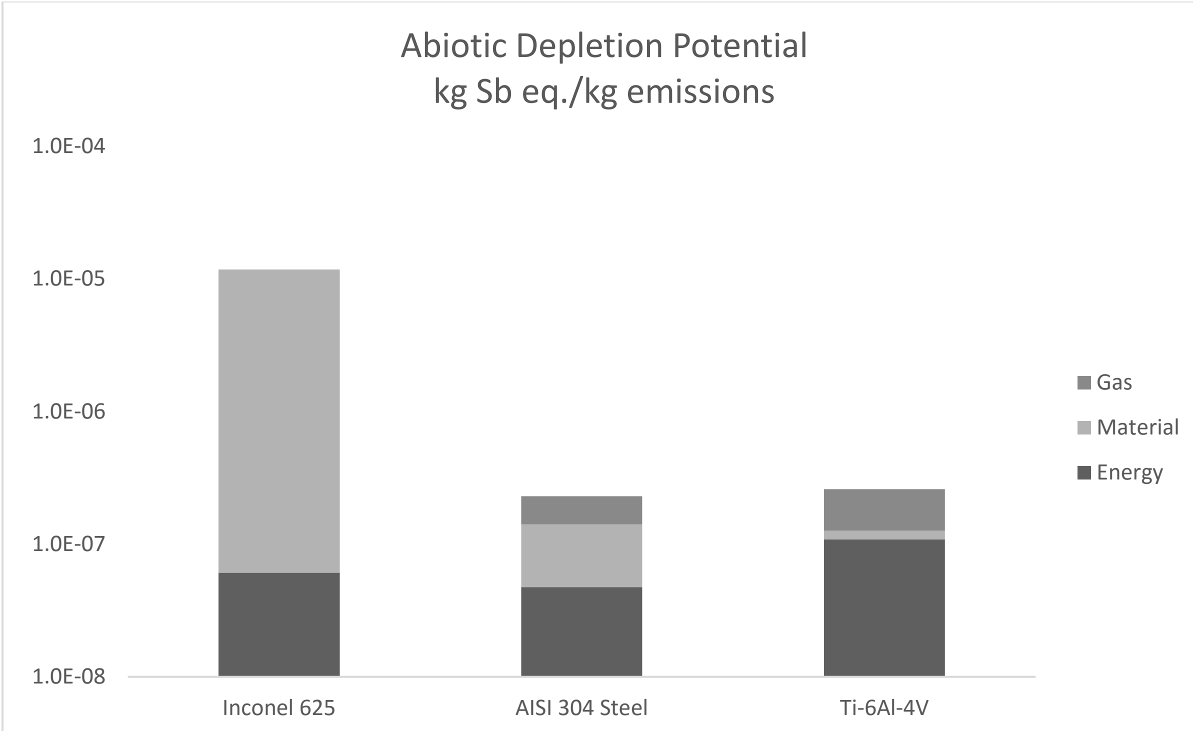


Figure 69 ADP comparison of LBW of three different materials.

#### 4.2.3.7. *Human Toxicity Potential*

Contributions of LBW of each material towards human toxicity potential is shown in Figure 70. It can be observed that for LBW of AISI 304 Steel and Ti-6Al-4V, gas consumption played a significant role towards human toxicity potential of LBW of respective materials. However, for LBW of Inconel 625, material consumption played an important role owing to the impact of material composition of Inconel 625 on human toxicity potential.

LBW of Inconel 625 had the highest overall impact on human toxicity potential among the three materials attributing to the material composition of Inconel 625.

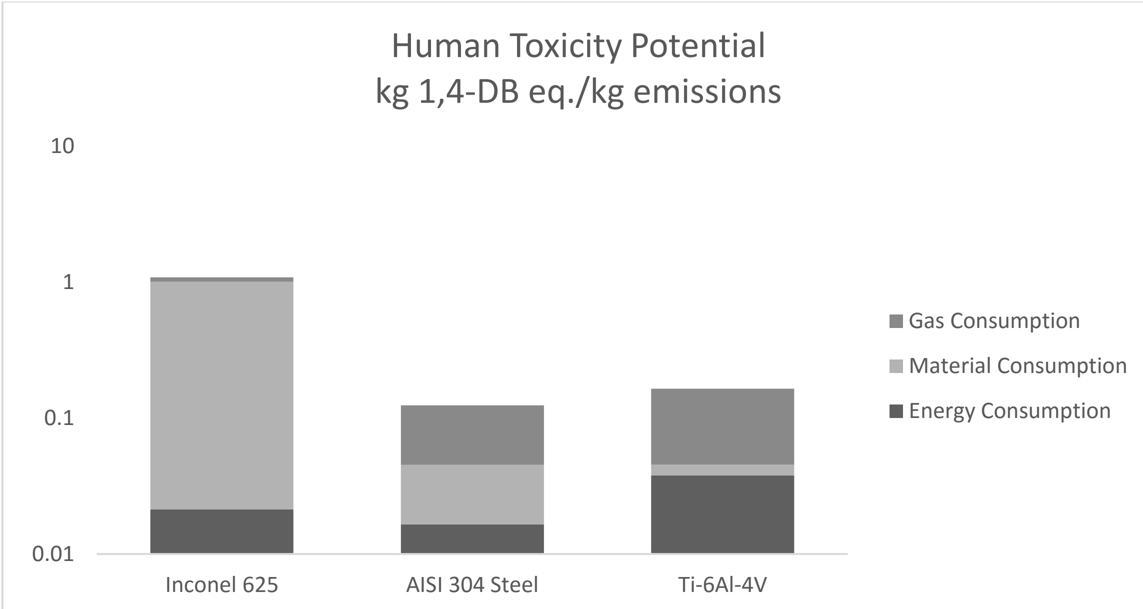


Figure 70 HTP comparison of LBW of three different materials.

#### *4.2.3.8. Terrestrial Ecotoxicity Potential*

Comparative plot of contributions of LBW of each material towards terrestrial ecotoxicity potential is shown in Figure 71. It was observed that gas consumption played a significant role towards terrestrial ecotoxicity potential of LBW. LBW of Ti-6Al-4V had the highest overall impact on terrestrial ecotoxicity potential among the three materials.

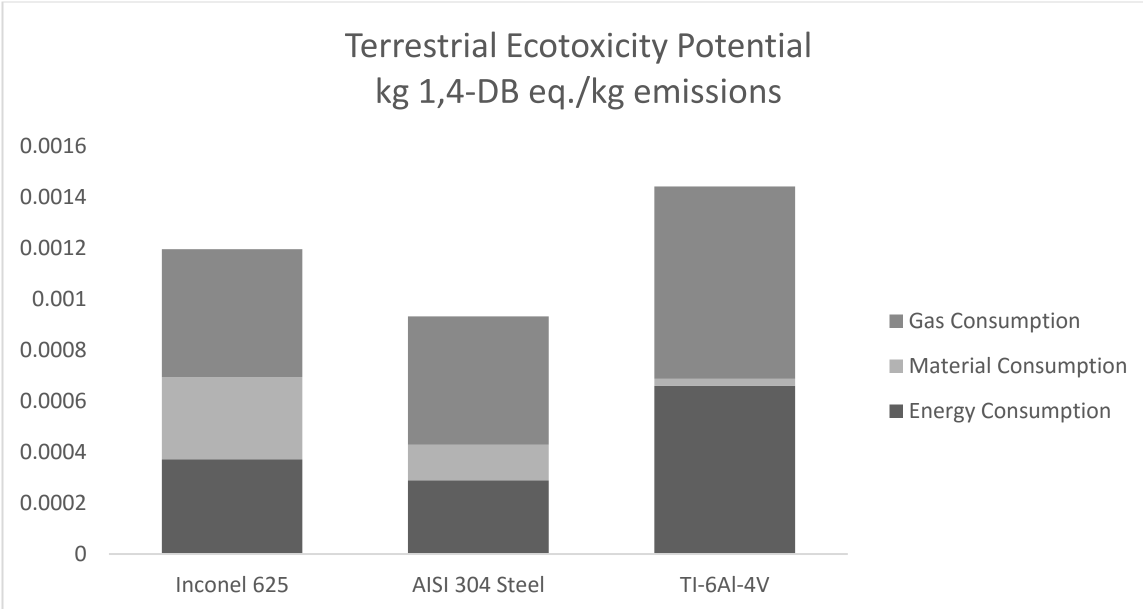


Figure 71 TEP comparison of LBW of three different materials.

#### *4.2.3.9. Marine Aquatic Ecotoxicity Potential*

Marine aquatic ecotoxicity potential is defined as the impact of toxic substances present Contributions of LBW of each material towards marine aquatic ecotoxicity potential is shown in Figure 72. It can be seen that for LBW of AISI 304 Steel and Ti-6Al-4V, gas consumption played a significant role towards marine aquatic ecotoxicity potential of LBW of respective materials.

However, for LBW of Inconel 625, material consumption played an important role owing to the impact of material composition of Inconel 625 on marine aquatic ecotoxicity potential. LBW of Inconel 625 had the highest overall impact on marine aquatic ecotoxicity potential among the three materials attributing to the material composition of Inconel 625.

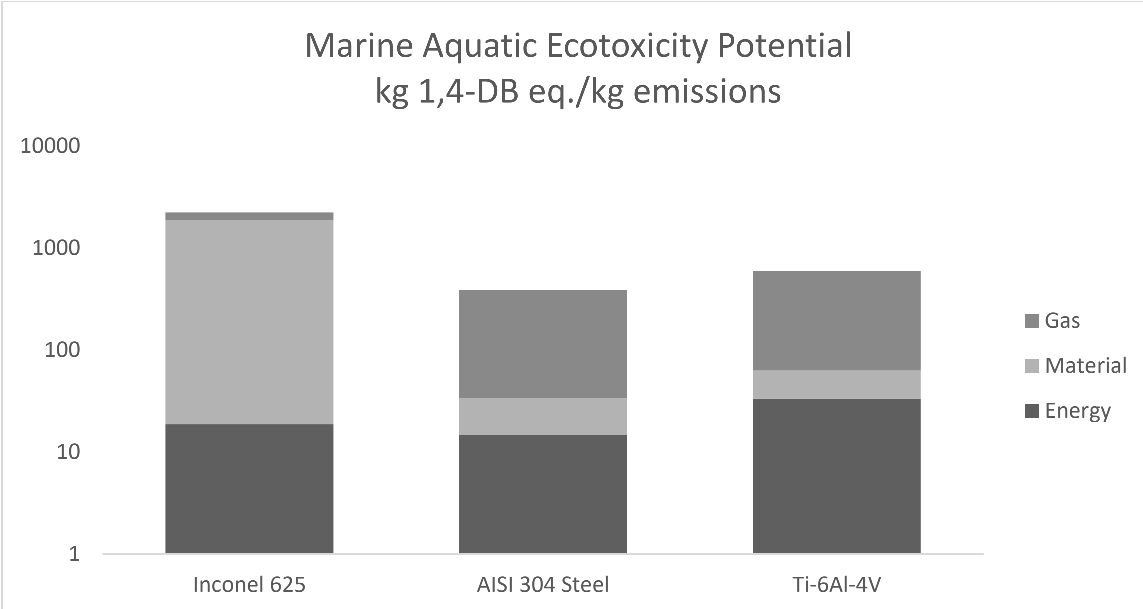


Figure 72 MAEP comparison of LBW of three different materials.

### *4.2.3.10. Fresh Water Ecotoxicity Potential*

A comparative plot of contributions of LBW of each material towards fresh water ecotoxicity potential is shown in Figure 73. It can be seen that for LBW of AISI 304 Steel and Ti-6Al-4V, gas consumption played a significant role towards fresh water ecotoxicity potential of LBW of respective materials. However, for LBW of Inconel 625, material consumption played an important role owing to the impact of material composition of Inconel 625 on fresh water ecotoxicity potential. LBW of Inconel 625 had the highest overall impact on fresh water ecotoxicity potential among the three materials attributing to the material composition of Inconel 625.

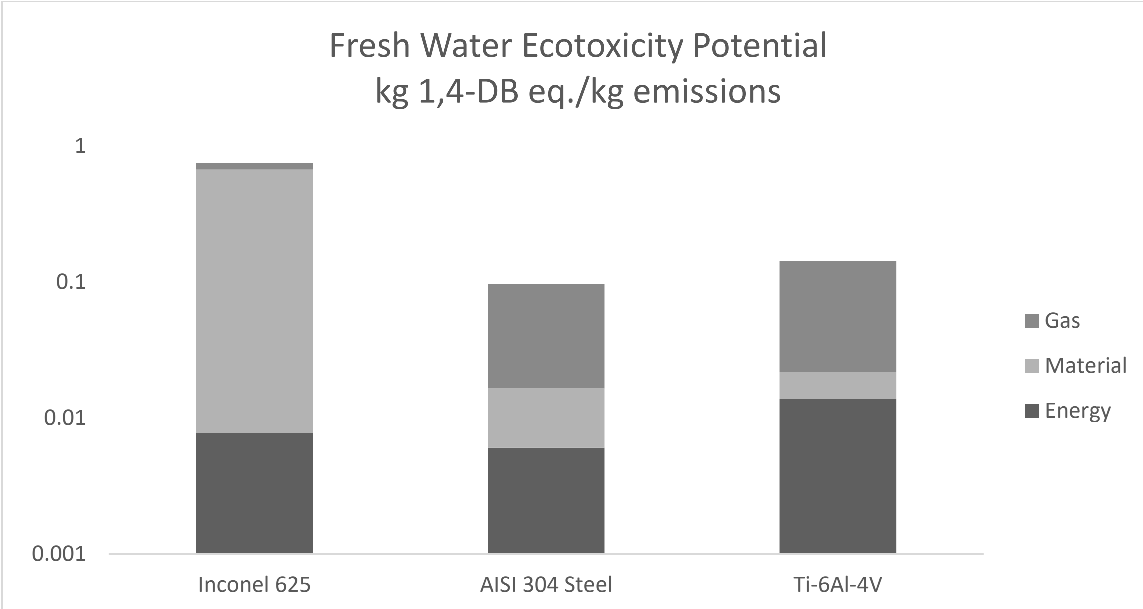


Figure 73 FWEP comparison of LBW of three different materials.

#### *4.2.3.11. Abiotic Depletion Fossil Fuel Potential*

Contributions of LBW of each material towards abiotic depletion fossil fuel potential is shown in Figure 74. It can be seen that gas consumption plays a significant role towards abiotic depletion fossil fuel potential of LBW. Gas consumption had the highest contribution towards abiotic depletion fossil fuel potential among the material, gas and energy consumption. LBW of Ti-6Al-4V had the highest overall impact on abiotic depletion fossil fuel potential among the three materials.

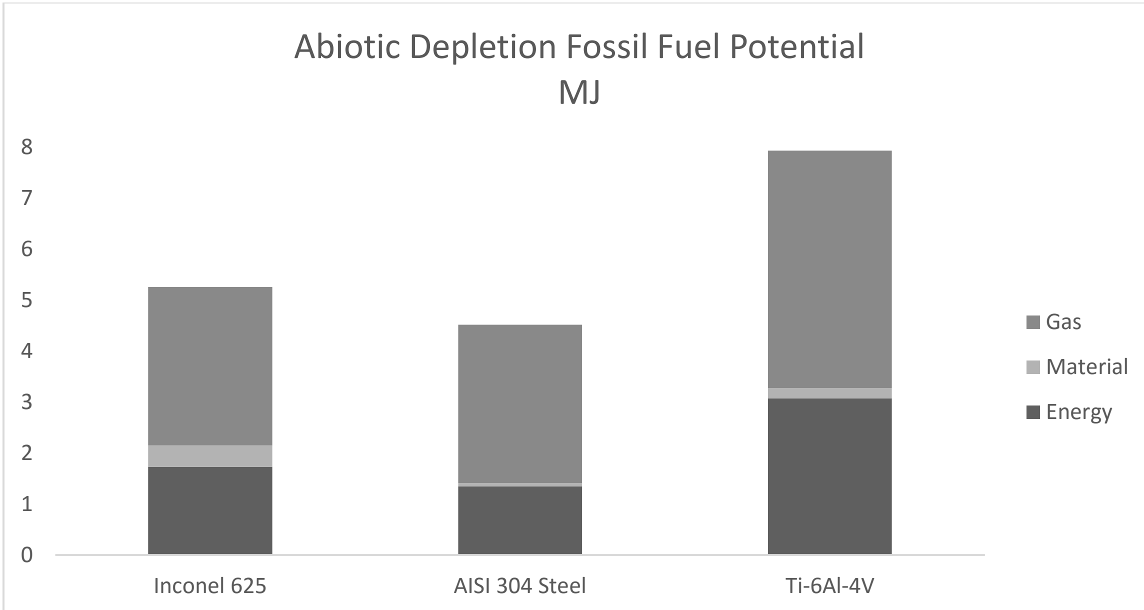


Figure 74 ADFFP comparison of LBW of three different materials.

Hence it can be concluded that LBW of AISI 304 Steel had the least deteriorating impact on the environment while Inconel 625 had significant impact towards the environmental impact categories affected by the material composition such as FWEP, MAEP and ETP etc.. LBW of Ti-6Al-4V had significant impact towards the rest of the environmental impact categories.

# CHAPTER 5. CONCLUSIONS AND FUTURE WORK

## 5.1. Conclusions

This thesis presented the comparative LCA analysis of LBW, FSW and GTAW. Quantitative comparison was made among the processes including the study of effect of workpiece thickness. Following are the conclusions of this research work:

- Among the welding processes used for welding of AISI 304 steel, FSW had the highest overall impact on the environment while LBW had the least overall environmental impact.
- For welding of AISI 304 Steel, it was found out that thicker workpiece results in more material, gas and energy consumption, resulting in high environmental impact as the relationship between workpiece thickness and environmental impact associated with it was found out to be linearly proportional.
- LBW of Inconel 625 and Ti-6Al-4V was found out to be more deteriorating for the environment as compared to AISI 304 Steel.
- LBW of Inconel 625 had the highest contribution towards the impact categories affected by the material composition such as fresh water ecotoxicity potential, marine aquatic ecotoxicity potential and human toxicity potential while LBW of Ti-6Al-4V had significant impact on the rest of the impact categories.

Due to growing concerns regarding environmental impacts of manufacturing processes in Saudi Arabia, this study is performed as an initiative towards environmental impact assessment as very few studies are available for environmental impact assessment for manufacturing processes in Saudi Arabia.

## 5.2. Future Work

For future analysis, with collaboration from manufacturing industry, the scope of current study can be extended. Insisting upon the environmental concerns related with welding processes and a worldwide growing concern regarding environmental issues, more studies should be performed based upon the data obtained from manufacturing and repair industry.

Detailed LCA analysis of further life stages of the products involved in welding process should be carried out for accurate representation of environmental impacts associated with the welding processes. Investigations should be carried for determining appropriate materials and process parameters used in welding processes to come up with a sustainable and economical welding technique.

LCA of products involving welding processes should also be extended to other fields as welding is only considered as secondary manufacturing process and further processing is often carried out to make the product functional. Moreover, economic analysis should also be incorporated to establish comprehensive framework for welding process selection.

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# Vitae

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## Educational Qualification

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| 1 | KFUPM | M.Sc Mechanical Engineering | 2019 | 3.4/4 |
| 2 | KFUPM | B.Sc Mechanical Engineering | 2017 | 3.3/4 |

## Publications:

- **Afzal, A.** Yilbas, B.A, Ashraf, F. and Shaukat, M. (Oct 2019), "Laser Welding of Various Alloys and Life Cycle Analysis." Optics and Laser Technology (Under Review)

- **Afzal, A**. Shaukat, M. (Nov 2019), "Environmental Impact Assessment of Laser, Friction Stir, and TIG welding of AISI 304 Stainless Steel using Life Cycle Assessment.", Lasers in Engineering (Under Submission)

## Languages

- Fluent in English, Arabic and Urdu