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Control and Repair Methods Applied in Quality Assurance of Welded Structures

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To those who look up at the stars and wish

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I would like to extend thanks to many people from many countries, and to the members of ANL MED Erasmus + who generously contributed to the work presented in this thesis, I feel honoured to be part of this particular research groups.

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ABSTRACT

Nowadays, there are many welding processes that respond to the wide variety of assemblies to be achieved and to the requirements of the industry. The first chapter of this thesis describes these different conventional and non-conventional processes applied, presently, in industrial companies. Following this, a detailed classification and description are given on discontinuities encountered during welding, as well as the limits of acceptance before they become defects, and, further, the right steps to remove and repair the welded joints.

The development of quality assurance and maintenance plan, which was applied in the next chapter, is the main objective of this work, presented in the third chapter, after having clearly explained the requirements of a quality welded joint and, generally, of the welded structures, from the Non-Destructive Testing (NDT) and quality control up to Quality Assurance (QA).

This work also includes, in the fourth chapter, an experimental programme necessary for the validation of the maintenance and quality assurance plan, consists of highlighting it for the repair of a defective engine block made of cast iron, used previously in a final year subject, preceded by a brief description on internal combustion engines, their compositions and operation, the cylinder blocks, their roles, their types, and their methods of fabrication, as well as a part on the gray cast iron that allows to interpret the existing defect on this engine block.

A modelling phase following the experimental test is essential, it is given in Chapter 5. By using the tools of numerical methods such as FEM and XFEM, simulation and modelling software such as SOLIDWORKS, CATIA, ABAQUS, and ANSYS, the generation and propagation of the existing crack in the engine block, was simulated, by the submission of the latter to its daily operating conditions and other abnormal conditions which has been extracted it from previous work, it has therefore managed to know and simulate, with the information given in chapter four, what could be the origin of the existing crack on the wall of the engine block. Personal

Key words: Welding processes, quality assurance, quality control, non-destructive testing, grey cast iron, engine block, modelling, simulation, crack propagation, finite element method.

RESUME

Il existe aujourd'hui de nombreux procédés de soudage répondant à la très grande variété d'assemblage à réaliser et aux caractéristiques des métaux utilisés. Le premier chapitre décrit ces différents processus conventionnel et non conventionnel utilisées aujourd’hui dans industries. Suite à cela, une explication plus détaillée est donnée sur les discontinuités rencontrées lors de soudage, ainsi que la marge d’acceptation avant que ceux-ci deviennent des défauts, puis, les bon pas pour les corriger.

L’élaboration d’un plan de maintenance et d’assurance qualité est le cœur de ce travail, présenté dans le troisième chapitre, après avoir bien expliqué les exigences de la qualité des cordant de soudure et des structures soudés, de l’inspection non destructif et le control qualité jusqu’à l’assurance qualité, ce plan a été mis à l’essai dans le chapitre qui suit.

Ce travail comporte donc également et dans le chapitre 4, un aspect expérimental nécessaire à la validation de notre plan de maintenance et d’assurance qualité, consiste à le mettre en évidence pour la réparation d’un bloc moteur défectueux élaboré en fonte grise, utilisé auparavant dans un sujet de fin d’étude, précéder d’une brève description sur les moteurs à combustion internes, leurs compositions et fonctionnement, les blocs moteurs leurs rôles, leurs types, et leurs méthodes d’élaboration, ainsi qu’une partie sur la fonte grise qui permet d'interpréter le défaut existant sur ce bloc moteur.

Une étape de modélisation suite à l’essai expérimentale est indispensable. Elle est donnée dans le chapitre 5. En utilisant les outils des méthodes numériques telles que la FEM et la XFEM, et les logiciels de simulation et modélisation tels que SOLIDWORKS, CATIA, ABAQUS, et ANSYS, nous avons simuler la génération et propagation de la fissure existante dans le bloc moteur, par la soumission de ce dernier à ses conditions de fonctionnement journaliers et d’autres conditions anormales dont nous l’avons extraite de mon travail de licence, nous avons donc réussis à connaitre et simuler, avec les informations données au chapitre 4, ce qui pourrait être l’origine de la fissure existante sur le mur du bloc moteur.

Mots clé : Soudage, procédés de soudage, Assurance qualité, Contrôle qualité, tests non destructif, fonte grise, bloc moteur, modélisation, simulation, propagation de fissure, méthode des éléments finis.

ملـــــــــــخص

هناك اليوم العديد من عمليات اللحام التي تستجيب إلى مجموعة واسعة من التجمعات التي يتعين صنعها وخصائص المعادن المستخدمة. يصف الفصل الأول هذه العمليات التقليدية وغير التقليدية المختلفة المستخدمة اليوم في الصناعات. بعد ذلك ، يتم تقديم شرح أكثر تفصيلًا عن حالات التوقف التي تحدث أثناء اللحام ، بالإضافة إلى هامش القبول قبل أن تصبح هذه العيوب ، ثم ، الخطوات الجيدة لتصحيحها.

إن وضع خطة للصيانة وضمان الجودة هو لب هذا العمل ، المقدم في الفصل الثالث ، بعد أن أوضح بوضوح متطلبات جودة التماس اللحام والهياكل الملحومة ، وعدم التفتيش المدمرة ومراقبة الجودة حتى ضمان الجودة ، تم اختبار هذه الخطة في الفصل التالي.

يشمل هذا العمل أيضًا في الفصل 4 ، جانبًا تجريبيًا ضروريًا للتحقق من صحة خطة ضمان الجودة والصيانة لدينا ، ويتضمن تسليط الضوء عليه لإصلاح كتلة المحرك المعيبة المصنوعة من الحديد الزهر ، وتستخدم سابقًا في موضوع السنة النهائية ، مسبوقًا وصفًا موجزًا لمحركات الاحتراق الداخلي ، والتركيبات والتشغيل ، وكتل القيادة أدوارها وأنواعها وطرق تحضيرها ، بالإضافة إلى جزء منها الزهر الرمادي الذي يسمح بتفسير العيب الموجود على كتلة المحرك هذه.

خطوة النمذجة بعد الاختبار التجريبي ضرورية. تم تقديمه في الفصل 5. باستخدام أدوات الطرق العددية مثل FEM و XFEM ، وبرامج المحاكاة والنمذجة مثل SOLIDWORKS و CATIA و ABAQUS و ANSYS ، قمنا بمحاكاة إنشاء ونشر الكراك الموجود في كتلة المحرك ، من خلال تقديم هذا الأخير لظروف التشغيل اليومية وغيرها من الظروف غير الطبيعية التي استخرجناها من عمل الترخيص الخاص بي ، تمكنا بالتالي من معرفة ومحاكاة ، مع المعلومات المقدمة في الفصل 4 ، والذي يمكن أن يكون أصل الكراك الموجود على جدار كتلة المحرك.

لكلمات المفتاحية: اللحام ، عمليات اللحام ، ضمان الجودة ، مراقبة الجودة ، الاختبارات غير المدمرة ، الحديد الزهر الرمادي ، كتلة المحرك ، النمذجة ، المحاكاة ، انتشار الكراك ، طريقة العناصر المحددة.

INTRODUCTION

When it was possible to obtain appropriate flame temperatures, by mixing gases such as oxygen and acetylene, which are now safely storable, the welding process appeared and has become one of the most important processes in the industry. Welding is applied in all sectors of industry, in its various forms such as Resistance Welding (RW) and arc welding, using electricity as a source of energy, or other variants such as Laser Beam Welding (LBW), Plasma Welding (PW), Electron Beam Welding (EBW), Explosion Welding (EXW), Friction Stir Welding (FSW) etc.

The difficulty of welding, compared to other joining processes, is that the difference between a possible filler metal and a base material or the case of bimetallic components can lead to weldability difficulties and high heterogeneity of materials in the weld zone. The process also involves thermal phenomena that can lead to deformations of the structure, significant distortions, and to the mismatch of component assemblies.

A welder who applies the rules of the profession can master the difficulties during welding like the appearance of other phenomena that can cause defects in welded structures under low mechanical or thermal loads in service, such as macroscopic defects, dimensional defects or defects of realization and metallurgical origin. In addition, non-destructive inspections can complement the action of the operator to ensure a satisfactory quality for welding.

However, this cannot guarantee the reliability of the welding connection in service, it takes us to apply a maintenance plan based on quality assurance’s rules, that is to say to ensure firstly that the discontinuities present in the welded structure remains within the tolerances defined by the standards, secondly, the validity of the design assumptions from which the discontinuities accepted at the end of the manufacturing process do not change. Then, having to deal with the unexpected such as the mechanisms of degradation unknown or neglected at the time of conception and which can be important through the feedback, both internal and external, the role of controls will then be in this case to verify that the discontinuities present in the structure allows him to maintain its integrity while ensuring its functionality, and the use of computer resources to know the upstream and downstream discontinuities present in the structure , this and it will be developed during the five chapters of this thesis.

General Presentation of the University "Dunarea de Jos" of Galati

My internship was performed in Romania, in the Department of Manufacturing Engineering, Faculty of Engineering, "Dunarea de Jos University of Galati. During five months, I worked in the Laboratory of Welding Equipment and Technology and Laboratory of Modelling and Simulation of Welding Process which have a direct connexion to my project.

"Dunarea de Jos" University of Galati functions according to the university charter, whose provisions are in agreement with the national legislation and with the principles of the European Space and Higher Education, being recognised by all members of the university community.

Figure 1. University "Dunarea de Jos" of Galati

The history of higher education in Galati covers the following stages:

- 1948: establishment of the Land Improvement Institute;
- 1951: establishment of the Naval-Mechanical Institute;
- 1953: merging the Naval-Mechanical Institute with the Agronomic Institute, and with the Fish Farming and Fishing Institute (transferred from other university centres), and the establishment of the Technical Institute in Galati;
- 1955: merging of the Technical Institute with the Food Industry Institute in Bucharest;
- 1957: transforming the Technical Institute into the Polytechnic Institute;
- 1959: establishment of the Pedagogic Institute and relocation of the Land Improvement Institute to Iaşi;
- 1974: establishment of the University of Galati by merging the Polytechnic Institute with the Pedagogic Institute (State Council Decree of 20 March 1974);
- 1991: University of Galati becomes "Dunarea de Jos" University of Galati (Government Decision of 4 January 1991).

In the structure of the above mentioned institutes, there were a series of study programmes that were unique in the country: Naval Constructions, Harbours and Ship Exploitation, Food Industry, Fish Farming Technology, Cooling Devices – which meant that an important creation process on elaborating educational curricula and syllabi, lectures, laboratory equipment etc., presently being used in other university centres around the country, was fully the work of the academics in Galati higher education.

The academic community of "Dunarea de Jos" University of Galati consists of>

- 12.500 students
- 1000 teaching staff
- 14 faculties
- 67 Bachelor Study Programmes
- 52 Master study Programmes
- 3 Doctoral Schools
- 13 Doctoral Study Programmes
- 230 doctoral students
- More than 2500 international students

"Dunarea de Jos" University of Galati has concluded more than 100 partnership agreements with universities from 34 countries.

Faculty of Engineering

The Faculty of Engineering is a strong branch of "Dunarea de Jos" University of Galati through its academic offer, the quality of the teaching staff and modern teaching and research spaces.
Studies are focused towards national and international subjects, increase contentment of the students and employees, promoting values during the development process of the human resources, multidisciplinary cooperation in all segments of teaching and scientific research activities.

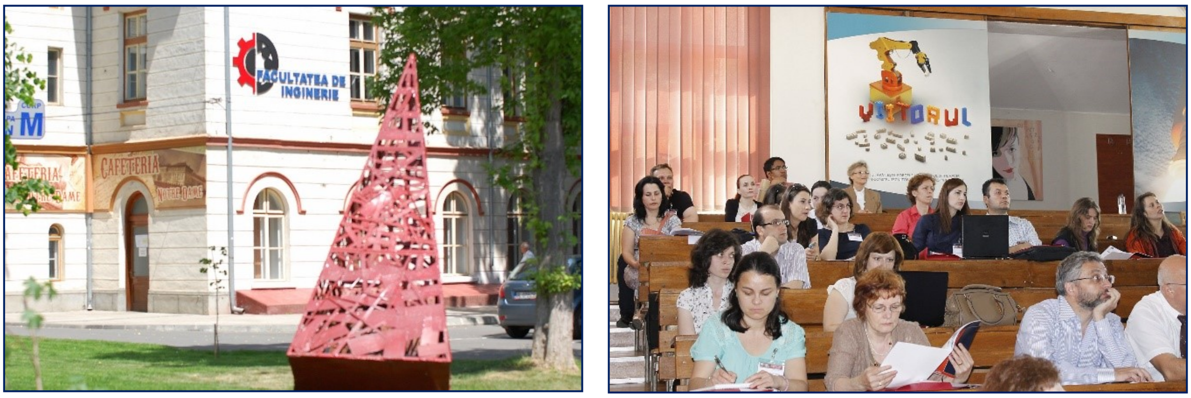


Figure 2. Faculty of Engineering

Motivation and Objectives of the Work

The **motivation** for performing this work has appeared due to the large applicability of welding in industry of aeronautics, automotive, shipbuilding, pipelines, as well as to frequent problems encountered in the daily routine by the companies involved in welding field around the world. The materials subjected to welding suffer chemical, mechanical and metallurgical modifications caused by the great influence of high temperatures reached during welding. The process generates stress and strains in similar or dissimilar materials to be welded, creating real problems, not only at the economic level, but also it could be a real danger for the health and the life of people.

Based on the motivation above, the main **objectives** of the dissertation thesis are the following:

- analysing the main welding methods in order to select the appropriate technique for repairing the welded structures;
- analysing the main defects generated by welding and understanding the causes of their occurrence;
- studying the methods of Non-Destructive Testing (NDT) control, in order to understand and to choose the appropriate method for detecting the defects in welded joints;
- developing a quality assurance plan to be applied for removing the defects and for achieving qualitative welded structures;
- applying the plan for repairing a crack developed in an engine block during service;
- developing a 3D numerical model for simulation of cracking mechanism and crack propagation in an engine block.

CHAPTER 1.

State-of-the-art on Welding Process and Applicability

1.1. Introduction

1.1.1. Joining Process

Fabrication and joining processes are part and parcel in manufacturing where two or more solid elements are joined temporarily or permanently to form a single component. Welding is one type of permanent joining process where two or more materials can be joined permanently by weld bead formation. In spite of the presence of many alternatives for welding processes, including few permanent joining processes and many temporary ones, welding is extensively used in manufacturing industries such as automotive industry, aeronautics, shipbuilding, pipelines fabrication, railway etc [1].

Several alternative definitions are used to describe a weld, such as:

- *A union between two pieces of metal rendered plastic or liquid by heat or pressure or both. A filler metal with a melting temperature of the same order as that of the parent metal may or may not be used* [2].
- *A localized coalescence of metals or non-metals produced either by heating the materials to the welding temperature, with or without the application of pressure, or by the application of pressure alone, with or without the use of a filler metal* [3].

1.2. Classification of Welding Processes

There are 50 different welding processes available today; some of them are frequently employed such as Shielded Metal Arc Welding (SMAW), GMAW, GTAW, SAW, FCAW etc. whereas USW, RSW, DW are limited to several industry branches [3]. Welding processes can be classified based on the following criteria [4], as well as on the heat source type [5]:

- Welding with or without filler material
- Source of energy of welding
- Arc and Non-arc welding
- Fusion and Pressure welding

As we could see billow, different welding processes regrouped and classified into six different categories. More welding specific terms according to ISO/TR 25901-1:2016 are mentioned in ANNEX (A).

1: Gas Welding
Air Acetylene
Oxy Acetylene
Oxy Hydrogen Welding

2: Arc Welding
Carbon Arc welding
Plasma Arc welding
Shielded Metal Arc Welding
TIG (Tungsten Inert Gas Welding)
MIG (Metal Inert Gas Welding)

3: Resistance Welding
Spot welding
Seam welding
Projection welding
Resistance Butt welding
Flash Butt welding

4: Solid State Welding
Cold welding
Diffusion welding
Forge welding
Fabrication welding
Hot pressure welding

5: Thermo Chemical Welding
Thermit welding
Atomic welding

6: Radiant Energy Welding
Electric Beam Welding
Laser Beam Welding

The European and American abbreviations of the main welding processes are shown in the table 1.1. and the classification of them is presented in detail in the figure 1.1 [3].

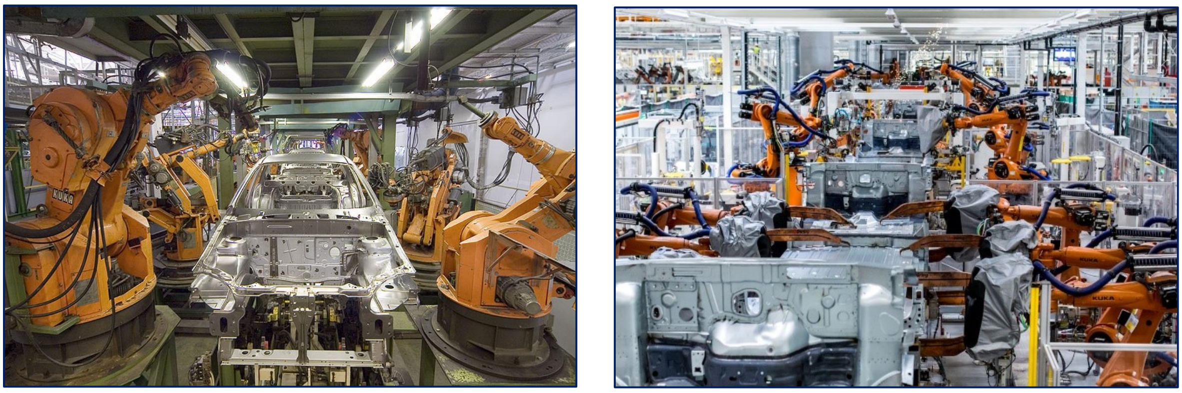


Fig. 1.1. Application of Welding in Automotive Industry [6]

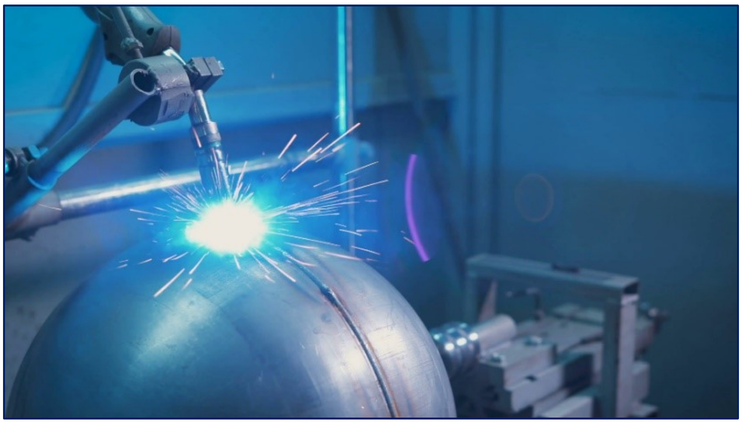


Fig. 1.2. Application of Laser Welding [7]

Table 1.1. Classification and abbreviations of welding processes

ISO 4063	European (EA) and American (AA) abbreviations		Full process name
111	EA	MMA	Manual Metal Arc Welding
	AA	SMAW	Shielded Metal Arc Welding
114	EA	FCAW	Flux-cored wire metal arc welding
	AA	FCAW	Flux-cored arc welding
12	EA	SAW	Submerged Arc Welding
	AA	SAW	Submerged Arc Welding
13	EA	GMAW	Gas Shielded Metal Arc Welding
	AA	GMAW	Gas Metal Arc Welding
131	EA	MIG	Metal-arc Inert Gas Welding
	AA	GMAW	Gas Metal Arc Welding
135	EA	MAG	Metal-arc Active Gas Welding
	AA	GMAW	Gas Metal Arc Welding
136	EA	FCAW	Flux-cored wire metal-arc welding with active gas shield
	AA	FCAW	Flux-cored arc welding
137	EA	FCAW	Flux-cored wire metal-arc welding with inert gas shield
	AA	FCAW-S	Flux-cored arc welding
141	EA	TIG	Tungsten Inert Gas Welding
	AA	GTAW	Gas Tungsten Arc Welding
21	EA		Spot Welding
	AA	RSW	Resistance Spot Welding
25	EA		Resistance Butt Welding
	AA	RSEW	Upset Welding
3	EA		Gas Welding
	AA	OFW	Oxy-fuel Gas Welding
311	EA		Oxy-acetylene Welding
	AA	OAW	Oxy-acetylene Welding
81	EA		Flame Cutting
	AA	OFC	Oxy-fuel Gas Cutting
86	EA		Flame Gouging
	AA		Thermal Gouging

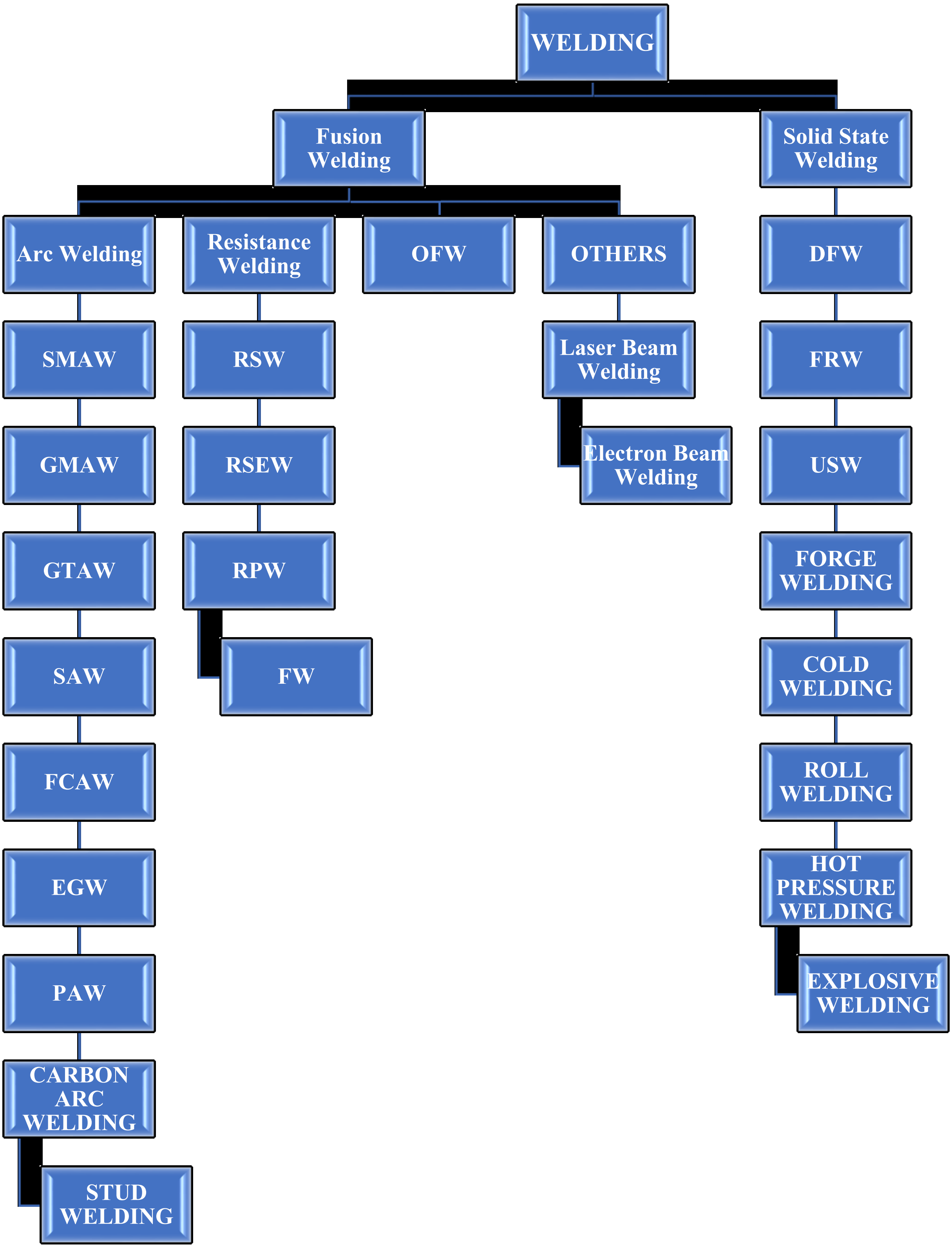


Fig. 1.3. Classification of Welding Processes

1.3. Welding Processes

1.3.1. Manual Metal Arc Welding

Manual Metal Arc (MMA) welding which is the most flexible and one of the most widely used arc welding processes is initiated by striking an electrical power supply to create and maintain an electric arc between an automatically fed wire electrode and the work piece to be joined. The welded joint is formed by a combination of melted base metal, and molten core wire from the electrode. The welding region is protected by some type of inert or semi-inert gas, known as a shielding gas. (They can use either direct (DC) or alternating (AC) current, and consumable or non-consumable electrodes) [8] [9] [10] [11] [12].

a. Principle

An electric arc is produced between a metal electrode and the workpiece, carrying a high current, the heat energy of the spark (temp 2700–5500°C) melts the parent metal at the same time, the end of the electrode is melted and droplets of molten metal pass through the arc to the base metal which admixture together to form, on cooling, a continuous solid mass. A flux coating on the electrode provides a gaseous shielding against oxidation. MMA welding can be used to join most steels, stainless steels, cast irons and many non-ferrous materials. For many mild and high-strength carbon steels, it is the favoured joining technic [10] [11] [8].

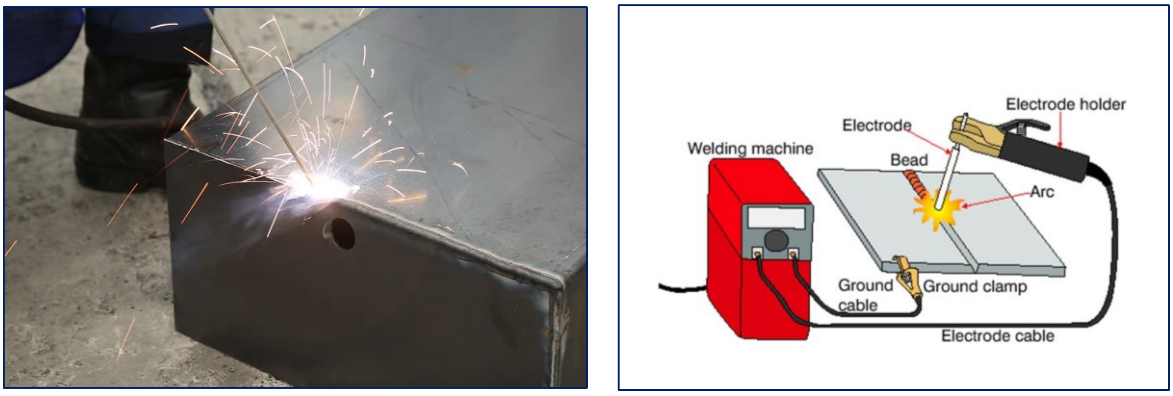


Fig. 1.4. Manual Metal Arc Welding [13]

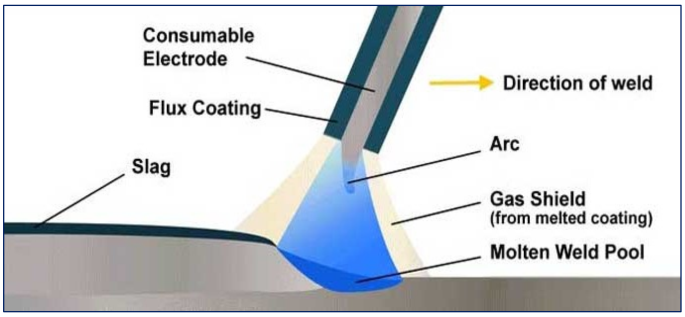


Fig. 1.5. Manual Metal Arc Welding Process [14]

1.3.2. MIG-MAG Welding

Continuous wire welding in a shielded atmosphere is often identified by the abbreviation GMAW. (Gas Metal Arc Welding). So GAS-METAL ARC WELDING (GMAW) is an arc welding process - same as TIG welding except a non-consumable electrode replaced by consumable electrode wire-, in which the arc burns between a melting electrode (which also acts as the weld filler) and the workpiece. An externally supplied gas or gas mixture is used as shielding gas for the arc and molten weld pool. This shielding gas is either inert (MIG - e.g. argon, helium and mixtures of these) or active (MAG) if the gas has a content of an active gas such as $C0_2$ [15] [16] [17].

Fig. 1.6. MIG-MAG welded products [18]

a. Principle

Continuous wire welding is a process that works on basic principle of heat generation due to electric arc which is maintained between the piece to be welded and the wire electrode. This heat is further used to melt consumable electrode and base plate's metal which solidify together and makes a strong joint, the welding zone is constantly fed with the welding material (the wire electrode) by means of a special torch, which also supplies the flow of gas (or gas mixture) whose purpose is to shield the wire electrode, the weld pool, the arc and the area surrounding the base material from other reactive gases, and this gives good surface finish and a stronger joint. The process is suitable for welding aluminium, magnesium alloys, plain and low-alloy steels, stainless and heat-resistant steels, copper and bronze, the variation being filler wire and type of gas shielding the arc.

The presence in the welding circuit of the gas cylinder (inert or active gas, or a mixture of the two) together with the use of solid wire electrodes identifies the gas shield welding process (MIG. or MAG.) [15] [16] [17] [19] [20].

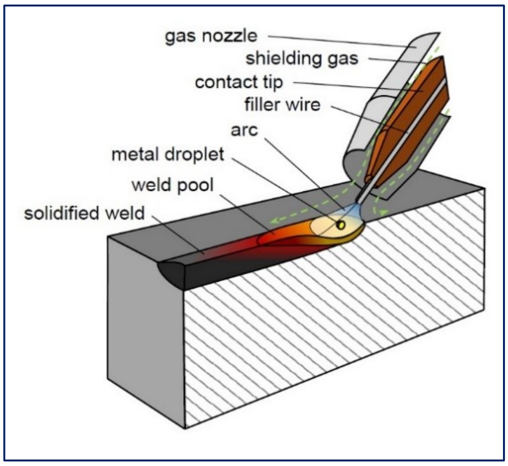


Fig. 1.7. MIG-MAG welding principle [21]

Fig. 1.8. MIG-MAG welding [22]

1.3.3. TIG Welding

TIG welding (also called Gas Tungsten Arc Welding, GTAW) involves striking an arc between a non-consumable tungsten electrode and the workpiece. The weld pool and the electrode are protected by an inert gas, usually argon, supplied through a gas cup at the end of the welding gun, in which the electrode is centrally positioned [23] [12].

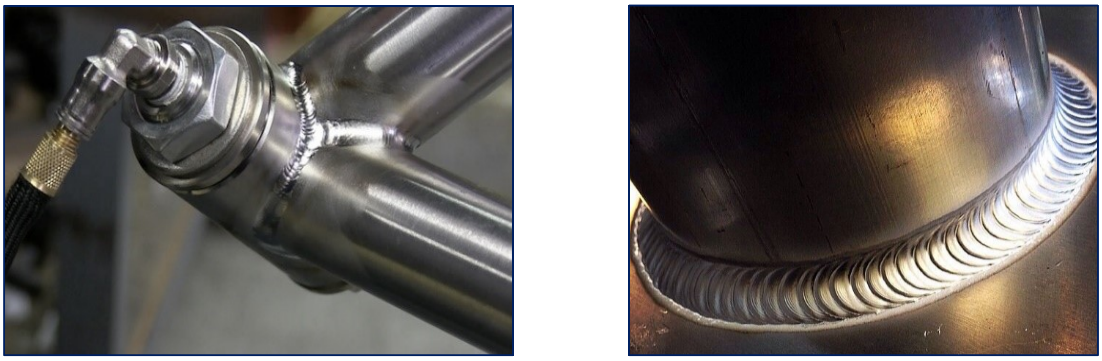


Fig. 1.9. TIG welded pieces [24] [25]

a. Principle

Arc welding in an inert gas shield with a non-consumable tungsten electrode (TIG. - Tungsten Inert Gas or GTAW. - Gas Tungsten Arc Welding) is a procedure in which the heat necessary to make the welding is generated by an electric arc which is maintained between the metals to be joined and a non-fusible tungsten (or tungsten alloy) electrode. The welding pool temperature can reach 2500 °C. The welding pool, the melted metal and the non-consumable electrode are protected from oxidization by a shielding gas which is supplied through torch. The inert gas is normally argon, helium, or a mixture of helium and argon. TIG welding is especially suited to sheet materials with thicknesses up to about 8 or 10 mm.

The TIG welding process can be used with the addition of external weld material (welding rod) or by melting the base material by way of the heat energy effect produced by the electric arc [16] [12] [26].

Note: In this welding mostly work piece is connected to the positive terminal and electrode is connected to negative

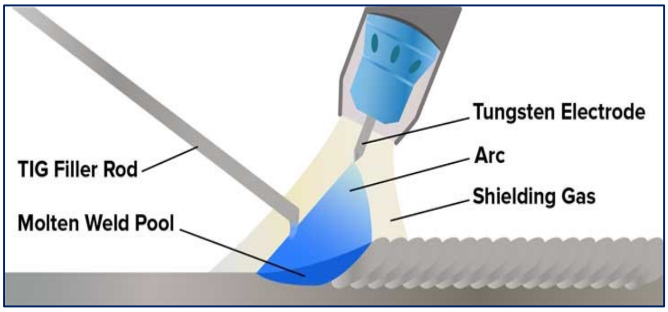


Fig. 1.10. Schematic Diagram of TIG Welding System [27]

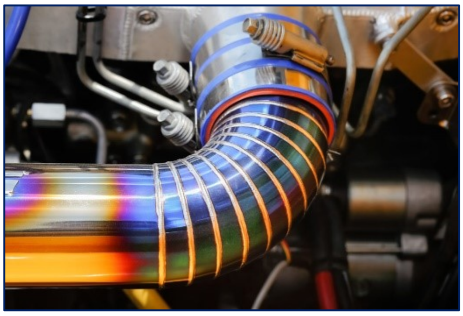


Fig. 1.11. TIG Welding [28]

1.3.4. Plasma Arc welding

Plasma arc welding (PAW) is extended form of TIG welding, in which the joining of metal is produced by heating with a constricted arc between a pointed tungsten electrode and the work piece, the heating temperature is about 30000 degree centigrade at which the gas converts into ionized form. In addition, pilot arc with a current intensity of 3 - 30 A burns between the tungsten electrode and water-cooled copper bowl that surrounds this tungsten. Shielding is obtained from the hot ionized gas issuing from the orifice, which may be supplemented by an auxiliary source of shielding gas. Shielding gas may be an inert gas or a mixture of gases. By positioning the electrode within the body of the torch, the plasma arc can be separated from the shielding gas envelope and the plasma is forced through a fine bore hole in the copper anode. The constriction of the arc, characteristic of plasma welding, is achieved by various physical effects (cooling effect of the nozzle, electromagnetic effects) [20] [16].

a. Principle

Principles of Operation: Once the equipment is set up and the welding sequence is initiated, the plasma and shielding gases are switched on. A pilot arc is then struck between a tungsten alloy electrode and the copper alloy nozzle within the torch (non-transferred arc mode), usually by applying a high-frequency open-circuit voltage. When the torch is brought in close proximity to the workpiece or when the selected welding current is initiated, the arc is transferred from the electrode to the workpiece through the orifice in the copper alloy nozzle (transferred arc mode), at which point a weld pool is formed [29] [30] [31].

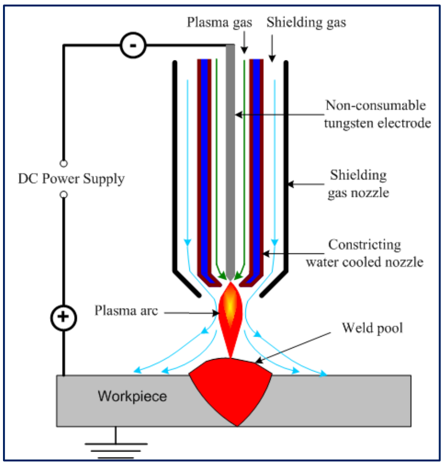


Fig. 1.12. Plasma Arc Welding Process [32]

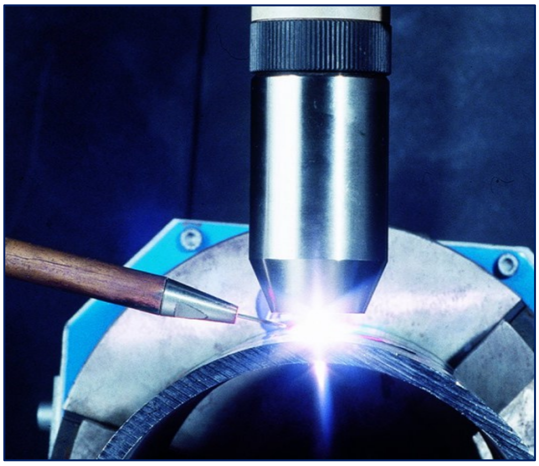


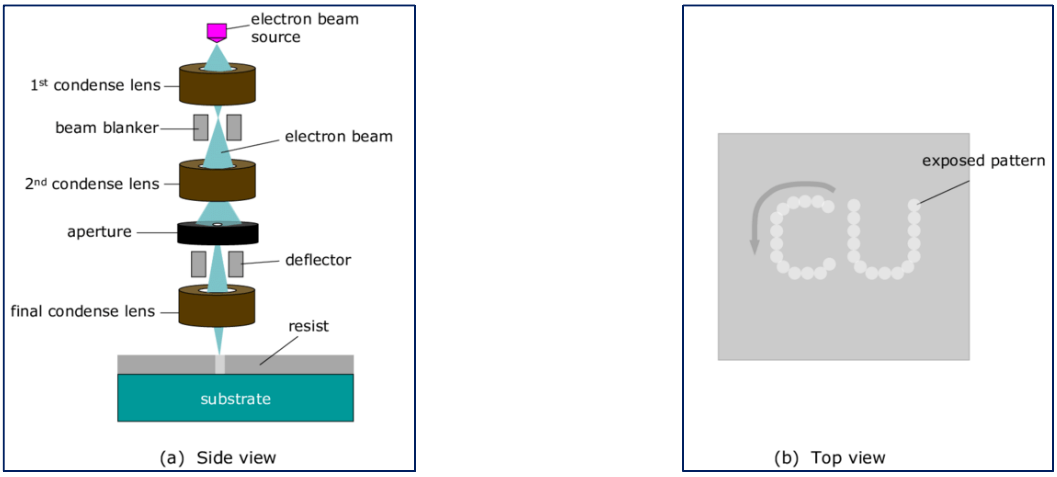
Fig. 1.13. Plasma Arc Welding [22]

1.3.5. Electron Beam Welding

Electron-Beam Welding (EBW) is a high-energy density fusion process that works on same principle of electron beam machining which is accomplished by bombarding the joint to be welded with an intense (strongly focused) beam of electrons that have been accelerated up to velocities 0.3 to 0.7 times the speed of light using electrical fields at 25 to 200 kV, respectively. As the electrons impact the materials their kinetic energy is converted into thermal energy as they impact and penetrate into the workpiece on which they are impinging, Electrons are elementary atomic particles characterized by a negative charge and an extremely small mass. Raising electrons to such high energy state by accelerating them provides the energy to heat the weld, and to fuse two metal plates together to form a weld joint. Electron-beam welding is used to weld any metal that can be arc welded: weld quality in most metals is equal to or superior to that produced by gas tungsten arc welding (GTAW). Because of the high voltages involved in EB welding and the required vacuum, the whole process is carried out in vacuum chamber to prevent it from contamination, and it is controlled and heavily automated. The advanced technology needs specialized fixtures to secure parts for joining, and CNC tables are commonly used to move the fixtures and workpieces within the welding chamber [20] [16] [33].

a. Principle

The electrons are "boiled off" as current passes through a filament which is in a vacuum enclosure. An electrostatic field, generated by a negatively charged filament and bias cup and a positively charged anode, accelerates the electrons to about 50% to 80% of the speed of light and shapes them into a beam. Due to the physical nature of the electrons - charged particles with an extremely low mass - their direction of travel can easily be influenced by electromagnetic fields. Electron beam welders use this characteristic to electromagnetically focus and very precisely deflect the beam at speeds up to 10 kHz. Recent machine developments make it possible even to go up to 200 kHz. With today's CNC controls, the beam focus as well as the beam deflection are part of the weld schedule and can be variably programmed along with other process parameters [20] [16].



(a) Side view

(b) Top view

Fig. 1.14. Schematic Illustration of Electron Beam Lithography [34]

In the images above, we can see that the Electron beam is focused on a resist film to create a pattern by exposing dot by dot: (a) side view of the lithography setup; (b) top view of the exposed pattern by a serial writing.

1.3.6. Laser Beam Welding

Laser Beam Welding is a fusion welding process in which two metal pieces are joined together using monochromatic, directional, coherent light to provide heating. The word "laser" originates from the acronym for "Light Amplification by Stimulated Emission of Radiation". The laser beams are focused to the cavity between the two metal pieces to be joined. The laser beams have enough energy and when it strikes the metal pieces produces heat that melts the material from the two metal pieces and fills the cavity. After cooling a strong weld is formed between the two pieces [20] [16].

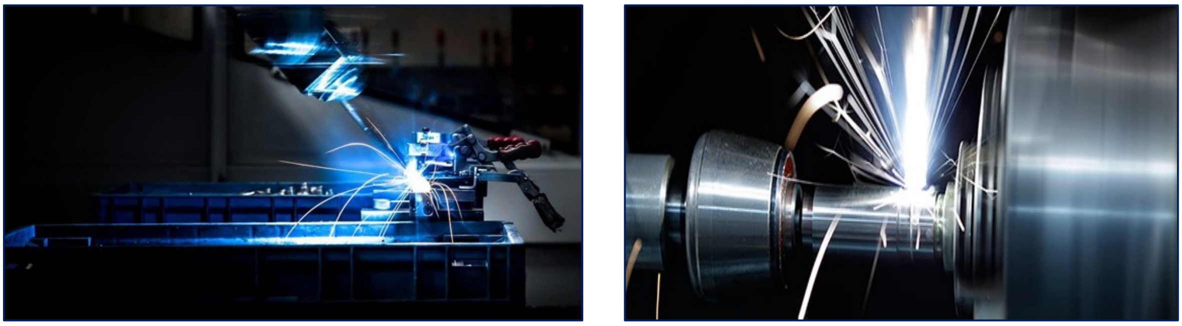


Fig. 1.15. Laser Beam Welding [35] [36]

a. Principle

It works on the principle that, atoms contained within a "lasing medium" are heated until they are excited (by absorbing some energy) - meaning that the electrons go into a larger orbital path than normal And then after some time when it returns back to its ground state, it emits a photon of light. The photons are bounced around in the lasing medium back and forth between two mirrors. Once a photon is going the proper direction, it can escape the partially reflecting mirror. The concentration of this emitted photon increased by stimulated emission of radiation and we get a high energy concentrated laser beam [20]. Light amplification by stimulated emission of radiation is called laser. The laser beam is focused by a lens or mirrors into a point only a few tenths of a mm in diameter in order to provide a high energy density. The focus point is arranged to fall on, or slightly below, the surface of the workpiece. The material immediately melts, with some even being vaporised. The vaporised metal in the hole forms a plasma which, being a good absorber of the incident light, further improves energy absorption and so efficiency of the process. Shielding gas is used, to prevent air from reacting with the material and to protect the lens from spatter and vapour [37].

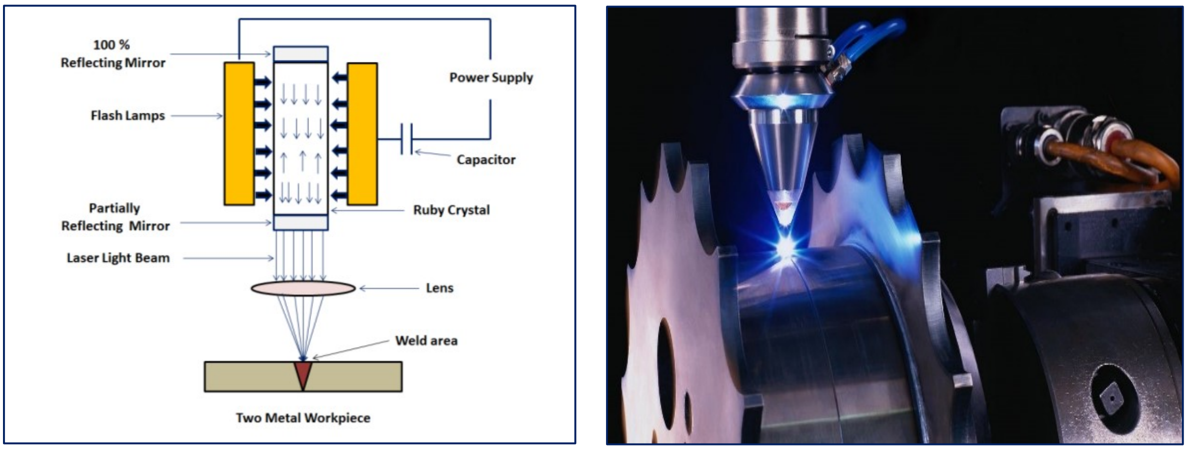


Fig. 1.16. Laser Beam Process and Tools [38] [39]

- First the setup of welding machine at the desired location (in between the two metal pieces to be joined) is done;
- After setup, a high voltage power supply is applied on the laser machine. This starts the flash lamps of the machine and it emits light photons. The energy of the light photon is absorbed by the atoms of ruby crystal and electrons get excited to their higher energy level. When they return back to their ground state (lower Energy state) they emit a photon of light. This light photon again stimulates the excited electrons of the atom and produces two photons. This process keeps continue and we get a concentrated laser beam;
- This high concentrated laser beam is focused to the desired location for the welding of the multiple pieces together. Lens are used to focus the laser to the area where welding is needed. CAM is used to control the motion of the laser and workpiece table during the welding process;
- As the laser beam strikes the cavity between the two metal pieces to be joined, it melts the base metal from both the pieces and fuses them together. After solidification we get a strong weld;
- This is how the Laser Beam Welding works [40].

1.3.7. Hybrid Welding

Hybrid laser-arc welding is a technique refers to processes in which laser welding is combined with other welding methods in the same welding pool, usually MIG or plasma welding. Combining a laser with MIG/MAG welding, the additional wire provides more material and, consequently the efficiency increases. In addition, when welding fillet joints, this combination provides reinforcement of the joint. The beam from any welding laser source (CO_2, Nd:YAG, diode, Yb fibre, Yb:YAG disk etc) can be combined with any arc process (MIG/MAG, TIG, SAW, plasma) [20] [39] [29].

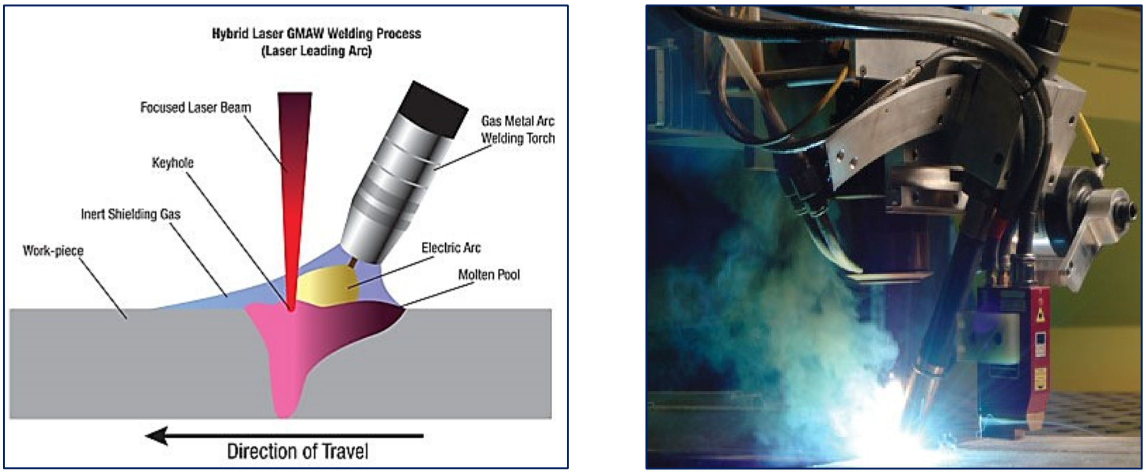


Fig. 1.17. Laser Hybrid Welding Process [29] [41]

1.3.8. Friction Stir Welding

Friction-stir welding (FSW) is a solid-state joining process which means that the objects are joined without reaching melting point, that uses a third body tool similar to a milling cutter, but with the difference that no metal is actually cut. The FSW process takes place in the solid-phase, at temperatures below the melting point of the material, and as a result does not experience problems related to re-solidification, such as the formation of second phases, porosity, embrittlement, and cracking. In addition, the lower temperature of the process enables joining with lower distortion and lower residual stresses] [42].

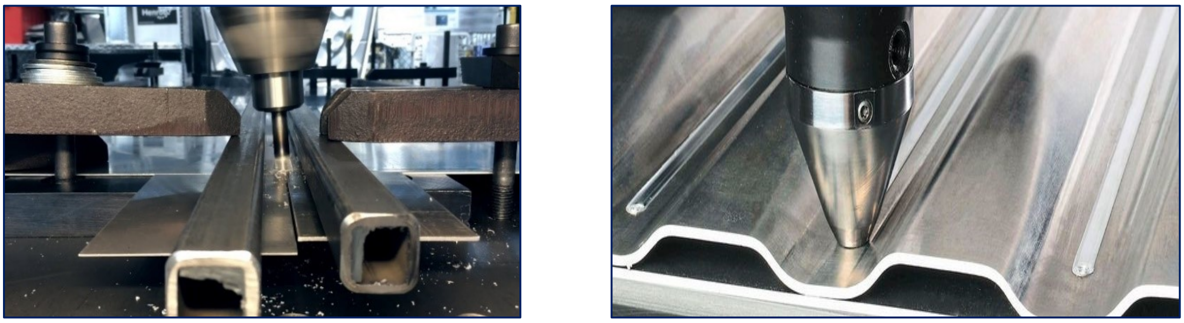


Fig. 1.18. Friction Stir Welding **[43]**

It is primarily used on aluminium, and most often on extruded aluminium (non-heat treatable alloys), and on structures which need superior weld strength without a post weld heat treatment.

a. Principle

In Friction Stir Welding the rotation of the tool at high speeds against the workpiece produces friction that is sufficient to lead to a very soft region (due to the elevated temperature) and the metal near the probe goes into plastic deformation region and join together, using mechanical pressure (which is applied by the tool), much like joining clay, or dough [44] [45] [20] [46].

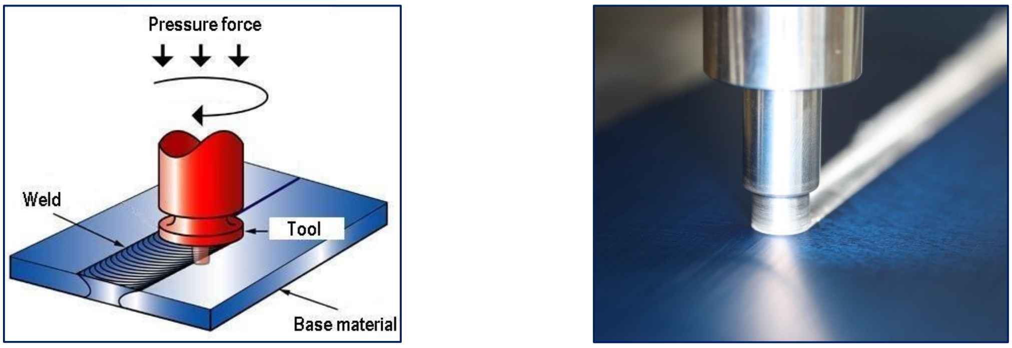


Fig. 1.19. Process and Principle of Friction Stir Welding Process [39] [47]

1.4. Conclusion

- Welding has traditionally been considered as a craft rather than a technological manufacturing process, but then, and with the need of the current market, the vision has completely changed, as we have seen in this chapter, the creation of new welding processes, and the great development of these have largely opened the doors of the world technological manufacturing in front of the welding.
- The variation of welding processes is a result of the industry's need as well as the technological advancement, so that each process, each method, has its benefits and misdeeds, without forgetting its specific field of application.

CHAPTER 2.

Imperfections and Defects in Welded Joints

In order to evaluate weldments, the weld inspector should have the ability to identify weld discontinuities. Discontinuities can be grouped into three classes. The first group relates to shape, size, and contour, which are the external dimensions of a weld. The second group relates to the internal consistency of welds, and is referred to as structural discontinuities. The third group is weld and base metal properties, which relates to the match between weld metal and base metal [48]. ISO 6520 classifies weld flaws while ISO 5817 and ISO 10042 prescribe acceptable limits for such defects.

2.1. Welding Defects

Improper welding procedure causes most weld defects. According to ASME, following factors bring about weld defects:

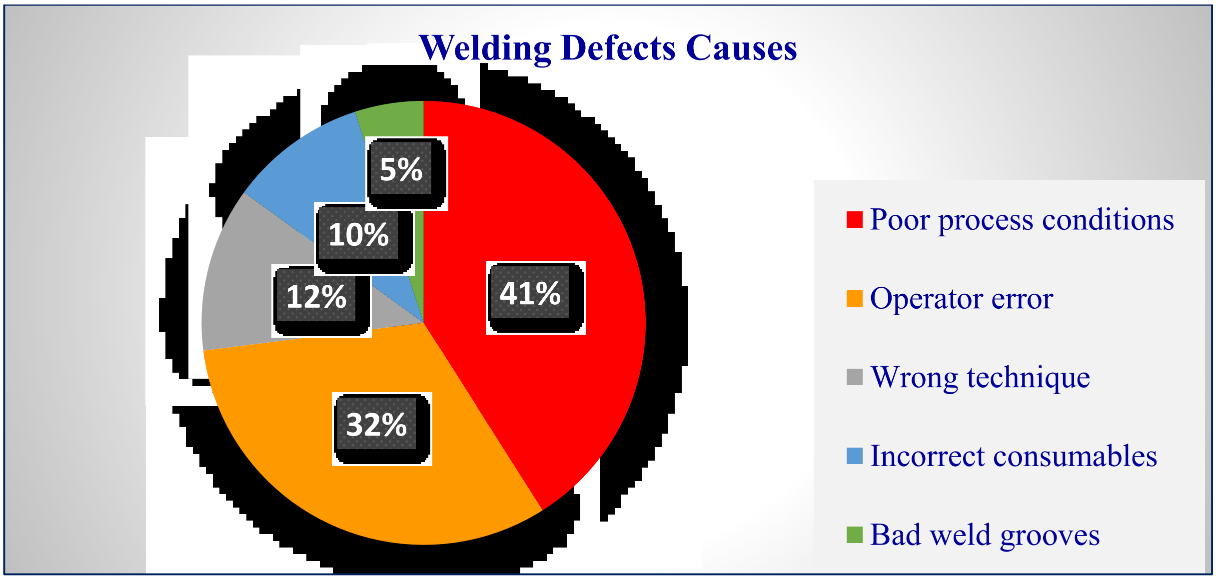


Fig. 2.1. Causes of Welding Defects

Issues caused by welding have existed for decade, but it should take into account of the following factors that influence and aggravate them:

- Ignorance on Weld Processes
- Absence of Process Ownership
- Needless Belief in Salespersons

2.1.1. Contour Defects

Contour defects may be in the form of insufficient or excessive leg size, overroll or overlap, excessive convexity or concavity of the bead, or simply a rough, uneven appearance [49]. These are mainly caused by the operator but by using the correct electrode, amperage, travel speed and electrode angle adjustments, many of these problems can be fixed [50].

2.1.2. Overlap Defects

The protrusion of weld metal beyond the weld toe or weld root [51] occurs in fillet welds and butt joints and produces notches at the toe of the weld that are undesirable because of their resultant stress concentration under load [52].

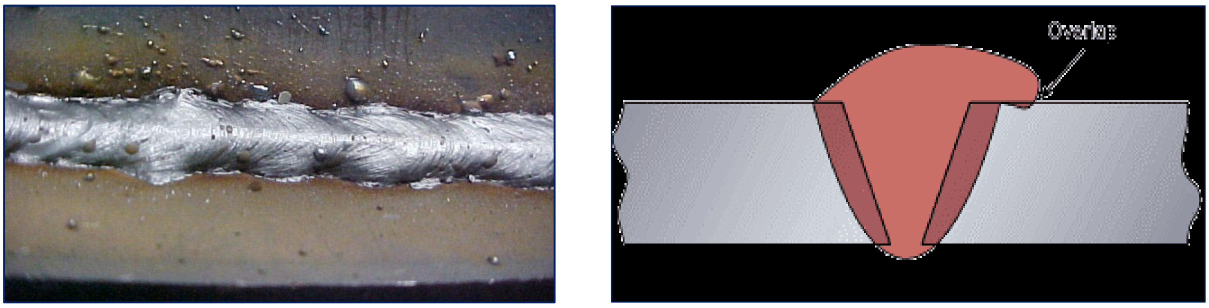


Fig. 2.2. Overlap Defect [53] [54]

a. Causes:

- Magnetic arc blow;
- Use old small welding speeds during joining of small thickness plates;
- Internal consistency of welds;
- Improper welding technique;
- Using of large electrodes which may occur this defect;
- High welding current conditions [49] [55].

b. Remedies:

- Select a proper technique for welding;
- Use small electrode;
- Reduce the welding current.

2.1.3. Undercut Defects

Undercut is defined as a groove or channel that is gouged in the base metal occurring continuously along the toes or root and is left unfilled by the weld metal [51]. Undercut area appears like a small notch in the weld interface [51].

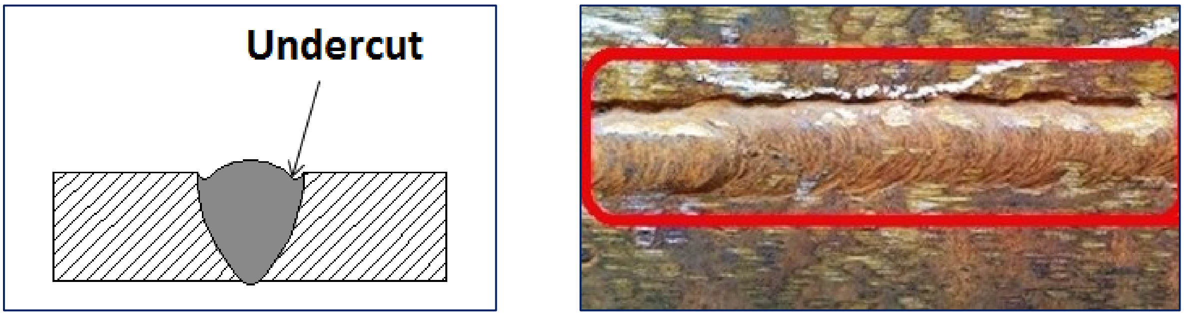


Fig. 2.3. Undercut Defect **[56] [57]**

a. Causes:

- Use of magnetic arc blows with direct current straight polarity;
- Undersize electrode and insufficient current conditions etc.
- Use of high welding speeds during joining of large thickness plates;
- Excessive arc length;
- Excessive side manipulation;
- Use of damp electrodes;
- Excessive amperage;
- Wrong electrode angles;
- The use wrong electrode or the angle of the electrode is wrong, may form the defect;
- Using a wrong geometry of the electrode [49] [51] [55].

b. Preventive Measures:

- Use appropriate welding amperages, manipulation speeds, arc lengths (voltage);
- Adjust the wire tracking location;
- Keep the electrode angle from 30 to 45 degree with the standing leg;
- The diameter of the electrode should be small;
- Reduce the travel speed of the electrode [51] [55].

2.1.4. Spatter

Spatters are small particles of the molten metal that jump from weld pool during welding operation and fall on the surface of the material you’re working on. [49] [51] [58]. Spatter is generally regarded as a nuisance and is a critical factor to consider when developing an application [58].

Fig. 2.4. Spatters defect [54] [59]

a. Causes:

- Use of low welding speeds during joining of large thickness plates;
- Excessive arc length;
- High amperage;
- Use of sample electrodes;
- The longer the arc the more chances of getting this defect;
- Incorrect polarity;
- Improper gas shielded may also cause this defect [49] [50] [55].

b. Remedies:

- Reducing the arc length and welding current;
- Using the right polarity and according to the conditions of the welding;
- Increasing the plate angle and using proper gas shielding [55].

2.1.5. Crater Defects

- At the end of welding in Gas Welding, a shallow spherical shape named crater.
- Crater -This is due to improper welding technique and is formed at the end of weld run.
- This may be remedied by proper manipulation of the electrode. When finishing a weld the operator should not draw away the arc quickly but should maintain the arc without moment until the crater is filled up.
- On re-striking the arc, to continue the weld bead, the arc should strike approximately 15mm in front of the previous bead, travel backwards and then forward the welding direction [49].

A ‘crater’ is a tiny explosion which will send droplets of molten metal in every direction. First detected by a loud popping which can stop the welding process in extreme cases. Most often it is the result of encountering tiny pockets of oxidation inside or on the surface of the metal being welded. Proper preparation of the work piece usually minimizes this problem. Other impurities in the metal itself have been known to be possible causes, as well as improper welding procedures being used [60].

a. Causes:

- Incorrect torch angle;
- Use of large electrode at the end of the weld bead;
- Improper welding technique [49] [55].

b. Remedies:

- Using a proper torch angle may reduce the stress on the metal;
- Using a small electrode may also decrease the crater;
- Use a proper technique [55].

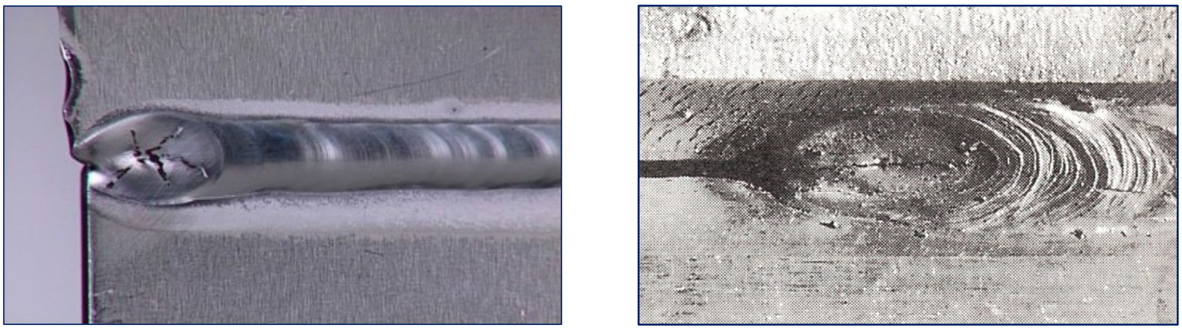


Fig. 2.5. Crater Defect [61]

2.1.6. Excessive Convexity and Concavity

Excessive concavity or convexity of a fillet weld exceeding specified limits can produce a notch effect in the welded area and, consequently, concentration of stress under load. For this reason, some codes and standards specify the maximum permissible convexity and concavity of a weld profile [62].

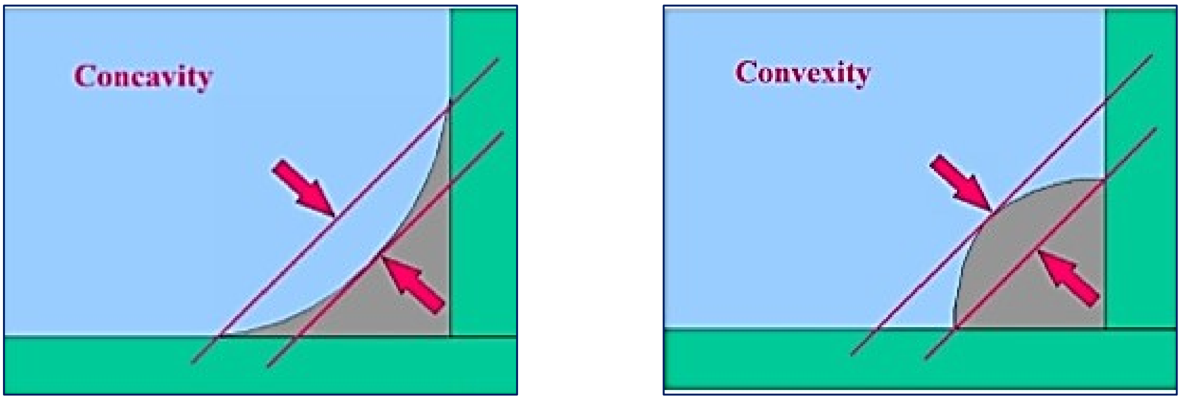


Fig. 2.6. Excessive Concavity and Convexity [63]

a. Causes:

- Use of low welding speed with direct current reverse polarity;
- Excessive or Insufficient current conditions;
- Use of large size electrodes for joining of small thickness plates;
- incorrect welding techniques [3].

b. Remedies:

- Use appropriate welding amperages, manipulation speeds, arc lengths (voltage), and electrode travel and work angles;
- Observe proper parameters and techniques [3].

2.1.7. Surface Porosity

Porosity is the presence of cavities (or group of small voids whereas blow holes or gas pockets) in the weld metal.

Porosity is caused by the absorption of nitrogen, oxygen and hydrogen in the molten weld pool which is then released on solidification to become trapped in the weld metal. Or also Contamination of either the filler or parent metals.

These gases may also be produced due to coating gradients in the electrode (or) moisture, oil, grease etc., on the base metal [49] [64] [17].

a. Causes:

- Improper coating of an electrode;
- Longer arc;
- High welding currents;
- Incorrect welding techniques;
- Electrodes with a damp coating;
- Rust, oil, grease etc on the job;
- High Sulphur and carbon contents in the base metal [64] [17].

b. Remedies:

- Preheat;
- Maintain proper arc length;
- Use low hydrogen electrode;
- Use recommended procedure for baking & storing electrodes;
- Clean joint surfaces & adjacent surfaces [65].

2.1.8. Burn Through

When an undesirable open hole has been completely melted through the base metal. The hole may or may not be left open [66] [67].

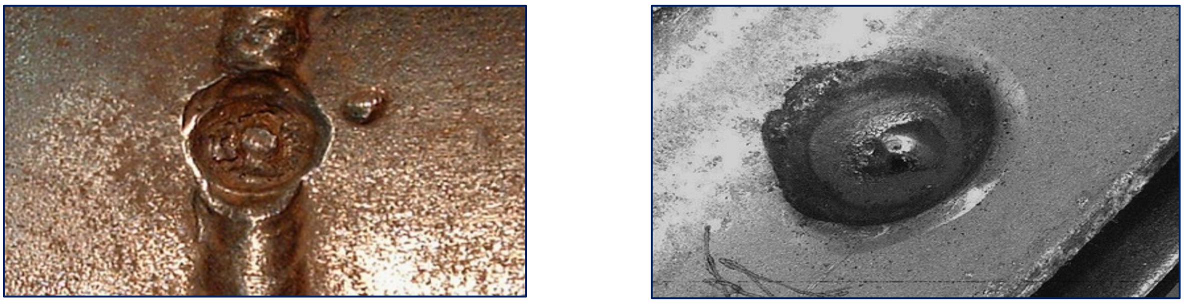


Fig. 2.7. Burn Through [68] [69]

a. Causes:

- Poor edge preparation;
- Too great a heat concentration;
- Too much root;
- Excessive heat input and heat concentration [55] [67].

b. Remedies:

Use appropriate root openings and welding amperage [55] [67]

c. Prevention measures:

Reduce heat input by increasing travel speed, or by reducing welding parameters.

2.1.9. Excessive Reinforcement

Weld metal that extends beyond the surface or plane of the weld joint.
Specifically defined by the standard. Typically, Reinforcement should be flush to 1/16(pipe) or flush to 1/8” (plate or structural shapes) [67].

a. Causes:

- Amperage too low;
- Too slow electrode manipulation;
- Too much root opening (root reinforcement) [67] [51].

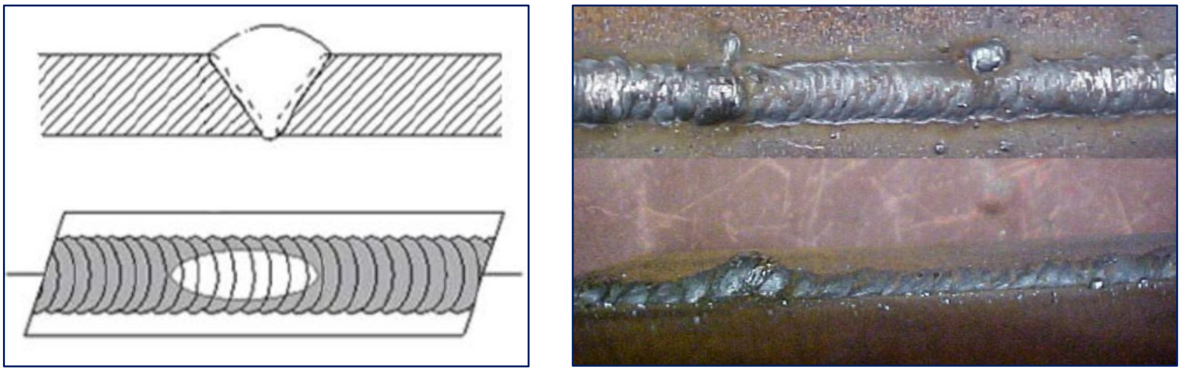


Fig. 2.8. Excessive Reinforcement [70]

b. Prevention measures:

- Use appropriate welding amperages;
- Manipulate electrodes at appropriate speeds;
- Control the electrode displacement (see the above drawings) [21].

c. Remedies:

Remove excessive reinforcement and make smooth transition from weld toes to base metal [67].

2.1.10. Insufficient Reinforcement

Specifically defined by the standard. Typically, Underfill may be up to 5% of metal thickness, not to exceed 1/32” as long as the thickness is made up in the opposite reinforcement. Not applied to fillet welds [67].

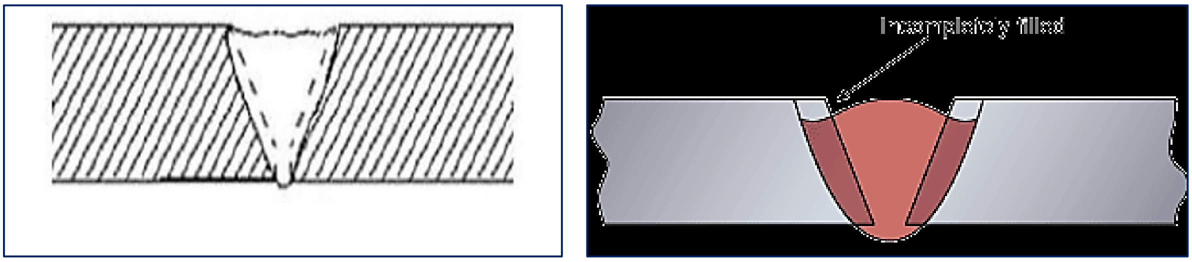


Fig. 2.9. Insufficient Reinforcement [67]

a. Causes:

On root reinforcement -Too little filler metal will cause thinning of the filler metal. In OH position, too hot or too wide will cause drooping of the open root puddle [67].

b. Prevention measures:

- Use proper welding technique;
- Use backing or consumable inserts;
- Use back weld or backing [21].

c. Remedies:

Possibly simply increase the face reinforcement. If back welding is not possible, must remove and reweld [67].

2.1.11. Slag Inclusion

Slag is formed by reaction with the fluxes and is generally lighter.
It has low density. So it will float on the top of the weld pool. And would chipped off after solidification.
However, the stirring action of the high-intensity arc would force the slag to go into weld pool and if there is not enough time for it to float, it may get solidification inside the fusion and end up as slag inclusion [49].

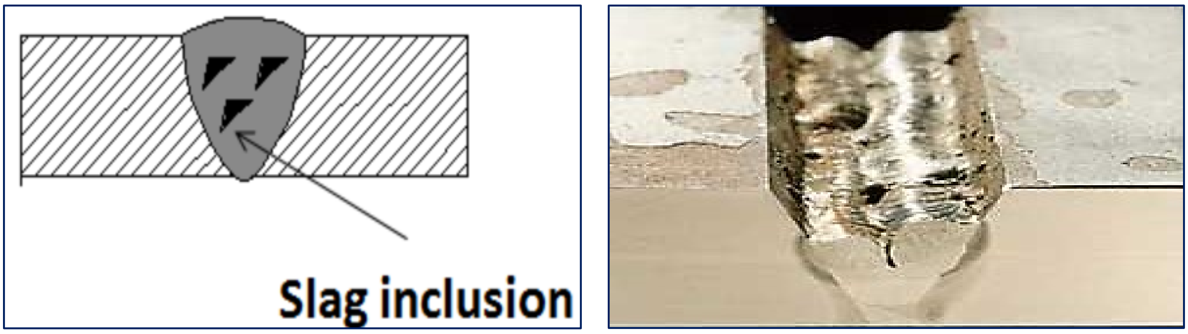


Fig. 2.10. Smooth weld bead profile allows the slag to be readily removed between passes [55] [71]

a. Causes:

- Use of forehead welding technique in welding;
- Incorrect select of flux powder;
- Improper cleaning of the weld beads in multi-pass welding;
- Undercut on the previous pass;
- Incorrect manipulation of the electrode. Slag inclusion like property weakens the metal by providing the discontinuities;
- Small welding current density, as it does not provide the required amount of heat for melting the metal surface;
- Too fast welding speed;
- Improper welding angle and travel rate of welding rod [49] [55].

b. Remedies:

- Increase the current density;
- Adjust the welding speed so that the slag and weld pool do not mix with each other;
- Clean the weld edges and remove the slags of previous weld layers;
- Have a proper electrode angle and travel rate [55].

Slag inclusions in MMAW can occur at the weld root; between weld runs, or on the weld surface. They generally occur in MMAW as a result of low amperage, poor electrode manipulation, working on dirty or contaminated metal, or incorrect joint preparation [50].

2.1.12. Blowholes defect

Blowholes are large holes in weld [66]**.**

a. Causes:

- Gas being trapped, because of the moisture;
- Contamination of either the filler or parent metals [66].

2.1.13. Cracking

Cracking is considered to be a serious weld fault and rarely is any amount of cracking tolerated. Cracks may be described depending on how, when and where they occur, eg longitudinal, transverse, crater, centre line, hot, cold, toe and underbead. Cracks may occur in either the parent metal, usually as fusion or heat affected zone cracks, or in the weld metal [66] [50].

a. Hot cracking: Appear during or immediately after welding and usually occurs in metals that are hot, short and/or have high rates of thermal expansion. Hot cracking most commonly occurs in the weld metal with the most common examples being longitudinal and crater cracks are formed when the weld bead cannot withstand the stresses unleashed by solidification. Cracking starts during or immediately after welding and the crack surface is blue.)

b. Cold cracking: or Induced Cracks (HIC): show up a day or so after welding Most commonly occurs in the base metal adjacent to the fusion zone.The most common example of this is underbead cracking in hardenable steels.

c. Crater cracks: pop up at the end of the weld bead if you incorrectly break the arc these come from hot shrinkage. The crater solidifies around all sides toward the centre, leading to a high concentration of stress at the centre of the crater. If the metal lacks ductility, or the hollow crater cannot accommodate the shrinkage, cracking may result. Crater cracks may, under stress, spread from the crater and lead to failure of the weldment. Is a peculiar crack that appears at the end of the weld where the arc is broken. Small and apparently innocuous, it is dangerous because it can spread into the weld joint.

d. ***Micro-fissures:*** make their presence felt long after you complete the weld. Metal fatigue, seismic activity, or stresses in the heat affected zone (HAZ) create these fissures. Heat treatment restricts them [73] [50].

e. ***Underbead crack:*** An underbead crack, also known as a heat-affected zone (HAZ) crack, [74] is a crack that forms a short distance away from the fusion line; it occurs in low alloy and high alloy steel. The exact causes of this type of crack are not completely understood, but it is known that dissolved hydrogen must be present. The other factor that affects this type of crack is internal stresses resulting from: unequal contraction between the base metal and the weld metal, restraint of the base metal, stresses from the formation of martensite, and stresses from the precipitation of hydrogen out of the metal [75].

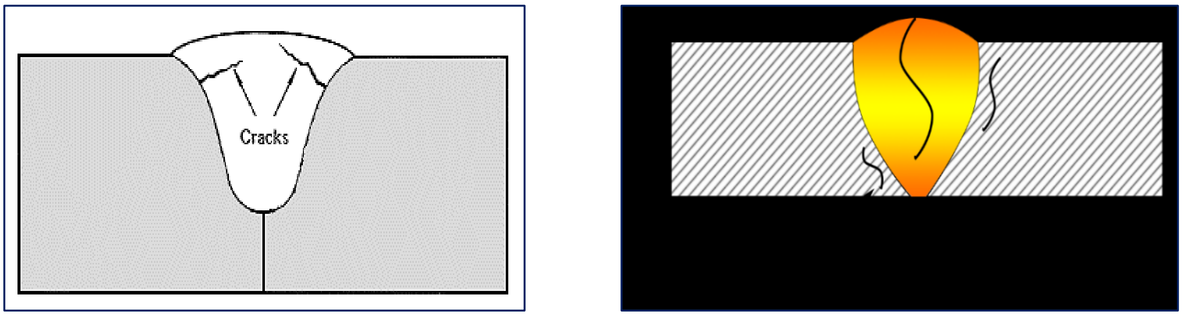


Fig. 2.20. Cracks in Welded Joints [76]

a. Causes of the Cold Crack Defect:

- Susceptible microstructure (e.g. martensite);
- Hydrogen present in the microstructure (hydrogen embrittlement);
- Service temperature environment (normal atmospheric pressure): -100 to +100 °F;
- High restraint [72].

b. Causes of the Crack Defect:

- Poor ductility of the given base metal;
- The presence of residual stress can cause a crack on the weld metal;
- The rigidity of the joint which makes it difficult to expand or contract the metals;
- If there is high content on sulfur and carbon then also the cracks may appear;
- Using hydrogen as a shielding gas while welding ferrous materials [55].

c. Remedies for the Crack Defect:

- Using appropriate materials may decrease the chances of crack;
- Preheating the weld and reducing the cooling speed joint helps in reducing crack;
- Reduce the gap between the weld joints by using reasonable weld joints;
- While welding releases the clamping force slowly which increases fill to capacity of welding material [55].

2.2. Discontinuities Encountered with Welding Processes

Table 2. 1. Discontinuities Commonly Encountered with Welding Processes

Welding Process	Porosity	Slag	Incomplete Fusion	Incomplete Penetration	Undercut	Overlap	Cracks
SW (Stud welding)	X		X		X		X
PAW(Plasma arc welding)	X		X	X	X		X
SAW (Submergedarc welding)	X	X	X	X	X	X	X
TIG (tungsten inert gas welding)	X		X	`X	X		X
EGW (Electrogas welding)	X		X	X	X	X	X
GMAW (Gas metal arc welding)	X		X	X	X	X	X
FCAW (Flux cored arc welding)	X	X	X	X	X	X	X
MMA (Manual Metal Arc Welding)	X	X	X	X	X	X	X
CAW (Carbonarc welding)	X	X	X	X	X	X	X
EBW (Electron beam welding)	X		X	X			X
ESW (Electroslag welding)	X	X	X	X	X	X	X
IW (Induction welding)			X				X
LBW (Laser beam welding)	X		X	X			X
TW (Thermite welding)	X	X	X				X

2.3. Conclusion

In order to evaluate the weldments, the inspector should have the ability to identify the discontinuities generated by welding. Discontinuities can be grouped into three classes, related to shape, size, and contour, which are the external dimensions of weld. If the filler metal does not match the base metal properties or the welding procedure is not appropriate or it is wrongly performed because of the non/qualified welder, then, the imperfections and discontinuities will appear in the welded structures. Even if there are technical solutions to remedy them, still the prevention and mitigation of the risks have to be taken into account in order to achieve a good quality welded joint.

CHAPTER 3.

Quality Assurance and Control of Welded Structures

3.1. Introduction

Weld quality assurance is, an important and necessary step that use the technological methods and actions to test or ensure weld satisfactory performances (the quality of welds), and secondarily to confirm the presence, location and coverage of welds. Because the connections between two or more metal surfaces may encounter loads and fatigue during product lifetime, there is a chance they may fail if not created to proper specifications. Various test procedures are followed to perform a weld inspection, like non-destructive testing procedures (NDT), which helps to evaluate the weld without causing any damage [77] [78]. Many characteristics of a weld can be evaluated during welding inspection - some relating to weld size, and others relating to the presence of weld discontinuities. The size of a weld can be extremely important, as it often relates directly to the weld's strength and performance. For instance, undersized welds may not withstand stresses applied during service [79]. Performance & longevity of welded structure in service depends on the presence or absence of defects in weld joints.

3.2. Non-destructive Testing

3.2.1. Generalities

Non-destructive Examination (NDE) or (Non-destructive testing (NDT)) is a general term used to identify the process of inspecting, testing, or evaluating materials, components or assemblies for discontinuities, or differences in characteristics without destroying the serviceability of the part or system.

Non-destructive Examination (NDE) Non-destructive Inspection (NDI), and Non-destructive Testing (NDT) are synonymous terms also used to identify these evaluation methods. The majority of prospective weld inspectors already know that visual examination certainly meets this criterion, but there are other NDE inspection methods.

In contrast to NDT, other tests are destructive in nature and are therefore done on a limited number of samples ("lot sampling"), rather than on the materials, components or assemblies actually being put into service [80] [81].

Some of the most conventional NDT methods used today are visual inspection, magnetic particle testing, liquid penetrant testing, ultrasonic testing, and radiography.

3.2.2. Inspection by Visual Examination

Visual inspection is often the most cost-effective method, for many types of welds, integrity is verified principally by visual examination, but it must take place prior to, during and after welding, even for weldments with joints specified for examination throughout by other non-destructive examination methods, visual examination is performed, because there is no point in submitting an obviously bad weld to sophisticated inspection techniques so many standards require its use before other methods as well as the ANSI/AWS D1.1, Structural Welding Code - Steel, states, "Welds subject to Non-destructive examination shall have been found acceptable by visual inspection." [82] [83]. The Visual Examination of the welds shall be performed before, during and after welding. Uniformity of surface, cleanliness & sharp edges can be checked on final completion of fabrication.

a. Principle

Visual examination includes either the direct or indirect observation of the exposed surfaces of the weld and base metal.

b. Direct Visual Examination

It is conducted when the access is sufficient to place the eye within 6 in. – 24 in. (150 mm – 600 mm) of the surface to be examined and at an angle not less than 30 degrees to the surface. Mirrors may be used to improve the angle of vision [84].

c. Direct Inspection

Direct inspection is employed when access is sufficient to place the eye within 6 in. – 24 in. (150 mm – 600 mm) of the surface to be examined and at an angle not less than 30 degrees to the surface Mirrors shall be used, when deemed necessary to improve the angle of vision, and aids such as a magnifying lens may be used to assist examinations [84].

d. Remote Visual Examination

May be substituted for direct examination. Remote examination may use visual aids such as telescopes, bore scopes, fiberscopes, cameras or other suitable instruments, such systems shall have a resolution capability at least equivalent to that obtainable by direct visual observation. In either case, the illumination should be sufficient to allow resolution of fine detail. These illumination requirements are to be addressed in a written procedure [85].

e. Equipment Requirements

Visual inspection equipment and consumables enable the test to be carried out correctly. These include a digital camera, measuring rules and tapes, torch, markers, weld profile and undercut gauges, mirrors, borescopes and photometer. Complex equipments like fibre optic connectors can be used for close visual inspections, where the device is used to access small holes or channels. Visual inspection reveals flaws that may or may not be detrimental to the quality of the weld. However, an inspector's aim should, at all times, be to find and report all significant flaws [86].

ASME Section V, Adrticle 9, (Paragraph T-940) lists requirements for visual examination. Codes and specifications may list compliance with these requirements as mandatory. Some requirements listed in this article include:

- A written procedure is required for examinations.
- The minimum amount of information that is to be included in the written procedure.
- Demonstration of the adequacy of the inspection procedure.
- Personnel are required to demonstrate annually completion of J-1 Jaeger-type eye vision test.
- Direct visual examination requires access to permit the eye to be within 6 in. – 24 in. (150 mm – 600 mm) of the surface, at an angle not less than 30 degrees.
- The minimum required illumination of the part under examination.
- Indirect visual examination permits the use of remote visual examination and devices employed.
- Evaluation of indications in terms of the acceptance standards of the referencing code.

Advantages	**Disadvantages**
Inexpensive highly portable	Surface only generally only large discontinuities
Immediate results	Misinterpretation of scratches [27].
Minimum training	
Minimum part preparation [27].	

3.2.3. Liquid Penetrant Testing (PT)

Liquid penetrant examination, often called dye penetrant or penetrant testing (PT), is capable of detecting surface-connecting discontinuities in ferrous and nonferrous alloys and find surface breaking defects. Liquid penetrant examination can be used to examine the weld joint surfaces, intermediate checks of individual weld passes, and completed welds. PT is commonly employed on austenitic stainless steels where magnetic particle examination is not possible [87]. The principle of this method is well explained below.

a b

Fig. 3.1. Liquid Penetrant Materials and Application [88] [89]

a. Principle

- A typical colour contrast procedure involves preparing the surface to remove any spatter, slag or other imperfections that could retain the penetrant and mask relevant indications.
- The surface is then cleaned, using the cleaner, to remove any surface oil or grease, which could prevent the red liquid penetrant being drawn into surface breaking cracks or indications. It is then dried using air or lint free cloths.
- The dye penetrant fluid is painted or sprayed on the area to be examined and left for a dwell time as specified in the procedure. This dwell time must be long enough to enable the fluid to penetrate into any defects such as cracks and crevices by capillary action and the surplus is removed using cloths dampened with the cleaner than a solvent-based powder suspension (developer) is normally applied by spraying. The cleaner must not be sprayed directly on to the component otherwise penetrant could be washed out of relevant indications.
- Any indication highlighted by the red penetrant against the white developer can then be assessed. In effect, PT is a form of enhanced visual technique that is often used to confirm visual uncertainties. Viewing is done under good lighting conditions of 1000 lux (100 ft candles).
- The surface can also be viewed under ultraviolet light in darkened conditions, when the fluorescent penetrant glows, indicating the crack. Surface scratches may mask the result and penetrant contamination of the crack occurs but the method is used as an addition to X-ray or gamma-ray inspection
- During PT, the test surface is cleaned and coated with a penetrating liquid that seeks surface-connected discontinuities.
- After the excess surface liquid penetrant is removed, a solvent-based powder suspension (developer) is normally applied by spraying. The liquid in any discontinuity bleeds out to stain the powder coating. An indication of depth is possible if the Inspector observes and compares the indication bleed out to the opening size visible at the surface.
- The greater the bleed out to surface opening ratio, the greater the volume of the discontinuity [90] [84].
- A limitation of PT is that standard penetrant systems are limited to a maximum of 125°F (52°C) so the weld must be cool which significantly slows down the welding operation.
- High-temperature penetrant systems can be qualified to extend the temperature envelope [90] [84].

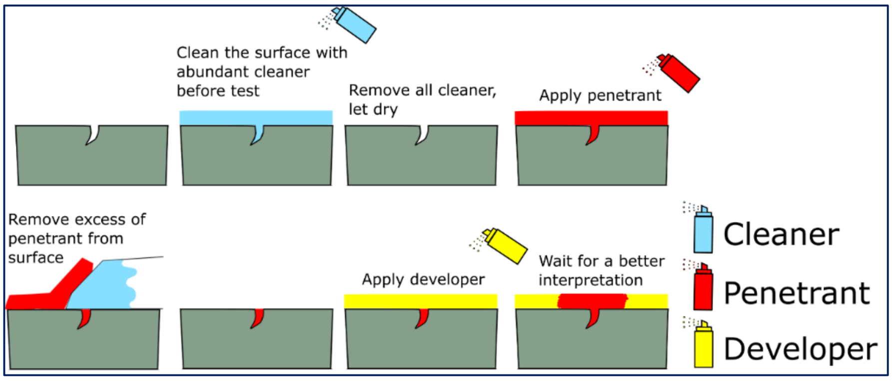


Fig. 3.2. Liquid Penetrant Testing Application [91]

Advantages	**Disadvantages**
Portable and inexpensive;	Locate surface defects only rough or porous surfaces;
Sensitive to very small discontinuities;	Interfere with test part preparation required (removal of finishes and sealant, etc.);
30min, or less to accomplish;	High degree of cleanliness required;
Minimum skill required [27].	Direct visual detection of results required [27].

3.2.4. Radiographic Testing (RT)

Radiography (X-ray) is a method of non-destructive examination that utilizes radiation to penetrate an object to determine internal soundness of the welds and record images on a variety of recording devices such as film or photosensitive paper, be viewed on a fluorescent screen, or be monitored by various types of electronic radiation detectors.

When an object to be examined is exposed to penetrating radiation, some radiation will be absorbed, some will be scattered, and some radiation will be transmitted through the test object onto the recording device. Radiation will be differentially absorbed over various areas of the test object. The term "X-ray quality," widely used to indicate high quality in welds, arises from this inspection method [82] [83].

a. Principle

In radiographic testing, the principle is based on the ability of X-rays and gamma rays to pass through metal and other materials opaque to ordinary light, and produce photographic records of the transmitted radiant energy, the part to be inspected is placed between the radiation source and a piece of radiation sensitive film. The radiation source can either be an X-ray machine *or a radioactive source.* All materials will absorb known amounts of this radiant energy depending on their density, thickness and atomic number, and, therefore, X-rays and gamma rays can be used to show discontinuities and inclusions within the opaque material. When X-rays or gamma rays are directed at a section of weldment, not all of the radiation passes are through the metal. Different materials. *The radiation that passes* through the part will expose the film and forms a shadowgraph of the part. The film darkness (density) will vary with the amount of radiation reaching the film through the test object where darker areas indicate more exposure (higher radiation intensity) and lighter areas indicate less exposure (lower radiation intensity [82] [92].

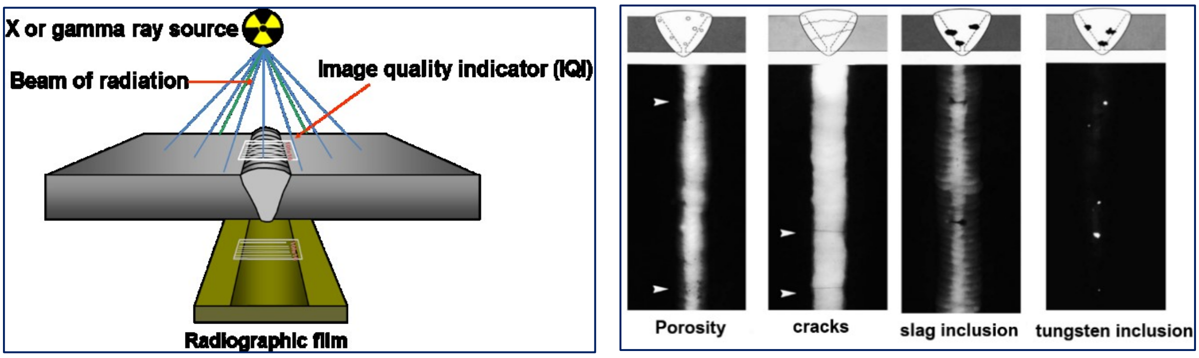


Fig. 3.3. Radiography Testing Application and Result [93]

b. *Essential Elements*

The basic process of radiographic examination involves the production of the radiograph, and the interpretation of the radiograph. The essential elements needed to carry out these two operations consist of the following [83]:

- A source of radiation (usually gamma or x-rays) and associated accessories;
- An object to be radiographed (weldment);
- An x-ray film enclosed in a lightproof film holder (cassette);
- A trained person to produce an acceptable radiograph;
- A means of chemically processing the exposed film;
- A person certified to interpret the radiographic images using adequate viewing devices.

To be sure that a radiographic exposure produces acceptable results, a gauge known as an Image Quality Indicator (IQI) is placed on the part so that its image will be produced on the radiograph. IQI's used to determine radiographic quality are also called penetrameters. A standard hole-type penetrameter is a rectangular piece of metal with three drilled holes of set diameters. The thickness of the piece of metal is a percentage of the thickness of the specimen being radiographed. The diameter of each hole is different and is a given multiple of the penetrameter thickness. Wire-type penetrameters are also widely used, especially outside the United States. They consist of several pieces of wire, each of a different diameter. Sensitivity is determined by the smallest diameter of wire that can be clearly seen on the radiograph. A penetrameter is not an indicator or gauge to measure the size of a discontinuity or the minimum detectable flaw size. It is an indicator of the quality of the radiographic technique.

c. *Remarques*

- An X-ray image of the interior of the weld may be viewed on a fluorescent screen, as well as on developed film. This makes it possible to inspect parts faster and at a lower cost, but the image definition is poorer. Computerization has made it possible to overcome many of the shortcomings of radiographic imaging by linking the fluorescent screen with a video camera. Instead of waiting for film to be developed, the images can be viewed in real time. This can improve quality and reduce costs on production applications such as pipe welding, where a problem can be identified and corrected quickly.

- By digitizing the image and loading it into a computer, the image can be enhanced and analysed to a degree never before possible. Multiple images can be superimposed. Pixel values can be adjusted to change shading and contrast, bringing out small flaws and discontinuities that would not show up on film. Colors can be assigned to the various shades of gray to further enhance the image and make flaws stand out better. The process of digitizing an image taken from the fluorescent screen - having that image computer enhanced and transferred to a viewing monitor - takes only a few seconds. However, because there is a time delay, we can no longer consider this "real time." It is called "radioscopy imagery.
- Existing films can be digitized to achieve the same results and improve the analysis process. Another advantage is the ability to archive images on laser optical disks, which take up far less space than vaults of old films and are much easier to recall when needed.

Advantages	**Disadvantages**
Detects surface and internal flaws;	Safety hazard;
Can inspect hidden areas;	Very expensive (slow process);
Permanent test record obtained;	Sensitive to flaw orientation;
Minimum part preparation [27].	High degree of skill and experience required;
	Depth of discontinuity not indicated [27].

3.2.5. Ultrasonic Testing (UT)

Ultrasonic testing is a Non-destructive method used to detect, locate, and evaluate internal defects within a weld or body of a component being tested. A probe employs waves above the frequency limit of human audibility and usually in the frequency range 0.6 to 5 MHz that is passed through the material of the specimen under test. If this sound wave hits a defect then all or part of it gets rebounded back to a receiver in the probe and the size and position of the defect can be plotted on a graph by a skilled operator. The sound is collected by the instrument, amplified and displayed as a vertical trance on a video screen shows the arrangement [87] [90].

Fig. 3.4. Ultrasonic Testing [94] [95]

a. Principle

Angled probes send the wave into a weld at angles suitable for the weld preparation bevel angles used. A zero degree 'compression' probe is used first to check for any laminations in the parent material that could deflect angled waves and mask defects in the weld. The surface of the component must be clean and smooth and a couplant applied to exclude air from between the probe and component. The couplant must be suitable for use on the material being tested and then be thoroughly cleaned off afterwards to prevent any risk of corrosion or degradation of the component in service. Wallpaper paste is often used as a couplant because when it dries it can be easily peeled off.

- The most common sound frequencies used in UT are between 1.0 and 10.0 MHz, which are too high to be heard and do not travel through air. The lower frequencies have greater penetrating power but less sensitivity (the ability to "see" small indications), while the higher frequencies don't penetrate as deeply but can detect smaller indications.

- The two most commonly used types of sound waves used in industrial inspections are the compression (longitudinal) wave and the shear (transverse) wave. Compression waves cause the atoms in a part to vibrate back and forth parallel to the sound direction and shear waves cause the atoms to vibrate perpendicularly (from side to side) to the direction of the sound. Shear waves travel at approximately half the speed of longitudinal waves.

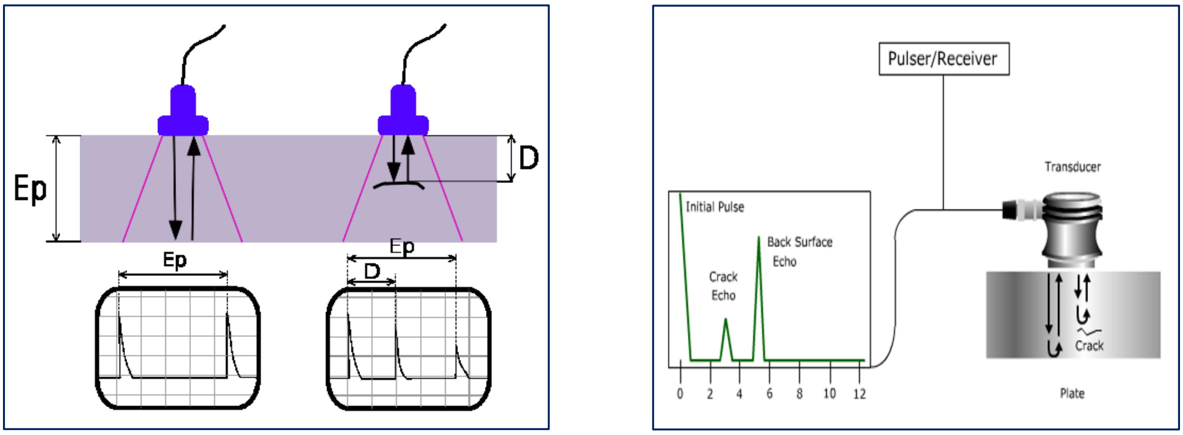


Fig. 3.5. Example of Ultrasonic Testing [96] [97]

Advantages	**Disadvantages**
Can find linear type defects in most orientations; Is portable; Is safe and therefore does not require production to be stopped or the area cleared [87].	Surfaces must be smooth and free of all spatter and arc strikes; Very dependent on skill of the operator; Normally limited to materials above 6 mm thick; Basic technique does not give a permanent record [87].

3.2.6. Magnetic Particle Testing (MT)

Magnetic particle testing is a non-destructive method of detecting mainly surface breaking defects in ferromagnetic materials. This method will detect surface discontinuities including those that are too fine to be seen with the unaided eye, so it is possible to find slightly subsurface defects (although sensitivity is reduced and the method should not be relied on to detect these discontinuities) when used with a permanent magnet or d.c. electromagnet. A magnetic flux (or field) is introduced into the material and any defects cutting across the magnetic flux can be detected when ink or powders containing ferromagnetic particles (iron filings) are applied to the material. What happens is that a flux leakage occurs at the defect, which effectively makes the defect a magnet in its own right. This 'magnet' attracts the ferromagnetic particles, which take the shape of the defect [87].

a. Principle

In this process, the weld (and heat-affected zone) is locally magnetized, creating a magnetic field in the material. Ferromagnetic particles are then applied to the magnetized surface and are attracted to any breaks in the magnetic field caused by discontinuities [84].

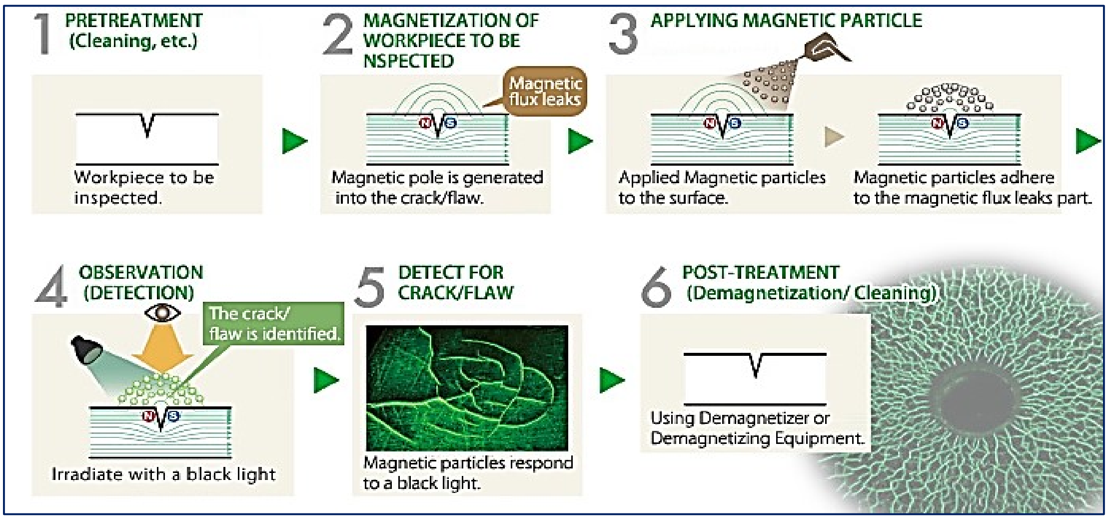


Fig. 3.6. Magnetic Particle Testing Procedures [98]

The magnetic flux can be introduced from:

- A permanent magnet;
- An electromagnet (either AC or DC);
- Electric prods (either AC or DC.) between which a current flows (and the current flow is surrounded by a magnetic field) [87].

Ferromagnetic particles can be applied to the material as:

- A black ink (viewed against a pre-applied white contrast paint);
- Fluorescent ink (viewed under UV light conditions);
- Red or blue dry powders (used at higher temperatures) [87].

The magnetic flux is applied in two mutually perpendicular directions. The reason for this is that if the flux direction runs parallel to the defect then magnetisation of the defect will not take place and the ferromagnetic particles will not be attracted to it. Testing in two directions it is ensured that the flux cuts any linear defects by at least 45°. The magnetic field can be checked using a checker such as a ‘pie gauge’ or ‘burma astrol strip’.

This technique is not a substitute for radiography or ultrasonic in locating subsurface discontinuities, but may present advantages in locating tight cracks and surface defects. It may often be employed to advantage in cases where the application of radiography or ultrasonic is neither available nor practical because of the geometry or position of the weld [82].

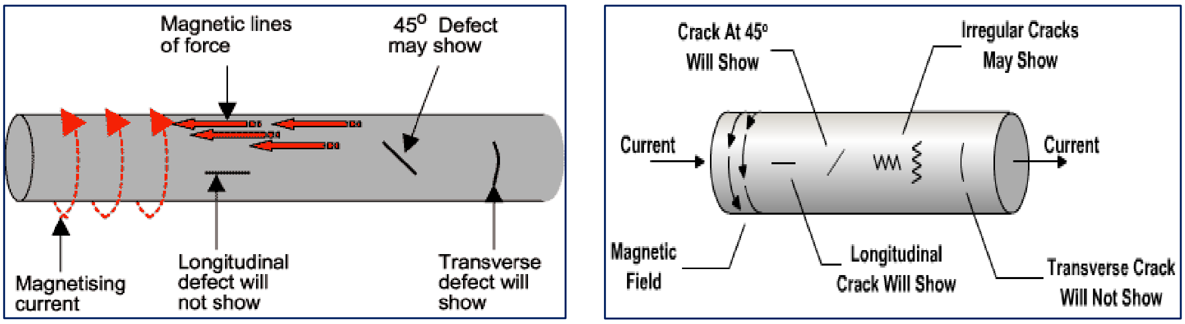


Fig. 3.7. Magnetic Particle Testing for Different Cracks [99] [100]

b. MPI inspection steps:

- Pre-cleaning;
- Demagnetisation, if necessary;
- Application of a background contrast paint if necessary;
- Magnetisation;
- Application of magnetic particle powders or inks;
- Inspection of surfaces for indications of flaws;
- Demagnetisation, and re-magnetisation by another method if necessary;
- Recording flaws, if any;
- Demagnetisation, if necessary;
- Cleaning and protecting [101].

Advantages	**Disadvantages**
Quick and simple to use;	Can only be used on ferromagnetic materials;
Can find slightly subsurface defects (under certain conditions);	Cannot be used on austenitic stainless steels (nonmagnetic);
Portable when permanent magnets used [87].	Electric prods can cause arc strikes;
	The component may need demagnetising on completion of testing [87].

ASME Section V, Article 7, (Paragraph T-750) lists requirements for magnetic particle examination. Some codes and specifications may list compliance with these requirements as being mandatory. ASME B31.3 and ASME Section VIII, Division 1, requires magnetic particle examination be performed in accordance with Article 7. Some of the requirements listed in this article include:

A. Examination procedure information.
B. Use of a continuous method.
C. Use of one of five magnetization techniques.
D. Required calibration of equipment.
E. Two examinations perpendicular to each other.
F. Maximum surface temperature for examination.
G. Magnetization currents.
H. Evaluation of indications in terms of the acceptance standards of the referencing code.
I. Demagnetization.
J. Minimum required surface illumination (visible or blacklight) of the part under examination.

3.2.7. Eddy Current Inspection (ET)

Electromagnetic testing was formerly called eddy current (electric current) testing which is a Non-destructive examination. Based on the principle that an electric current will flow in any conductor subjected to a changing magnetic field. Eddy current inspection is used to detect surface discontinuities, and in some cases subsurface discontinuities in tubing, pipe, wire, rod and bar stock. ET has limited use in weld inspection. Eddy current can be used as a quick test to ensure that the components being joined during welding have the same material properties, and as a quick check for defects of the weld joint faces. It can also be used to measure the thickness of protective, nonconductive surface coatings and measure cladding thickness. Test frequencies vary from 50 Hz to 1 MHz, depending on the type and thickness of material and the application [84] [82].

a. Principle

Non-destructive examination by electromagnetic methods uses a magnetic field to create circulating currents (eddy or Foucault currents) in electrically conductive material (test piece) and measuring the changes caused in those currents by discontinuities or other physical differences in the test piece c. Discontinuities in the material will alter the magnetically induced fields and present them on the unit's display. As with the magnetic particle inspection, this technique is most sensitive for defect detection when the currents are perpendicular to the discontinuity. Thus, such examinations can be used not only to detect discontinuities but also to measure variations in test piece dimensions and resistivity. Since resistivity is dependent upon such properties as chemical composition (purity and alloying), crystal orientation, heat treatment, and hardness, these properties can also be determined indirectly [82].

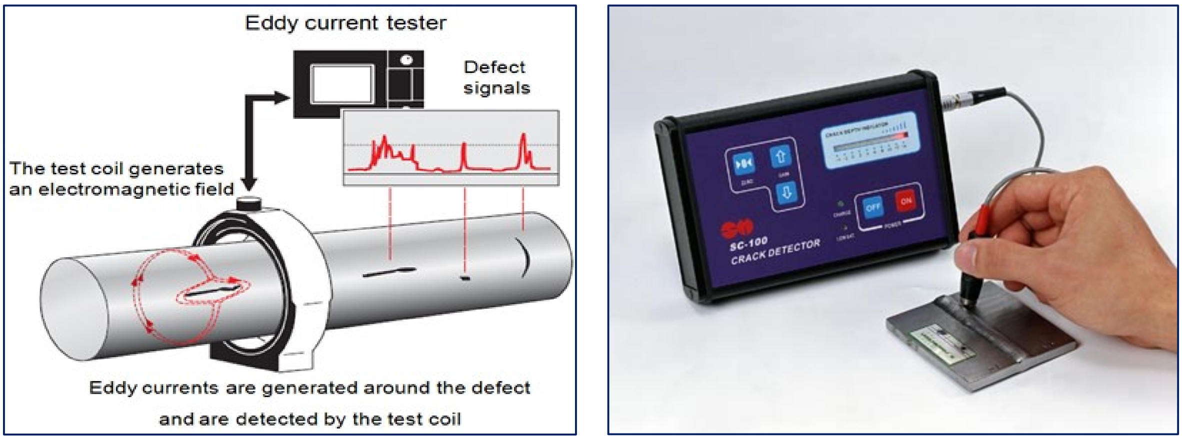


Fig. 3.8. Eddy Current Testing **[102] [103]**

Advantages

Sensitivity to surface defects;
Can detect through several layers: The ability to detect defects in multi-layer structures (up to about 14 layers), without interference from the planar interfaces;
Can detect through surface coatings (in excess of 5mm thickness);
Can be automated;
Little pre-cleaning required;
Portability [104].

Disadvantages

Very susceptible to magnetic permeability changes;
Only effective on conductive materials;
Will not detect defects parallel to surface;
Not suitable for large areas and/or complex geometries;
Signal interpretation required;
No permanent record (unless automated) [104].

3.3. Welding Quality Control

A weld is considered to be "in quality" if it can meet, and continue to meet, the intended requirements. Which can be assured using a good NDE inspection program that recognize the inherent limitations of each process. For example, both radiography and ultrasound have distinct orientation factors that may guide the choice of which process to use for a particular job. Their strengths and weaknesses tend to complement each other. While radiography is unable to reliably detect lamination-like defects, ultrasound is much better at it. On the other hand, ultrasound is poorly suited to detecting scattered porosity, while radiography is very good , and that' For instance, "*A good weld is any weld which does what it is intended for during the service of the structure*" (Miller, 1997). If the quality of a weld is better than aforementioned, it may increase the cost without any added benefit (Schwartz, 1985) [83] [105].

The Lincoln Electric Company suggests the five "PS" to achieve a quality weld as follows:

1. Process selection. The process must be right for the job.
2. Preparation. The joint configuration must be correct and compatible with the welding process.

3. Procedures. To assure uniform results, the procedures must be spelled out and they must be followed.
4. Pretesting. By full scale mockups on simulated specimens, the process and procedures are proven to give the desired standard quality.
5. Personnel. Qualified people must be assigned to the job [83].

"*The five P's are important in that their requirements must be met long before any inspection will take place*" (Schwartz, 1985). Whatever inspection techniques are used, paying attention to the "Five P's" of weld quality will help reduce subsequent inspection to a routine checking activity. Then, the proper use of NDE methods will serve as a check to keep variables in line and weld quality within standards [83] [105].

3.3.1. Advantages and Limitations of the Examination Method.

The advantages and limitations of the examination method help to determine which method is best for detecting discontinuities of a particular size, shape, and orientation. For example, radiography can detect discontinuities with major planes aligned parallel with the radiation beam, such as cracks oriented normal to material surfaces. Radiography, however, usually cannot detect laminations in material or cracks oriented parallel to the plate surface. Conversely, ultrasonic examination can detect cracks oriented in any direction provided the sound beam is oriented essentially perpendicular to the major axis of the crack [82].

3.3.2. Acceptance Standards

The statement "the weld shall be radiographically examined" is incomplete unless acceptance standards are specified. Acceptance standards define characteristics of discontinuities and state whether particular types of discontinuities are allowed. Certain discontinuities such as slag or porosity may be acceptable providing their size and distribution are within specified limits. These criteria have to be incorporated in the acceptance standards. A few acceptance criteria are mentioned in the last chapter "chapter 2" [82].

Table 3. 1. Quality levels for weld imperfections in ISO 5817

Level symbol	Quality level
D	Moderate
C	Intermediate
B	Stringent

Most codes and specifications such as AWS D1.1, *Structural Welding Code—Steel*, ASME *Boiler and Pressure Code*, contain acceptance standards. These and other construction standards are shown in the table below:

Table 3.2. Standards used in the welding industry for fabrication and examination or inspection

Category	Society	Title
Pressure Vessel	American Society of Mechanical Engineers (ASME) Three Park Avenue New York, NY 10016	Boiler and Pressure Vessel Code, Section V, Non-destructive Examination
Piping	American Society of Mechanical Engineers (ASME) Three Park Avenue New York, NY 10016 American Petroleum Institute (API) 1220 L Street N.W. Washington, DC 20005	B31.1—Power Piping B31.3—Chemical Plant and Petroleum Refinery Piping B31.4—Liquid Petroleum Transportation Piping Systems Standard 1104—Standard for Welding of Pipelines and Related Facilities API-RP-2X—Recommended Practice for Ultrasonic and Magnetic Examination of Offshore Structural Fabrication and Guidelines for Qualification of Technicians
Structural	American Welding Society (AWS) 550 N.W. LeJeune Road Miami, FL 33126 American Institute of Steel Construction (AISC) 400N. Michigan Avenue Chicago, IL 60611	D1.1—Structural Welding Code—Steel D1.2—Structural Welding Code—Aluminium D1.3—Structural Welding Code—Sheet Steel D1.4—Structural Welding Code—Reinforcing Steel D1.5—Bridge Welding Code D1.6—Structural Welding Code—Stainless Steel D9.1—Sheet Metal Welding Code D3.6—Specification for Underwater Welding D14.3—Specification for Welding Earthmoving, Construction, and Agricultural Equipment. D15.1—Railroad Welding Specification for Cars and Locomotives QC1—Standard for AWS Certification of Welding Inspectors QC2—Recommended Practice for Training, Qualification, and Certification of Welding Inspector Specialist and Welding Inspector Assistant Quality Criteria and Inspection Standards, 2nd Edition, Specifications for the Designing, Fabrication, and Erection of Safety Related Structures for Nuclear Facilities

Category	Society	Title
Shipbuilding	American Bureau of Shipping (ABS) Two World Trade Center 106th Floor New York, NY 10048	Rules for Building and Classing Steel Vessels, Section 43
Military	Naval Publication and Forms Center 5801 Taber Avenue Philadelphia, PA 19120	Navy NAVSEA S9074-AQ-GIB-010/248 Requirements for Welding and Brazing Procedure and Performance Qualification. Navy NAVSEA S9074-AR-GIB-010/278 Requirements for Fabrication Welding and Inspection, and Casting Inspection and Repair for Machinery, Piping and Pressure Vessels. Navy NAVSEA T9074-AS-GIB-010/271, Requirements for Nondestructive Testing Methods. MIL STD 2035, Nondestructive Testing Acceptance Criteria MIL STD 1689, Fabrication, Welding and Inspection of Ships Structure.

3.3.3. Quality Control and Quality Assurance

a. Quality Control (QC)

Is the process of ensuring that the quality of a product or service has met certain predetermined standards. QC involves preventing defects in the finished products after they have been developed or manufactured [106].

b. Quality Assurance (QA)

It is a process used to control and improve the product or service development to ensure it will meet all specifications and requirements. QA involves improving the product development and manufacturing process, rather than looking at the end products themselves [107].

c. Influence of Quality Assurance (QA) and Quality Control (QC)

More recent standards specify three levels of quality assurance, which permits, when selecting the extent of testing, to give consideration also to the level of quality assurance achieved by the performer of welding work. The welded-joint quality (Q) may be defined as a sum of quality assurance (QA) and quality control (QC) [108]. The maximum quality in the instance selected may be achieved if all means of quality assurance available are taken into account and all NDT methods available are applied.

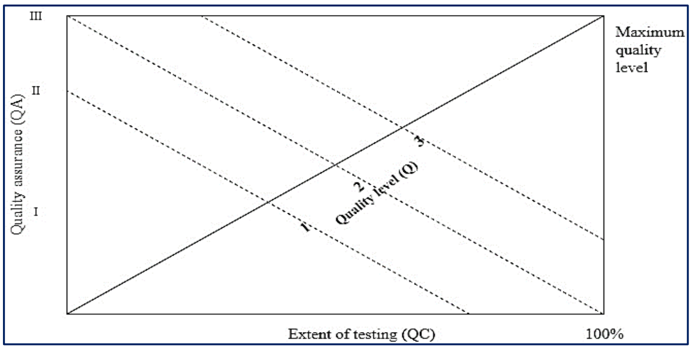


Fig. 3.9. Ratio Between Quality Assurance (QA) and Quality Control (QC) [108]

Table 3.3. Extent of testing as a function of QA and requirements [108]

QA level	**Requirements**		
	Low	**Medium**	**High**
III	0%	25%	50%
II	0%	50%	75%
I	25%	75%	100%

Table 3.4. Survey of Testing Methods Specified [108]

Field of application	**Level of requirements**	**Extent and method of testing**
Steam boilers and steam superheaters	-	30 % RT
Steel structures	S I II	100 % RT, MT and PT if required 10-50 % RT, MT and PT if required RT of out-of-position welds
Pipelines JUS C.T3.010	I II III IV	100% RT or VT, 100 % MT or PT 50 % RT or VT, 100 % MT or PT 10 % RT or VT, 30 % MT or PT -
Pressure vessels	I II A II B III A III B IV A IV B I c II c I D II D III D	100 % RT or VT, 100 % MT or PT 70 % RT or VT, 100 % MT or PT 50 % RT or VT, 100 % MT or PT 30 % RT or VT, 30 % MT or PT 10 % RT or VT, 30 % MT or PT no requirements 30 % MT or PT 100 % UT, 100 % MT or PT 50 % UT, 50 % MT or PT 100 % UT, 100 % MT or PT 70 % UT, 100 % MT or PT 310%UT, 30%MT or PT

Main pipelines	Zone I	10 % RT, MT or PT if required
	Zone II	50 % RT, MT or PT if required
	Zone III	100 % RT, MT or PT if required

Note: For all quality levels a 100 % visual inspection is required. MT and PT are performed only if there is a risk of cracks.

- Quality assurance requires a number of operations usually expressed by levels. The new European standard specifies elementary (I), standard (II) and comprehensive (III) levels.
- The level selected may be achieved by a higher level of quality assurance and less control (instance a) and vice versa (instance b). Both instances are shown in figures 3.10, and 3.11

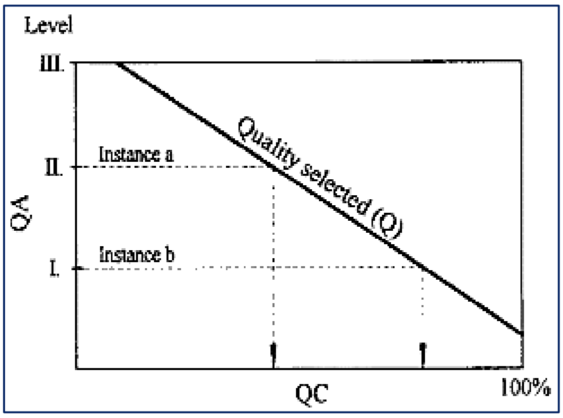


Fig. 3.10. Quality Selection - QA and QC [108]

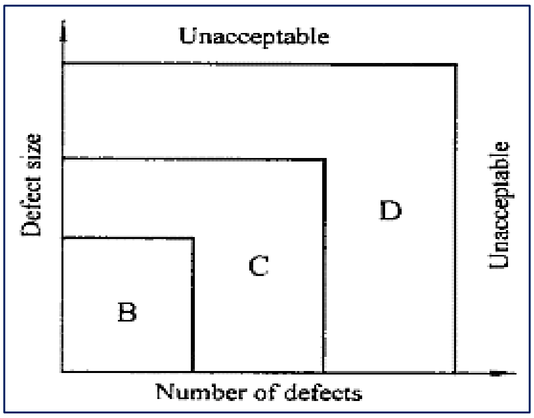


Fig. 3 11. Quality Levels [108]

3.4. Dealing with Welding Defects

3.4.1. What should be done when Welding Defects are detected

The items should be rejected and put them temporarily on hold. It should determine the cause and try to implement a corrective action to avoid future reoccurrence. Then an authorized professional should decide if the defects are repairable or not. If yes, an appropriate procedure should be selected. Standard procedures may be approved for routine application.

3.4.2. Repair Welds

a. The Quality of Repair Welding

Having identified a welding discontinuity to be unacceptable according to the relevant code of practice, then, in roost cases, corrective action must be taken to rectify the situation. In some cases, this can be achieved by removal of material. Dressing out of minor surface imperfections by grinding is an example. However, in the vast majority of situations, the removal of the unacceptable discontinuity has to be followed by further welding to complete the repair. Repair welding is an essential process in fabrication. Properly repaired structures may have equivalent static strength, ductility, fracture toughness and fatigue strength levels as the base structures.

Repair welding can be carried out as a logical procedure that ensures the production of a usable and safe component such as [109] [110]:

- ***Welding procedure***: the welding procedure must be accessible to the use of the welders. It must include the process that is used and specific information concerning the welding joint technique required.
- ***Welding equipment***: sufficient welding equipment should be supplied, then delays will not occur. Standby equipment may also be required. This not only comprises welding equipment, but also includes sufficient holders, grinders, wire feeders if required, cables, etc.
- ***Materials***: sufficient materials must be accessible to the entire job. This includes the filler metals, which should be stored properly for use on the repair. It also includes materials such as insert pieces, reinforcing pieces, etc. Materials also include fuel for maintaining preheat and interpass temperature, shielding gases if used, and fuel for engine powered welding machines.
- ***Alignment markers***: before weld making, alignment markers are occasionally employed. These can be nothing more than centre punch marks made across the joint at various locations.
- ***Welding Sequences***: the welding sequence should be well described in the welding procedure.
- ***Safety***: ultimately, safety cannot be overlooked throughout the welding operation. For instance, when fuel gases are used for preheating, etc., ventilation must be provided
- ***Weld quality***: the quality of the weld must be constantly checked. The final weld should be smooth and there should be no notches and reinforcing. In order to use it, it should flowed smoothly throughout the existing structure. In fact, grinding should be done to maintain smooth flowing contours [110].

A thorough welding procedure should be established to minimize the effect of the repair on the remaining portion of the weld. This procedure must consider the procedure used to create the original weld. It must also consider the following:

- The condition of the base metal and weld
- The type of filler metal to be used in the repair
- The welding sequences
- Any in-process inspection required during the repair
- Tooling required for the repair
- The final weld’s mechanical properties

b. Dimensional Repair

Dimensional repairs are repairs that are required because the weld is too small for the material and joint type. These repairs involve the addition of material to increase weld size and are usually necessary due to the insufficient addition of filler metal during the welding operation. Conditions that require dimensional repairs are as follows [111]:

- ***Crown height is too low***, Figure 3.12. A low crown does not provide adequate reinforcement of the weld. Repair this type of defect with stringer beads to minimize weld shrinkage. Add only enough new filler metal to build the crown to height requirements. Do not overweld.
- ***Surfacing or overlay type weld height is too low***, Figure 3.13. Surfacing or overlay that is not high enough reduces the durability and service life of the surfaced material. Repair this type of defect with stringer beads to minimize dilution and distortion.

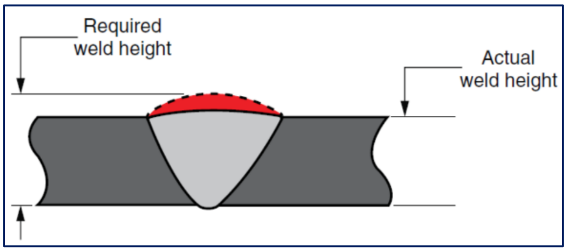


Fig. 3.12. A Groove Weld crown with Insufficient Height [111]

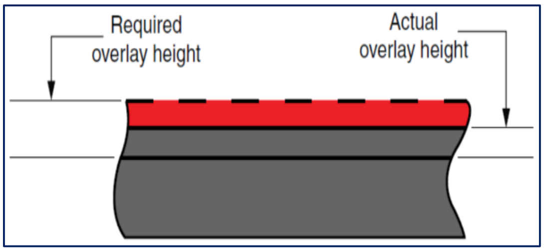


Fig. 3.13. An Overlay Weld Deposit with Insufficient Height [111]

- ***Fillet weld size is too small***, Figure 3.17. A small fillet weld does not provide adequate strength in the joint. The weld is repaired by removing the inadequate weld and rewelding to create the proper size fillet weld.

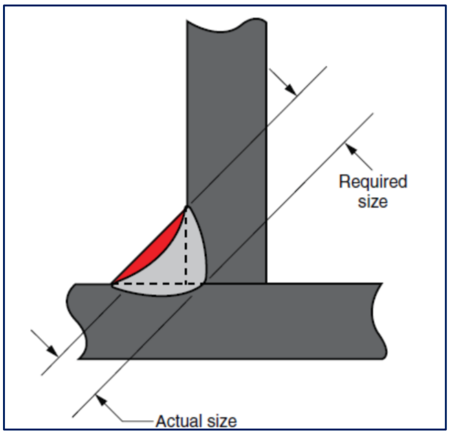


Fig. 3.14. Fillet Weld Leg Length is Satisfactory [111]

c. *Surface Defect Repair [111]*

Defects seen on the surface of the weld can extend deep into the weld. For this reason, the defect must be removed. After the defect has been removed, the area must be inspected again before a repair can be attempted. Common defects and factors to be considered when repairing them are as follows:

- *Longitudinal, transverse, or crater cracks,* (Fig. 3.15). For steel alloys, use a small grinding wheel to remove cracks. Remove only the metal amount required to eliminate the crack.

- *Undercut* at the edges of the weld, Figure 13.16. Dirt, scale, and oxides may be present in the undercut area. These impurities can cause further defects if not removed prior to weld repair. Remove these impurities by grinding or routing as previously described. Be careful not to remove base metal adjacent to the undercut. Since the repair will widen the original crown size, use lower currents and sufficient wire to prevent additional undercuts and underfill.

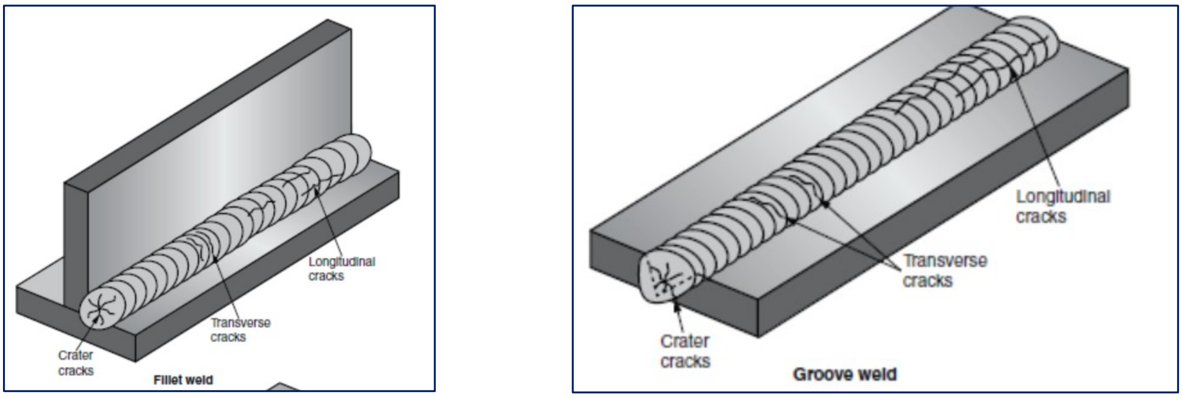


Fig. 3.15. Types of cracks typical for but and fillet welded joints [111]

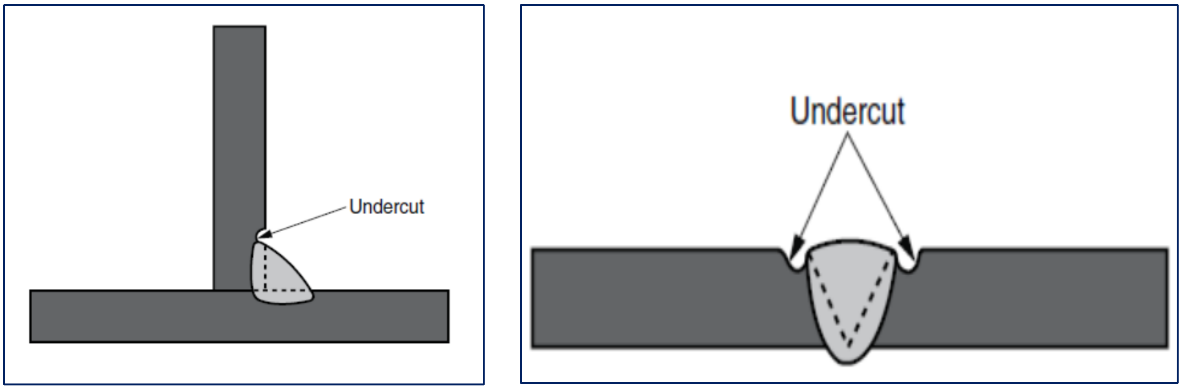


Fig. 3.16. Undercut defect in butt and fillet welded joints [111]

- *Porosity*, or *pores* in the weld (Fig. 3.17). Remove isolated or single pores with a rotary tool for weld repair. Remove multiple and linear (aligned in a row) pores by grinding or machining. Then reinspect the weld by radiographic or ultrasonic inspection to ensure that the porosity has been completely removed before repairs are started. For weld repair, always fill the deepest part of the recessed area first. Keep each layer of weld level until the area is completely filled.

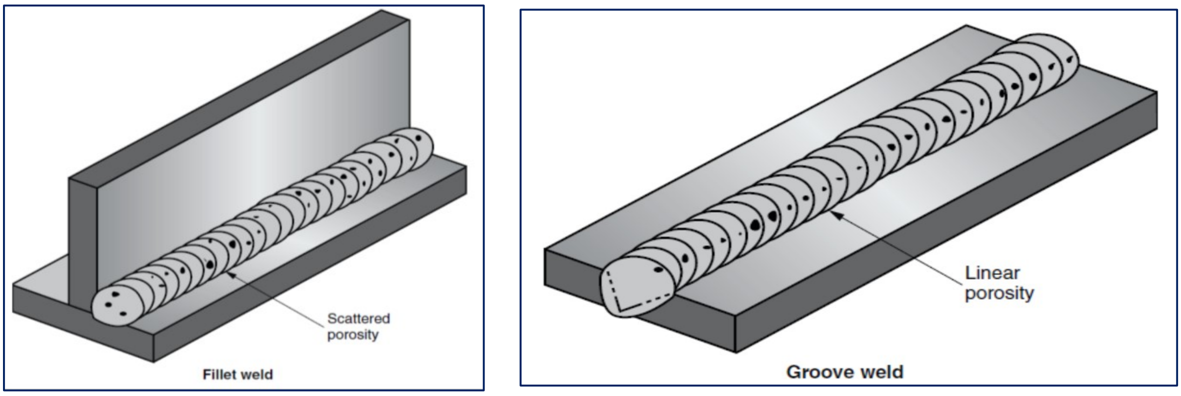


Fig. 3.17. Isolated pores developed in welds [111]

- ***Cold laps***, Figure 3.18. , are areas of the weld that have not fused with the base metal. Cold laps can occur on fillet welds or butt welds, usually as a result of a travel speed that is too slow. Since the extent of the overlap cannot be determined by NDT, remove the entire area by grinding or routing. Use extreme care when grinding into lap joints to prevent grinding into adjacent metal and creating more problems. When the overlap material has been removed, perform a penetrant test to determine if the defect is entirely gone. Continue removing material until the penetrant test is satisfactory. If weld repair is required to satisfy crown height requirements, use low currents and sufficient wire to match the crown with adjoining material.

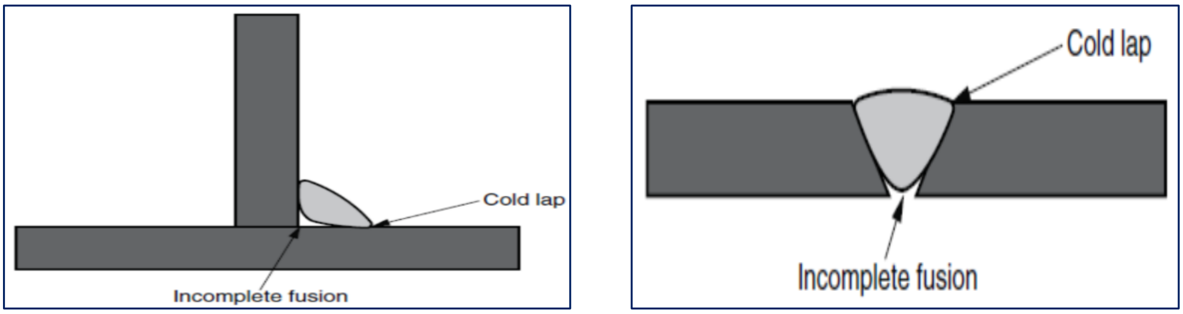


Fig. 3.18. Fillet weld cold laps located on the bottom side of the weld [111]

- *Incomplete penetration* on the root side of butt welds. Other types of defects can also occur on the root side of the weld, such as concave root surface, cracks, porosity, melt through, etc. (Fig. 3.19). Remove these areas by grinding or routing. To ensure complete removal of all defects, perform a penetrant test before repairing the weld. Since oxides form in this area during welding, clean the repair area to bright metal before rewelding. Use stringer beads and add only enough wire to build a small crown.

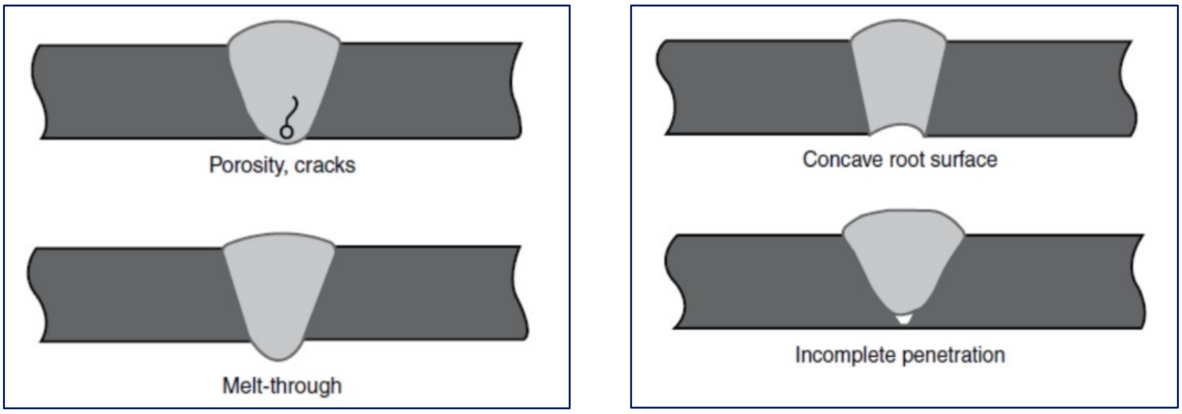


Fig. 3.19. Defects in the root side of the weld [111]

d. Internal Defect Repairs *[111]*

The following is a suggested procedure for repairing an internal defect in a groove weld:

1. If the defect depth is known, remove metal to within approximately 1/16″ (1.6 mm) from the defect. During the metal-removal process, use a magnifying glass to inspect the ground area. If the crack is in the right plane, a light blue surface will sometimes be found at the edge of the crack. This is caused by overheating of the crack edge. This is also a good situation for a dye penetrant test;
2. Perform a penetrant test on the grooved area. If no indication of a crack or defect is seen, remove the penetrant;
3. Grind .010″–.015″ (.25 mm–.38 mm) deeper;
4. Penetrant test the grooved area again. Continue penetrant testing, grinding, and retesting until the defect is found;
5. If the defect is still not found, X-ray to determine if the defect remains.

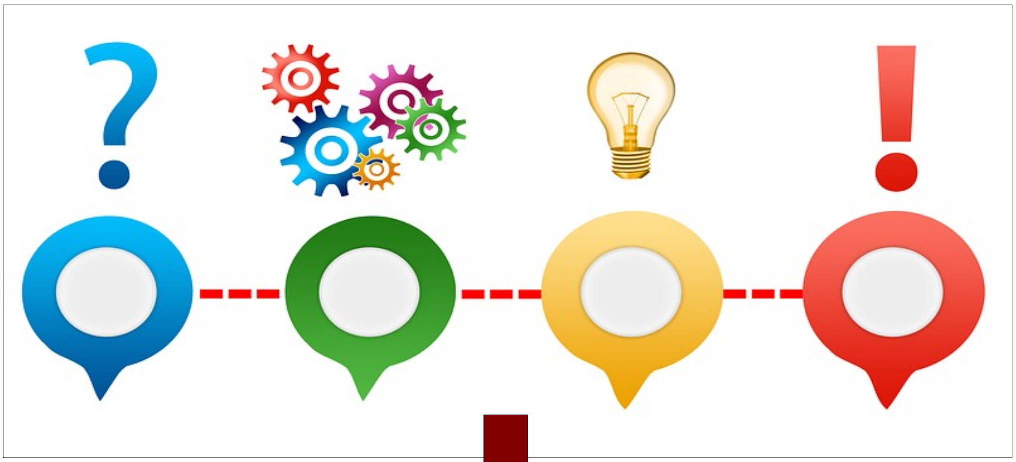
Note: If the crack is not found after removing metal halfway through the part, reweld the ground area. Then try from the opposite surface to completely remove the defect.

3.4.3. Post-Weld Inspection

For the final acceptance of the weld, one of the Non-Destructive Testing (NDT) techniques must be used after the weld repairing is done. This means that even if several inspections were satisfactory before the joint was rejected, the inspection must be done again. Repairs can cause new problems in a weld. After a repair is made, the entire weldment must be re-inspected [111].

3.5. Plan for Quality Assurance of Welded Structures

Or what should be done in order keep any structure between the margins of quality assurance and quality control? The following schema is an answer for that:



1
- **Inspection Preparation**
  - The choice of an adequate NDT method, and set it's parameters, cleaning and preparing the area that will be inspected

2
- **Detecting the Discontinuities**
  - Control using the NDT: Visual inspection; Liquid penetrant; X-Ray,...

3
- **Recognising the Defects**
  - According to the standards of acceptance critaria

4
- **Repairing Preparation**
  - The choice of an adequate welding procedure depending on the type of defect, material of structure, working consitions,...,Cleain

5
- **Design of Welding Specification Procedure (WPS)**
  - Selecting the filler metal, calculus of process parameters, welding conditions

6
- **Repairing Phase**

7
- **Post-Welding Inspection**
  - Using NDT methods
  - Yes or No Tree

3.6. Conclusion

- Non-destructive testing (NDT) is essential to ensuring that defects in welds are detected on the assembly line prior to being put to use.
- Lack of NDT testing by which the defects can be detected could lead to crash and failure, some them being disastrous for the environment or even for people (i.e., oil or gas pipeline, bridges, airplanes etc.).
- Welded joints can be subjected to loads that determine fatigue during lifetime and, consequently, the result is the failure of the welded structures. That is why the standards and specifications have to be totally applied.
- In conclusion, the NDT control plays a vital role. It can identify both surface and sub-surface deficiencies while the welding process is underway, or before the item goes into production. Knowing the causes and the possible flaws position, a NDT control method can be appropriately selected and applied.

CHAPTER 4.

Inspection and Repair of an Engine Cylinders Block

4.1. Gray Cast Iron Alloys

Gray cast iron is one of the most widely used alloys of iron for production of industrial components, it’s the first and most material used for manufacturing of engine blocks, Though the aluminium alloy also contains many similarities with low weight, it is still used in the manufacturing of diesel engine blocks because their internal stresses are higher. It has superior machinability to that of other types of cast irons and requires lower levels of lubrication from the metalworking fluid used. The graphite in gray cast iron has a flake-like structure which is largely responsible for the high machinability of this metal. The flake-like graphite structure gives rise to discontinuities in the metal matrix and subsequent reduced cutting forces. The graphite in gray cast iron also provides lubrication during machining. This reduces the demand and level of lubrication required from the metalworking fluid used in addition to the effects of the graphite structure on gray cast iron machinability. The strength depends on the matrix in which graphite (free carbon) is embedded. The matrix can range from ferrite to pearlite and various combinations of the two phases. Large graphite flakes do not only increase the its machinability, but also reduce the strength and ductility [112] [113].

4.1.1. Chemical Properties

The gray cast iron contains 2.5 – 4 % C, 1 - 3 % Si, 0.2 - 1% Mn, 0.02 - 0.25 % S, and 0.02 - 1 % P. It has good wear and thermal resistance, and it is easily machinable and less cost due to its availability [114]. Gray cast iron is one of the most widely used alloys of iron. The strength of gray cast iron depends on the matrix in which graphite (free carbon) is embedded. The matrix can range from ferrite to pearlite and various combinations of the two phases. Large graphite flakes reduce the strength and ductility, so inoculants are used to promote fine flakes [113].

4.1.2. Mechanical Properties

Table 4.1. Gray Cast Iron properties [115]

Property	Value	Unit
Modulus of Elasticity	124	GPa
Tensile Strength	276	MPa
Fatigue Strength	138	MPa
Hardness (Brinell)	180-302	HB

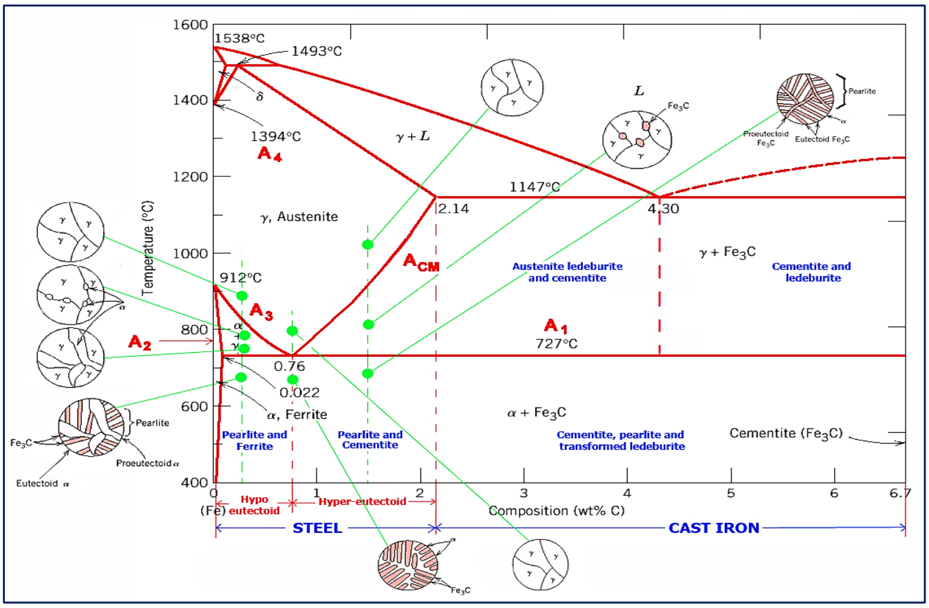
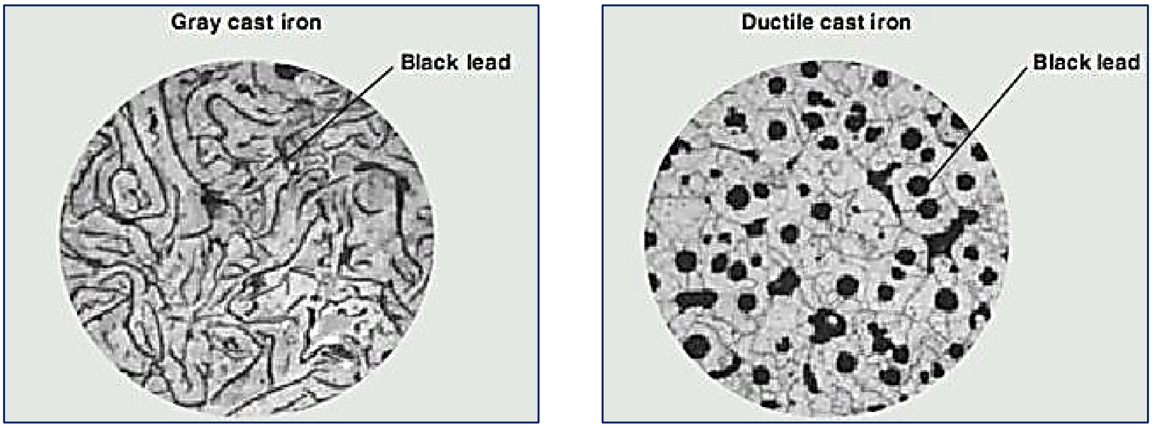


Fig. 4.1. Iron Carbon Phase Diagram [116]

4.2. Defects in Gray Cast Iron Alloys

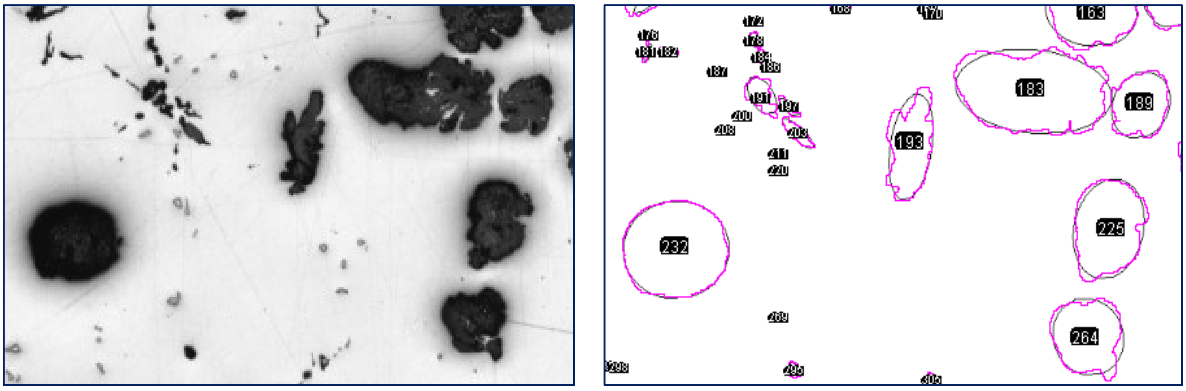
Defects morphology primarily affect the mechanical of gray cast iron. In a large castings, porosity and clusters of degenerate graphite are heterogeneously dispersed into the ferrous matrix and serve as initiation sites for fatigue and fractures processes. In the littiratury, it is on a preliminary investigation aimed at correlating the effect of the graphite microstructure to the mechanical properties of the material via a simplified geometrical description of the defects. In cast iron, like in most part of natural materials, defects and voids come in a mixture of diverse shapes (Fig. 4.2.a). A possible simplifying assumption is to replace them by elliptical holes of different shapes and aspect ratios whose distribution could be identified from microstructural information, as done in Fig.4.2.b. The holes’ distribution is expected to have a significant effect on fatigue strength, especially when they are close enough so that interaction occurs depending upon the loading conditions [117].



a) Graphite flakes

b) Graphite balls

Fig. 4.2. Stereo microscope photo of gray (a) and ductile cast iron (b) (x100) [118]



a b

Fig. 4.3. (a) Typical morphology of graphite inclusions and defects in cast iron; (b) distribution of elliptical voids approximating various defects [117]

4.3. Internal Combustion Engine

4.3.1. Generalities

The internal combustion engine (ICE) is a power generating machine in which the burning of a fuel occurs in a confined space called a combustion chamber. This exothermic reaction of a fuel with an oxidizer (usually air) creates gases of high temperature and pressure, which are permitted to expand. The defining feature of an internal combustion engine is that useful work is performed by the expanding hot gases acting directly to cause movement, the force is applied typically to pistons, turbine blades, rotor or a nozzle or even by pressing on and moving the entire engine itself. This force moves the component over a distance, transforming chemical energy into useful mechanical energy, or It converts potential energy of the fuel into heat energy and then into rotary motion [119] [120].

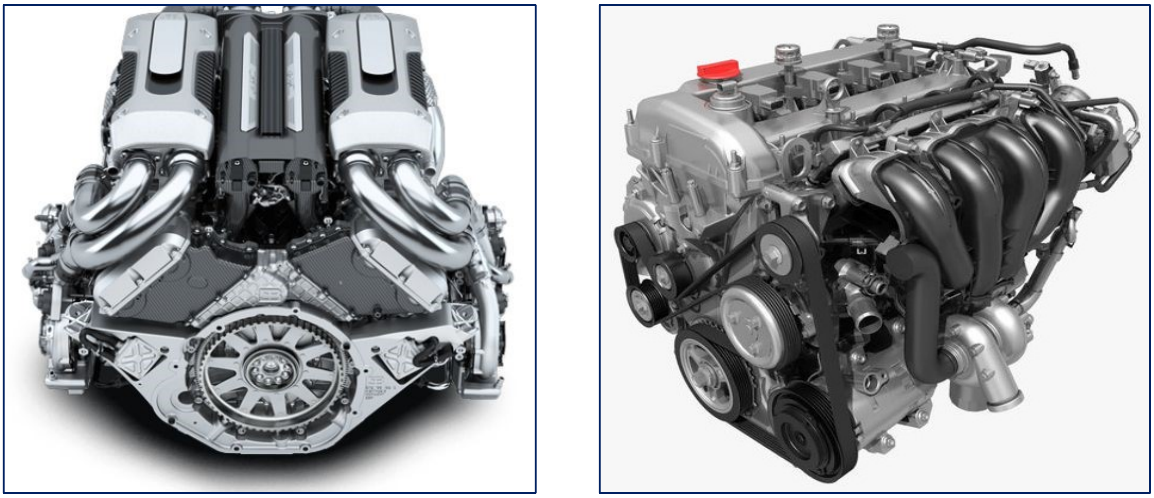


Fig. 4.4. Internal Combustion Engine [121]

4.3.2. Classification

Engines for automotive and construction equipment may be classified in several ways: type of fuel used, type of cooling employed, or valve and cylinder arrangement. They all operate on the internal combustion principle. The most satisfactory classification, however, is by cylinder arrangement. This is the method usually employed because it is more completely descriptive than the other classifications [122].

Based on type of fuel used

Engines using volatile liquid fuels (like gasoline, benzene, kerosene, alcohol etc.)
Engines using gaseous fuels (like charcoal powdered coal etc.);
Engines using viscous liquids fuels (like heavy and light diesel oils.);
Engines using two fuels [123].

Based on type of fuel used

Engines using volatile liquid fuels (like gasoline, benzene, kerosene, alcohol etc.);
Engines using gaseous fuels (like charcoal powdered coal etc.);
Engines using viscous liquids fuels (like heavy and light diesel oils.);
Engines using two fuels [123].

Based on method of charging

Naturally aspirated engines;
Supercharged engines [123].

Based on type of ignition

Battery Ignition system;
Magneto Ignition system [123].

based on type of cooling

Air cooled engines;
Water cooled engines [123].

Based on cylinder arrangement

Cylinder row;
Cylinder bank [123].

4.3.3. Areas of Use

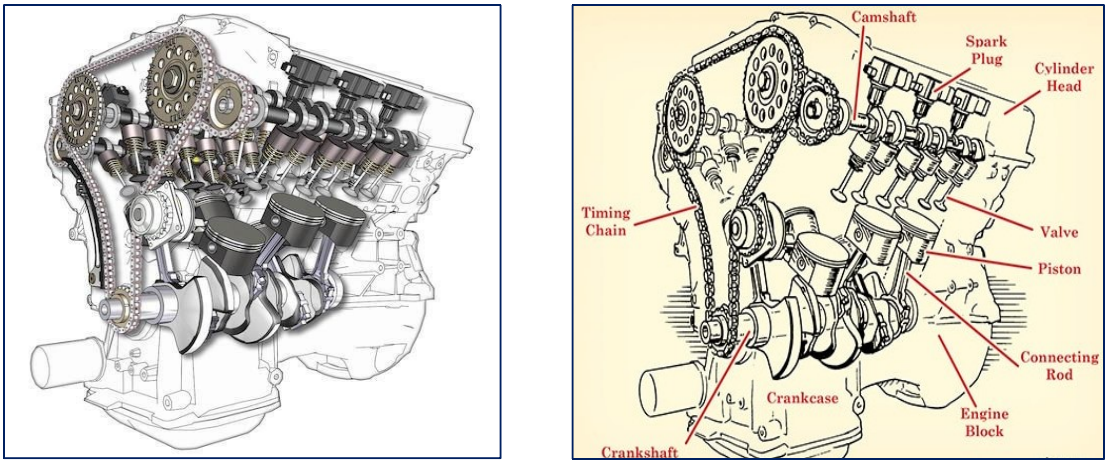
Internal combustion engines are most commonly used for mobile propulsion in automobiles, equipment, and other portable machinery. In mobile scenarios internal combustion is advantageous, since it can provide high power to weight ratios together with excellent fuel energy-density [124] [119].

4.3.4. Chemical Energy

The most common fuel in use today are made up of hydrocarbons and are derived from mostly petroleum. These include the fuels known as diesel fuel, gasoline, and petroleum gas, and rare use of propane gas [119].

4.3.5. Components

The cylinder block;
Cylinder head;
Piston;
Piston rings;
Connecting rod;
Crankshaft;
Engine bearing;
Crankcase;
Valves;
Spark plug;
Injector;
Manifold;
Camshaft;
Gudgeon pin or piston pin;
Pushrod and Flywheel [120] [125].



a) b)

Fig. 4.5. Internal combustion engine component: a) 3D model; b) sketch [126] [127]

4.4. Cylinder Block

The cylinder block is cast component which forms the body of the engine and constitute 20% to 25% of his total weight, its role is to ensure with certain precision the relative position of the parts and the component mechanisms in both static and functional condition. And because all engine auxiliaries are installed on the engine block: lubrication system, cooling system, power plant, part of the electrical system, etc., it plays a key role in the lubrication, temperature control and stability of the engine, that’s why it has to be of the highest quality so there is no room for short cuts [128] [129].

4.4.1. Cylinder Block Function

Contains the cylinders inside which the engine runs through its outer walls to ensure the heat transfer to the coolant (to the water-cooled engines), to fix the cylinder head and to support the crankshaft and the distribution shaft through its bearings. Through the walls of the engine block, the gas pressure forces from the cylinder head to the body of the bearings are transmitted, the motor torque response of the entire car. During operation, the engine block is subjected to gas pressure forces, inertial forces and moment of inertia having a variable character, the frictional forces generated by moving parts forming different kinematic couplings (e.g., kinematic coupler, cylinder cam -piston-segment, landing gear or manikin and suitable bearing, etc.). At the same time, additional demands arise due to the engine's operating regime (thermal loads), but also to the assembling of the various parts [128] [129].

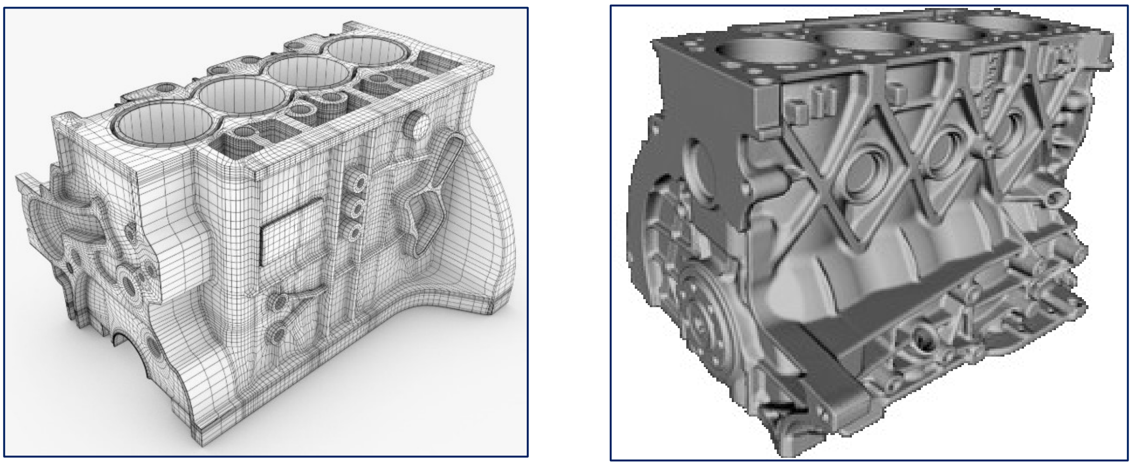


Fig. 4.6. Cylinders Block [16]

In addition to its functional role, the engine block must also meet a number of requirements such as: mechanical strength and high stiffness, wear and corrosion resistance, dimensional accuracy, geometric and reciprocal position, a certain quality processed surfaces, low deformations due to temperature variations. Having regard to the above-mentioned technical conditions (requirements) on one side and its configuration on the other hand, the engine block must also meet tightness conditions. In most cases it is made of gray cast iron, and sometimes lightweight aluminium alloys are used for smaller cars (for cars) [128] [129].

4.4.2. Classification of Cylinders Block

As is already known, there is a wide variety of engine block design solutions, and their classification is based on several criteria, as follows:

- The number and layout of the cylinders (in line, in V, in star, opposite, etc.);
- The mounting the cylinders (mono-bloc or removable);
- The type of removable shirts (wet or dry);
- The cooling system (liquid or air);
- The location of the valves (block or head);
- The material used gray cast iron or aluminium alloys, etc.).

4.4.3. Tooling Required for Casting Engine Block

The main tool needed for sand casting is the mould, the mould is generated by a mixture of sand, clay, and water. The pattern is the main tool required to form the mould, it is normally machined by wood or aluminium which can be easily machined. The pattern is kept on the wood or metal frame and the sand mixture is poured in to it, then vibrations are applied for the mixture to get free from air bubbles. After the mould has being hardened it can be used for the casting process. The blocks of the engine block, when using gray cast iron, are poured into moulds, after which an annealing treatment is carried out, resulting in a hardness of 180-200 HB. When aluminium alloys are used, the semi-finished products are poured into the shell, after which an artificial aging is made in order to obtain a suitable structure.

After the casting process is over the casted engine block is passed through few machines to get the surface finish and correct dimensions. Computerized milling machines and boring machines are used in this operation [128].

Fig. 4.7. Casting Engine Block [128]

The core shown below provides the space for water jackets around the cylinders. The core has been painted to seal the gas formed during the casting process within the core. And the pink coloured ends are not painted to let the gas escape to the outside. Aluminium reinforcing rods are used to give more strength to the core. These rods get melted due to the molten metal poured during casting [128].

4.5. Inspection and Repair of an Engine Cylinders Block

4.5.1. Engine Block Refurbishment

The engine block refurbishment technology will take into account both the size and constructional features of the part in question. After the parts have been removed from the sample or subassembly they are part of, washed and dried, a thorough inspection, in the first stage, is a visual analysis to determine the degree of damage, the existence of various major defects, etc. , then performing specific measurements, predetermined, for dimensional and geometric accuracy control, for the determination of the size and distribution of the weights in order to determine the reconditioning rates, to control the surface roughness and their hardness, to control hidden defects [130]. Based on visual analysis or measurements, the pieces-in this case the motor blocks will be divided into three categories:

- ***Good pieces***, reusable without any intervention, are those parts which are free of wear or wear or are within the limits accepted by the technical conditions imposed on the piece;
- ***Reducible parts*** (reformable), which exhibit major defects, deformations or wear above the maximum admissible limits or not worth rebuilding from an economic point of view. These parts will be replaced by new ones or reconditioned parts;
- ***Repairable parts*** are those that have defects, deformations or wear within the acceptable limits for reconditioning.

4.5.2. Engine Block Reforming Conditions

The main technical conditions for reconditioning an engine block are:

- Cracks or cracks in the walls of more than 300 mm in length (L_f & g_t; 300 mm) (1 *);
- Cracks or cracks encountered at the level (on the right) of the bearing housings (2 *);
- Cracks or cracks irrespective of the size or position of the cylinder walls (between work surface and cooling channel) (3 *);
- Cracks or cracks in the connecting bridges (walls) between cylinder boreholes;
- Cracks or cracks where welding is not possible (4 *);
- Rupture or breakage (material breakage) of which the perimeter exceeds 80..100 mm (5 *);
- Deformations of the cylinder head surface (deviations from flatness) which, by machining, lead to the condition; $H_{ef} < H_{min\ ad}$ (6 *);
- Cracks or holes in the threaded holes, especially those used in the assembly with the cylinder head or the bearing caps (7 *);
- Wear in diameter of the drum sleeve guide portion (at the press bushing solution) above the maximum permissible limit.

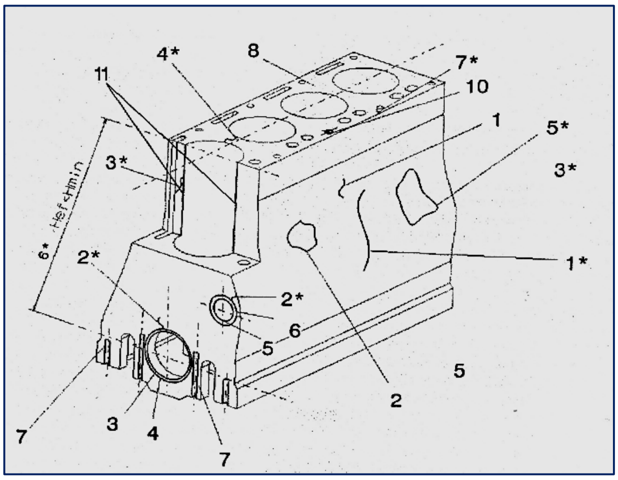


Fig. 4.8. Position of the main engine block defects [18]

4.5.3. Reconditioning Technology by employing Welding

For cracks of the outer walls of the engine block, the length of which is not more than 300 mm outside the areas. The findings are made by visual examination for accentuated cracks and cracks and by hydraulic test at p = 0,4 MPa for two minutes or non-destructive defectoscopy control (x-rays, y-rays, ultrasounds, fluorescence method, etc.) in case of micro-cracks [130]. Reconditioning can be done by welding or hot oxyacetylene welding, following next steps:

- Two holes are provided in the likely direction of the crack trajectory to prevent propagation;
- The visible trace of the crack is machined;
- Heat the engine block at a temperature of 600 to 650 degrees Celsius;
- Welding (electrical welding) or autogenously welding in 15-20 mm staple bars to prevent internal stresses.

- For gray cast iron blocks (Fc 200, Fc 250, Fc 300), either the welded bead (VTS 300) with diameters ranging from 4 to 6 mm or EM (MONEL) electrodes with the composition Ni 60% and 25% with good mechanical strength and attenuation of the formation of internal thermal stresses in the welded area.
- For light alloy blocks, oxyacetylene welding is recommended using eutectic or hypoeutetic aluminium alloys as input material or welding in inert gas protective environment [130].

- Reconstruction of cracks in the outer walls of the engine block can also be accomplished by using temperature-resistant synthetic adhesives, following the manufacturer's instructions regarding both the preparation of the reconditioned surface and the application technology of these epoxy resins.

- No matter what the applied technology is, after the reconditioning, the part is subjected to a quality control through the hydraulic test (at P = 0.4 MPa for two minutes) or a non-destructive defectoscopic control [130].

4.5.4. Fracture of Materials

a. Perimeter less than 80-100 mm

- Determining the defect in this case is done by a visual exam using possibly a measuring instrument (eg a caller); to measure the perimeter of breakage or rupture; restoration of breakage or rupture will be done by petition through the following steps:
- Machining (by polishing or milling) the contour of the rupture or rupture to give it a regular shape;
- A cast iron cast iron (Ex.Fc250) or carbon steel for gray cast iron blocks and aluminium alloys made of lightweight alloys is produced in the shape of the contour, the breakage being ruptured;
- Polishing the edges of the splinter and patch for the feed material;
- Preheat the engine block in the oven at a temperature of 600-650 degrees Celsius;
- Electrically or autogenously welding (welding by welding) into staple buses with the engine block;
- Special material is used to repair the defects described above. It should be noted that in this case, synthetic adhesives can be used for the application of the patch, after reconditioning, quality assurance of the assembling and especially the leak testing as at the previous point (hydraulic test or non-destructive defectoscopy control) will be performed [130].

4.6 Identifying and Repairing the Defects

4.6.1. Controlling Phase Using NDT Methods

For the detection of open surface defects that may occur at the engine block, it is opted for penetrating fluid control, a method that uses a set of liquids shown in Figure 4.9 [131].

The penetrant fluid set consists of a cleaner or degreaser, a penetrant that is a light petroleum-based lamp with the property of penetrating into fine capillary spaces and a developer that is an absorbent substance (chalk, talc) suspended in a volatile liquid.

This control method allows us to detect open surface defects by performing the following steps:

a) Surface preparation. Remove all impurities and oxides from the surface to be controlled using mechanical methods (grinder, wire brush) followed by degreasing with the cleansing spray (degreaser) from the penetrating fluid kit. Surface cleaning is done in such a way that the cleaning method does not fade the possible defects;
b) Application of penetrant. Using the red vial, a uniform penetrant coating is sprayed on the surface of the engine block as shown in Figure 4.10.

Fig. 4.9. Penetrant liquids

Fig. 4.10. Application of the penetrant

The red penetrant will penetrate into open surface defects, requiring a waiting time of at least 15 minutes.

- Removing the penetrant applied in excess. After the penetration time has expired, excess penetrant is removed using one of the recommended methods for the type of penetrant used. Penetrants are water soluble, soluble in organic solvents or post-emulsifying. The penetrant moves harder the more sensitive it can penetrate into the smallest defects. In our case, the excess penetrant was removed by washing with a stream of water followed by wiping. The way to remove the excess penetrant can be seen in figure 4.11.

a) Developer application. After drying the surface to be controlled, we applied a thin layer over the entire surface of the engine block by spraying after proper agitation of the developer bottle. The white developer has the ability to extract the penetrant that has penetrated into the defects of the controlled surface.
b) Surface observation. Immediately after application of the developer, the naked eye or a magnifying glass, the surface is observed and any defects are revealed. In our case, after applying the developer we noticed a crack as seen in figure 4.12.

Fig. 4.11. Removing the penetrant excess

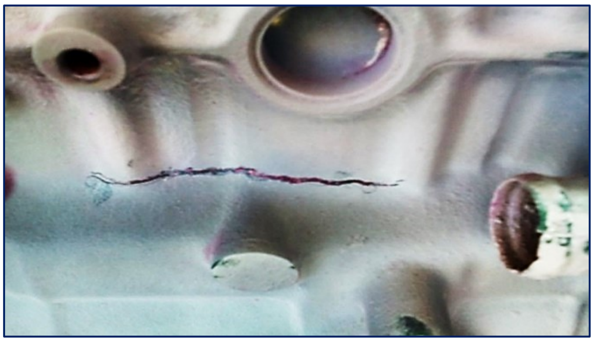


Fig. 4.12. Crack identified on the engine block

It can be seen how the developer extracted the penetrant from the defect by highlighting it. The image obtained is a classic crack represented by a tremendous red line on the developer's white background, thinner at the ends and thicker in the middle.

4.6.2. Repairing Preparation Phase

Using the welding equipment available, the repair of the crack was performed by Manual Metal Arc (MMA) Welding with coated electrodes, following the next steps:

- Preparing the joint. Limiting the crack, by preparing two holes with 6.5 mm diameter.

Fig. 4.13. Limiting the crack through holes

- Then, using a conical milling cutter that we mounted in a manual drilling machine, we made a “V” groove, as in figure 4.14.

4.6.3. Setting-up the Welding Parameters

a. Material of the engine block is gray cast iron (Fc 250)

Taking into account the chemical composition of the engine block and the wall thickness, a copper-nickel electrode was selected for cold welding of the cast iron (Fig. 4.15.)

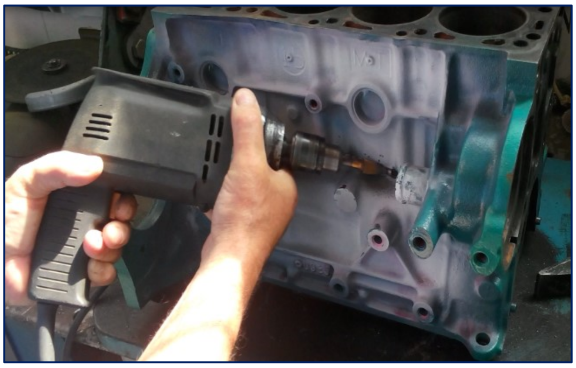


Fig. 4.14. Performing the “V” groove

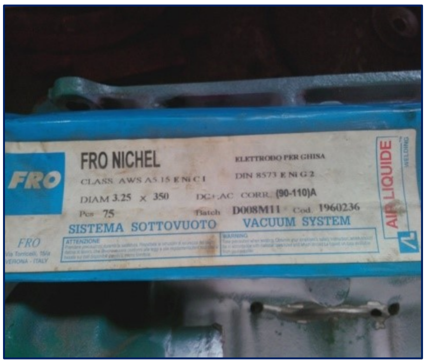


Fig. 4.15. Copper-Nickel electrode

After the defect has been removed, short welds of maximum 3 cm were made, by using the following process parameters [132]:

- diameter of the electrode $d = 3.25$ [mm]
- amperage $I = 110$ [A]
- Voltage $U = 22$ [V]
- Welding velocity, v_s, computed as follows:

$$Vs = \frac{s}{t} = \frac{2{,}8\ \text{cm}}{0{,}6\ \text{min}} = 4{,}66\ [\text{cm/min}] \tag{4.1}$$

- Heat input rate, E_l, computed with the following relation:

$$El = 60 \cdot \eta \cdot \frac{Ua \cdot Is}{Vs} = 60 \cdot 0{,}8 \cdot \frac{22 \cdot 110}{4.66} = 24927\ [\text{J/cm}] \tag{4.2}$$

4.6.4. Repairing Phase

The way of performing the welds is presented in figure 4.16. After each deposition, the stress level is reduced by using a hammer, hammering the until the ambient temperature is reached. The stress level was relieved as it can be seen in figure 4.17.

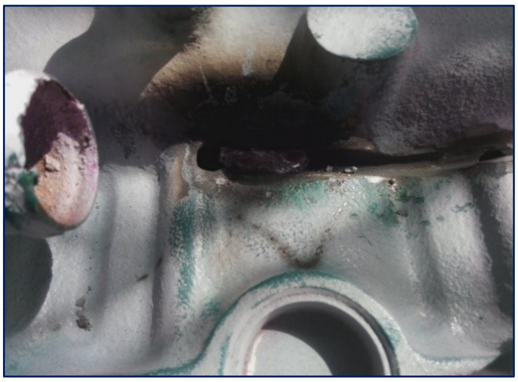


Fig. 4.16. How to perform the welds

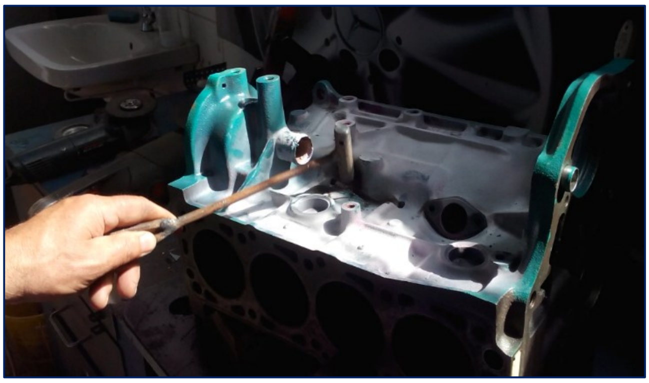


Fig. 4.17. Relieve of stress by hammering

After the welds were performed, the holes were filled with the same filler metal (Fig. 4.18).

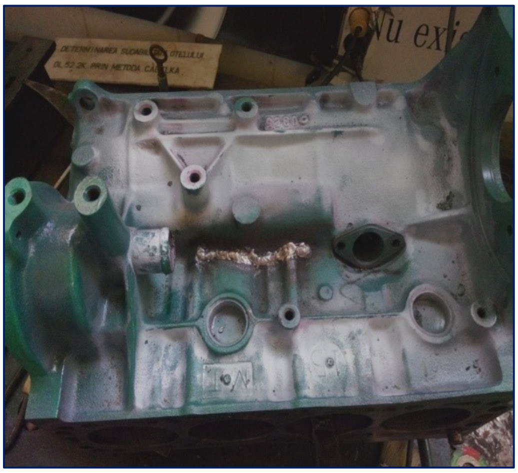


Fig. 4.18. Filling the holes

Fig. 4.19. NDT control

4.6.5. Post-weld Inspection Phase

The visual inspection and Liquid Penetrant NDT method were applied in order to detect the possible defects. Finally, no any flaw was noticed in the engine block (Fig. 4.19).

4.7. Conclusion

- Using the repair and maintenance plan shown in the previous chapter, a crack developed during service of an engine block was removed and, further, the area has been prepared and welded with Cu-Ni electrodes.
- Defects morphology affect the mechanical properties of the products. Flaws as large castings, porosity and clusters of degenerate graphite could be causes of defects developed during service. An alternative solution could be the replacing of gray cast iron with aluminium, the advantage of easier weight being obvious.

CHAPTER 5.

Simulation and Analysis of Engine Block Behaviour Using Numerical FEM

5.1. Introduction to Finite Element Method

The finite element method (FEM) is considered as one of the well-established and convenient technique for the computer solution of complex problems in different fields of engineering: civil engineering, mechanical engineering, nuclear engineering, biomedical engineering, hydrodynamics, heat conduction, geo-mechanics, etc. From other side, FEM can be examined as a powerful tool for the approximate solution of differential equations describing different physical processes [133].

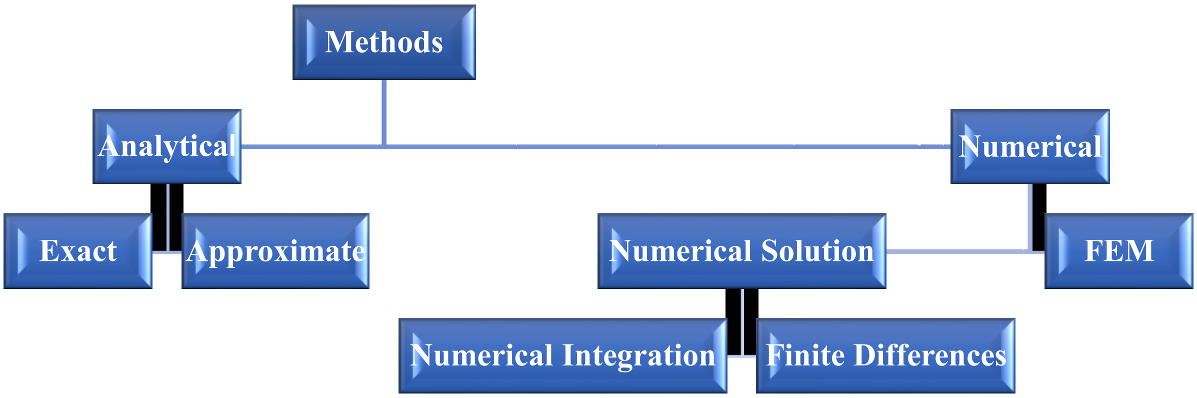


Fig. 5.1. Classification of mathematical methods [133]

FEM was treated previously as a generalisation of the displacement method for shaft systems. For a computation of beams, plates, shells, etc. by FEM, a construction is presented in a view of element assembly. It is assumed that they are connected in a finite number of nodal points. Then it is considered that the nodal displacements determine the field of displacements of each finite element. That gives the possibility to use the principle of virtual displacements to write the equilibrium equations of element assembly so, as made for a calculation of shaft systems [133].

5.2. Finite Element Program Packages

Universal tool for a wide range of problems. Hence a number of computer program packages have been developed for the solution of a variety of structural and solid mechanics problems. Among more widely used packages are ANSYS, NASTRAN, ADINA, LS-DYNA, MARC, SAP, COSMOS, and ABAQUS. Each finite element program package consists from three parts:

- Programs for preparation and control of the initial data, (Solid works and CATIA);
- Programs for solution of the finite element problem, (ABAQUS and ANSYS);
- Programs for processing of the results. ABAQUS [133].

5.2.1. Design Parameters of Engine Block

The design parameters of the engine block are shown in the figure 5.3.

5.2.2. Development of the Engine Block 3D Model

In this thesis, the 3D solid model of engine block has been built using SolidWorks software, which is a very productive 3D CAD software tool, with its integrated analytical tools and design automation to help stimulate physical behaviour such as kinematics, dynamics, stress, deflection, vibration, temperatures or fluid flow to suit all types of design, but and according to the needs of finite element analysis, we have simplified the model by rebuilding another one using CATIA software, that allows the creation of 3D areas, from images, sheet-metal, compounds, shaped made or pedalling areas up to the meaning of technical devices.
For this Engine block design, 2D Drawing inputs are taken from previous work. The Engine block model is single body consists of cylinders, cooling jackets, studs, etc.

Limitations: Due to limited access to computer capacity, because the analyses in this study are executed on a computed laptop with an Intel core i7 processor and with only 8GB RAM. Consequently, the number of elements in the models could not exceed 300,000 to keep the computation time reasonably low.

A. SolidWorks Model

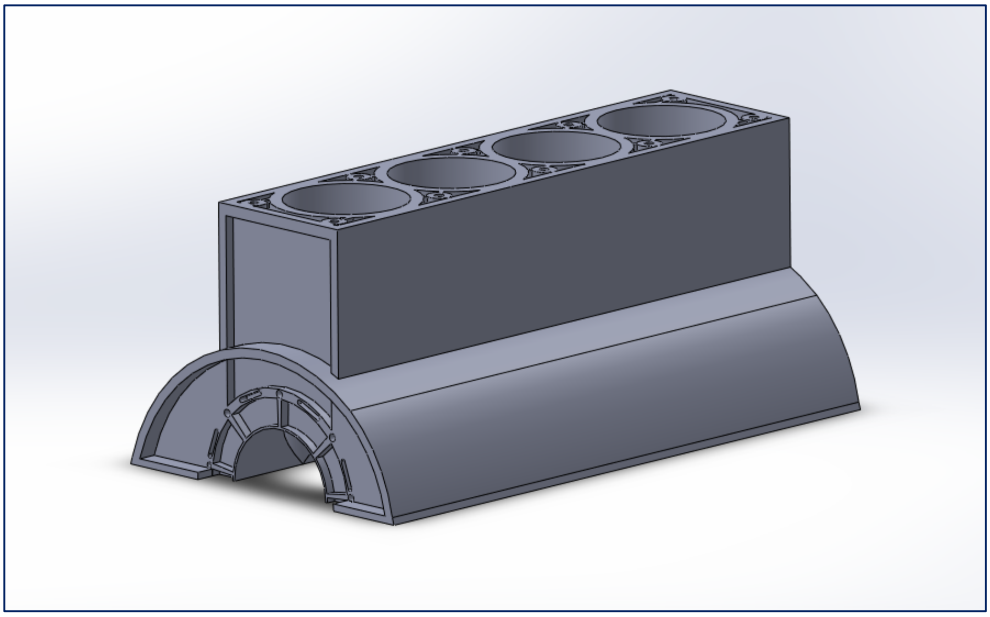


Fig. 5.2. Four Cylinders Block Modal designed by SolidWorks

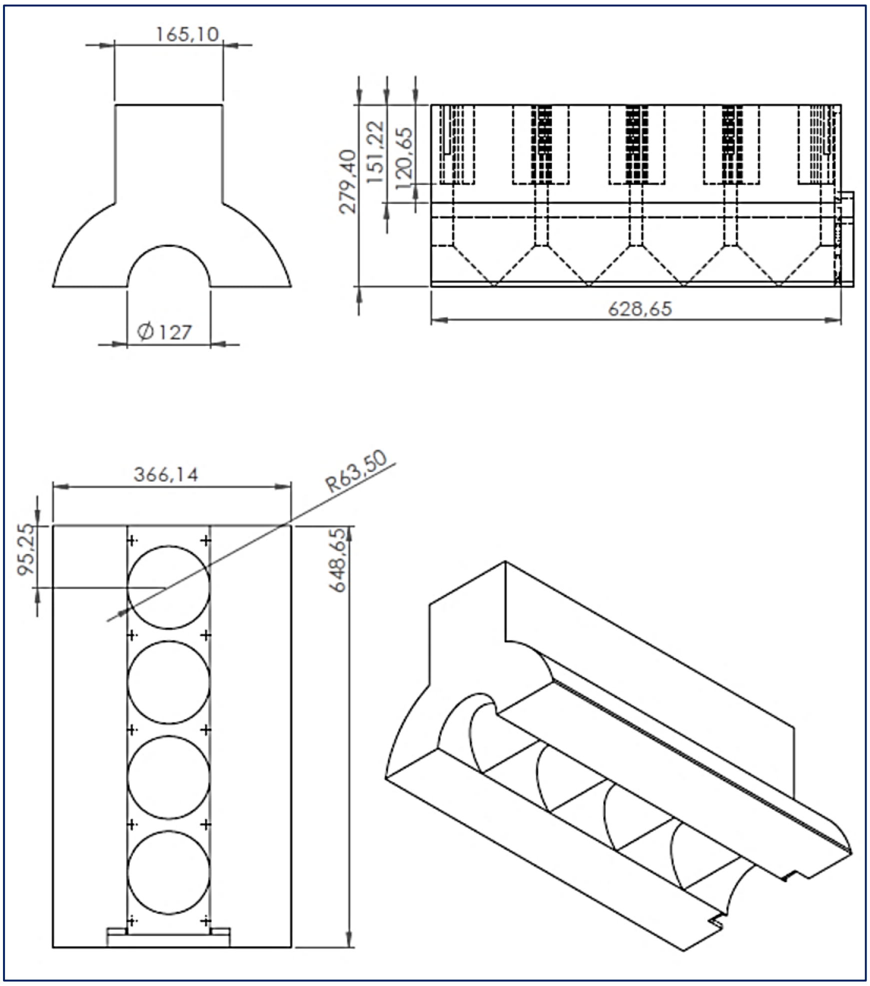


Fig. 5.3. Development Plan of the Four Cylinders Block –SolidWorks

B. CATIA Model

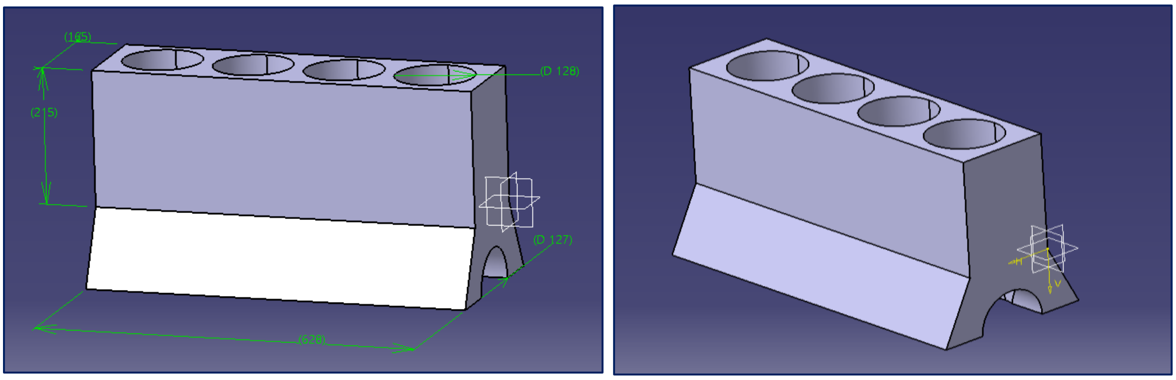


Fig. 5.4. Simplified Cylinders Block Modal –CATIA

5.2.3. Simulation Processing

This part of simulation is carried out using ANSYS 18.1.

ANSYS is a Finite Element Analysis (FEA) code broadly utilized as a part of the Computer Aided Engineering (CAE) field. ANSYS programming permit to develop PC models of structures, machine segments or frameworks, apply working burdens and other plan criteria and concentrate physical reactions, for example, stretch levels, temperature dispersions, weight, and so on. The ANSYS program has an assortment of outline examination applications, running from vehicles to such exceedingly modern frameworks as flying machine, atomic reactor regulation structures and scaffolds. There are 250+ components determined for different applications in ANSYS. In the present application shell, pillar and mass components that have auxiliary static and dynamic investigation capacities were considered. The loads that are acting in the engine block are Combustion load, Piston side loads, balance shaft loads, main bearing loads, main bolt clamp load, thermal load and head bolt clamp load. The loads that are considered in this thesis for the analysis of the engine block, are Combustion loads. The resulting stress history are shown in the next part. The coordinate used in the whole study is the Global Cartesian Coordinate System

a. Mesh Generation

Table 5.1. Mesh configuration

Object Name	Mesh
State	Solved
Size Function	Adaptive
Automatic Mesh	On
Minimum Edge Length	20mm
Nodes	84107
Elements	54026

Object Name	Body Sizing
State	Fully Defined
Scoping Method	Geometry Selection
Geometry	1 Body
Suppressed	No
Type	Element Size
Element Size	15, mm

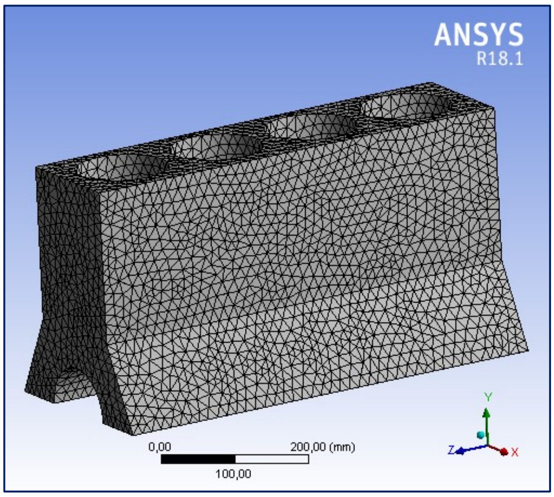


Fig. 5.5. The Cylinder Block Mesh

The meshing is the same used for the whole simulation study in ANSYS.

b. Material Configuration

The FEM analysis was performed in ANSYS Workbench. The simulation of the investigated Engine Block was solved as a linear isotropic material model with given material properties of Grey Cast Iron ($E = 1{,}1.10^{11}$ Pa, ν = 0.28Pa).

5.2.4. First Case: Random Vibration

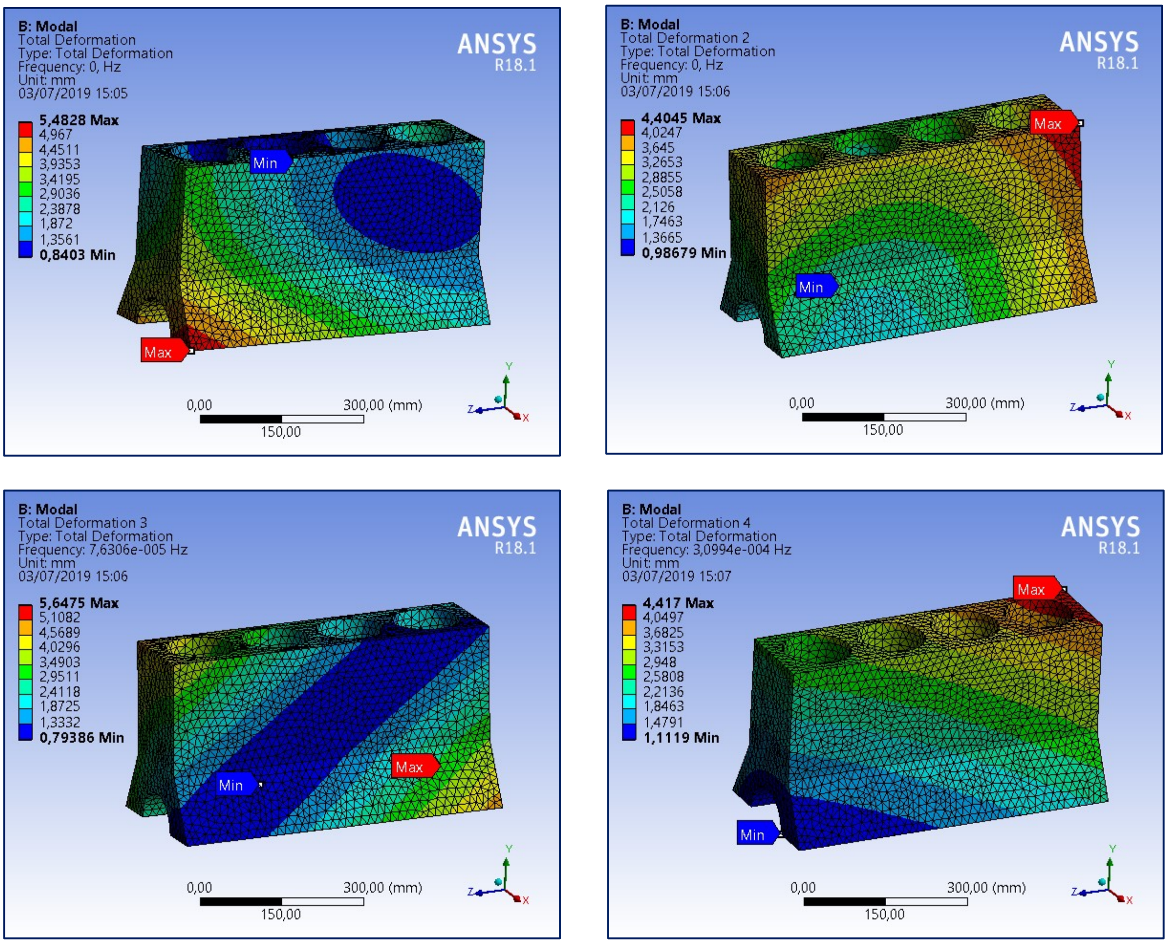
It is opted for this configuration to simulate the behaviour of cylinders block in some abnormal working conditions.

A. First Configuration

The Engine Block displacement was allowed in all directions.

B. Second Configuration

To make the simulation closer to the real working conditions of an Engine Block, several boundary conditions have been added, in order to fix the cylinders block. The external walls displacements were removed in all directions, as shown in figure 5.7.



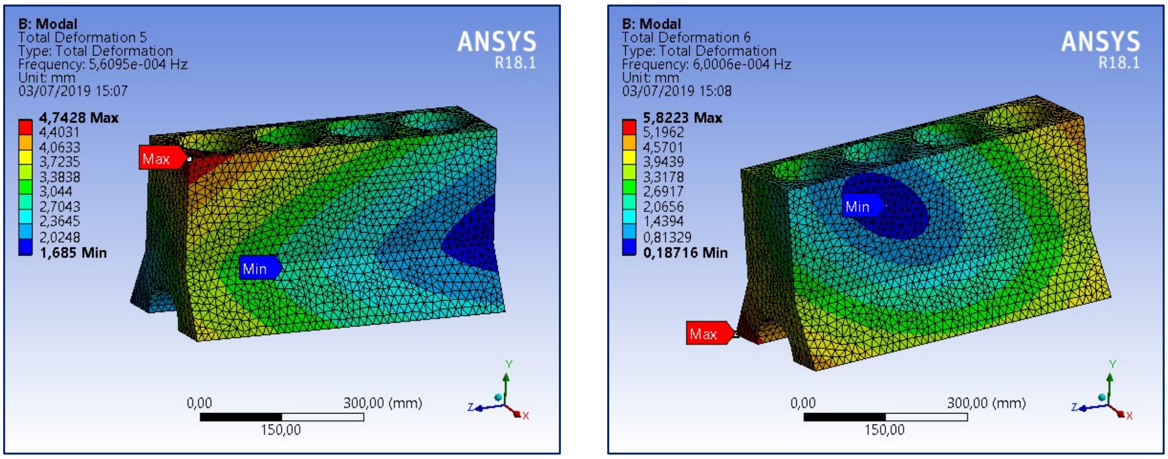


Fig. 5.6. First configuration: Random vibration analysis without Boundary Conditions

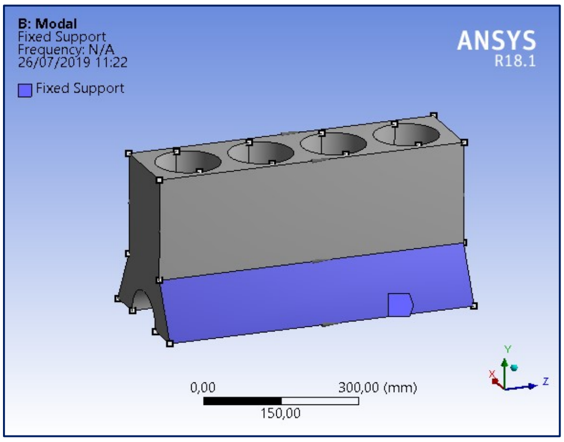
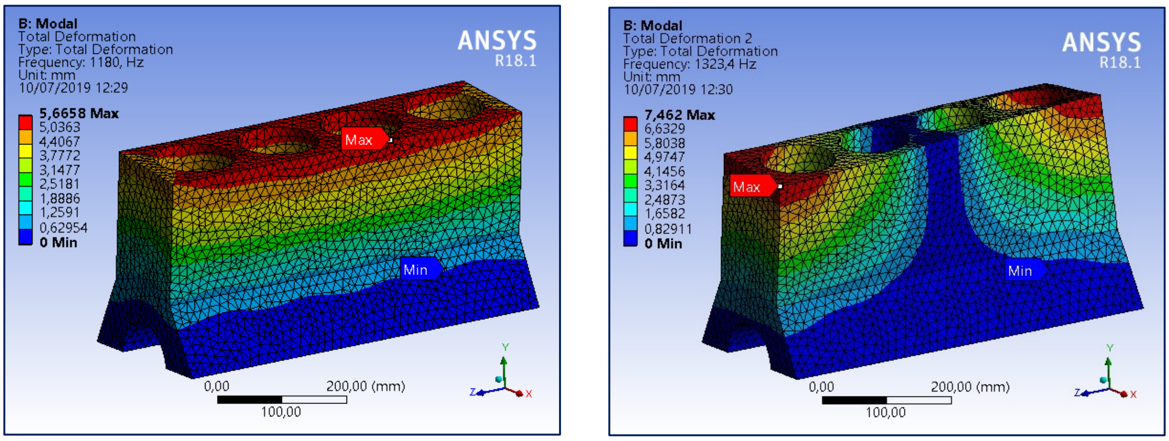


Fig. 5. 7. Fixed Support



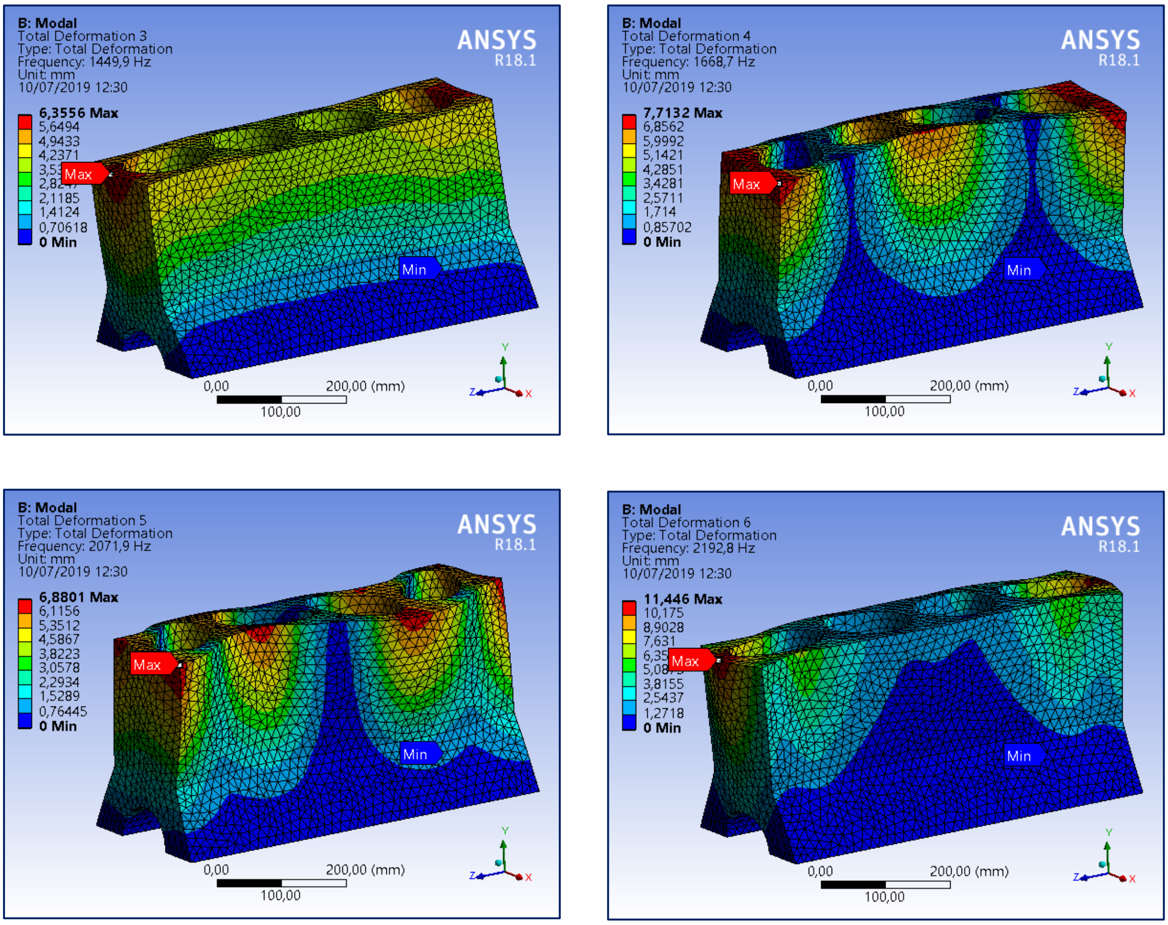
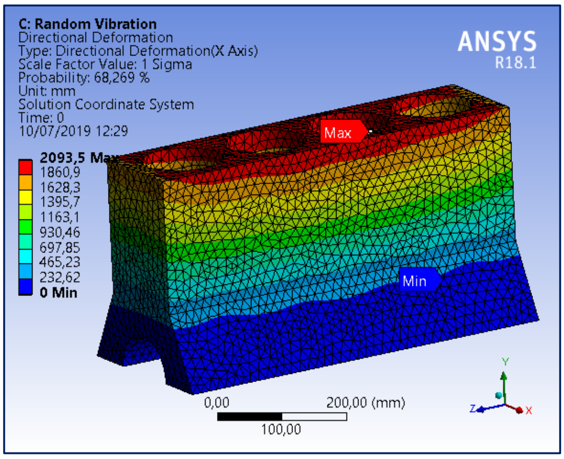


Fig. 5.8. Second configuration: Random vibration analysis with Boundary Conditions



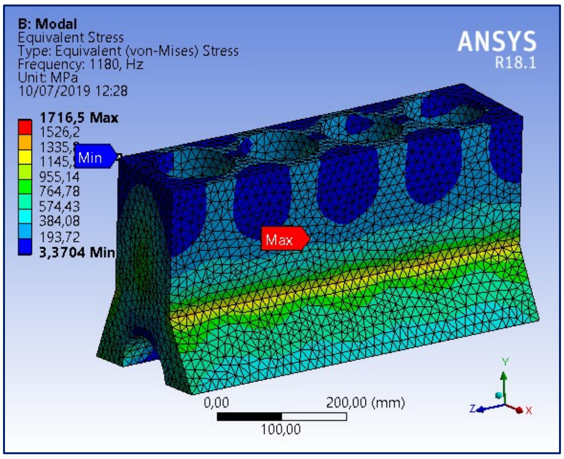


Fig. 5.9. Total Displacement

Fig. 5. 10. Total Equivalent Stress

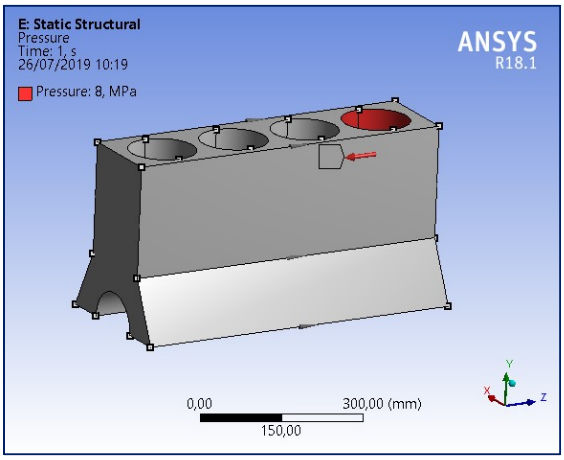
5.2.5. Results and Discussion

From the above results it is observed that the critical frequency 1180 Hz generates stress of 1716.5MPa. This configuration, which is more realistic, shows a very high level of stress and, consequently, crack and failure of the cylinders block may occur.

5.3.5. Second Case: Pressure

a. Configuration

Loads: Pressure 8MPa applied on the inner wall of the first cylinder with a temperature from 0°C to 120°C.



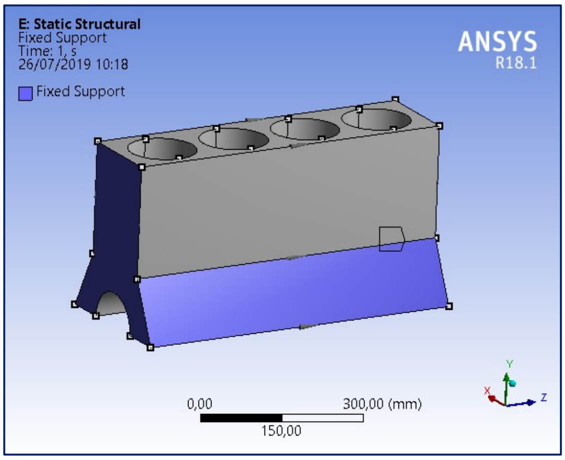
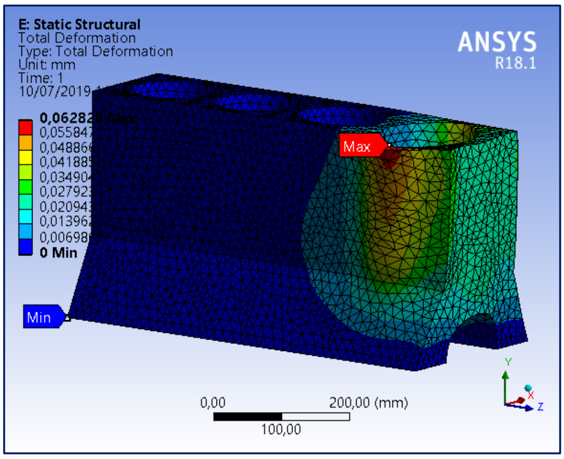


Fig. 5.11. Application of Pressure

Fig. 5.12. Fixed Support

A. First Configuration (Pressure, p)



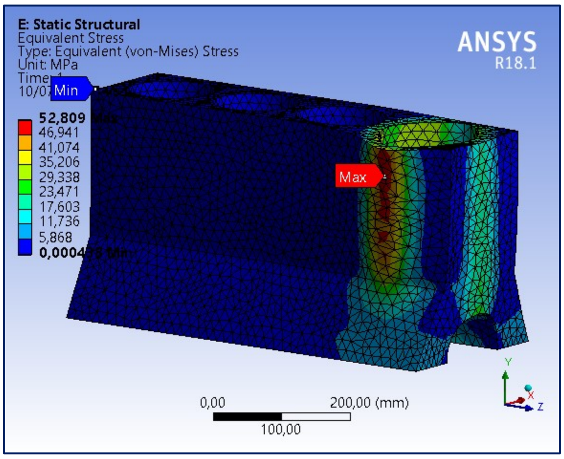


Fig. 5.13. Total Deformation (Pressure)

Fig. 5.14. Equivalent Stress

B. Second Configuration (Pressure, p & Temperature, T)

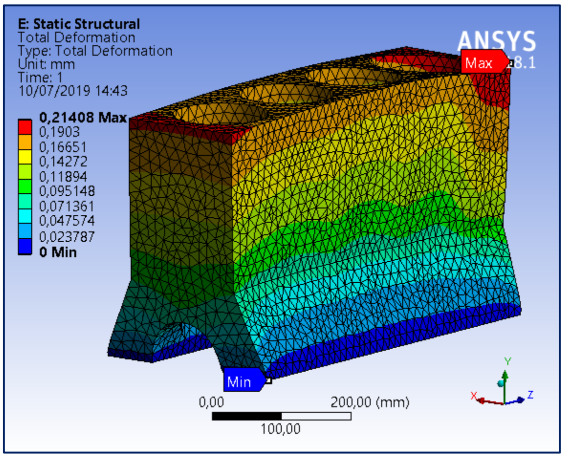


Fig. 5.15. Total Deformation (p & T)

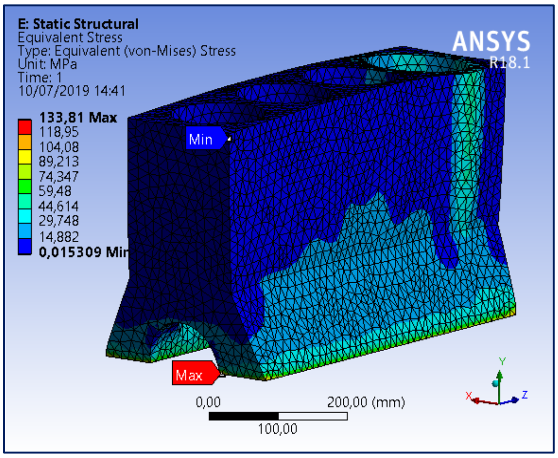


Fig. 5.16. Equivalent Stress (p & T)

5.3.6. Results and Discussion

Table 5.2. Results of the second case (first configuration)

Object name	Total deformation	Equivalent stress
Minimum	0,006 mm	0,0004 MPa
Maximum	0,062 mm	52,809 MPa

Table 5.3. Results of the Second Case (Second Configuration)

Object name	Total deformation	Equivalent stress
Minimum	0,023 mm	0,01 MPa
Maximum	0,214 mm	133,81 MPa

The results of simulation for normal working conditions of the Cylinder Block, with or without presence of high temperature, show that the engine block stays under the limits of its construction material, taking into consideration that this last does not present any discontinuity. The results of equivalent stress will be used in the next study, to simulate the crack growth on the external wall of cylinders.

5.3. Numerical Simulation of Fatigue Crack Growth

Fatigue crack growth is a typical reliability concern in most engineering components under cyclic loading such as the cylinder block, because it is a complex part at the heart of an engine which adapts the cylinder head, crankcase, engine mounts, drive housing and engine ancillaries, with passages for coolants and lubricants. Due to complex geometry and loading, it is often necessary to simulate crack growth numerically. In this thesis, the non-conventional methods

such as the extended finite element method (XFEM) is developed. The XFEM is a relatively new method which has been developed during the last decade. The method has many possibilities since it does not need remeshing when the crack propagate.
The crack Growth Analysis of the Engine Block is carried out using ABAQUS software.

5.3.1. Importing the Geometry to ABAQUS

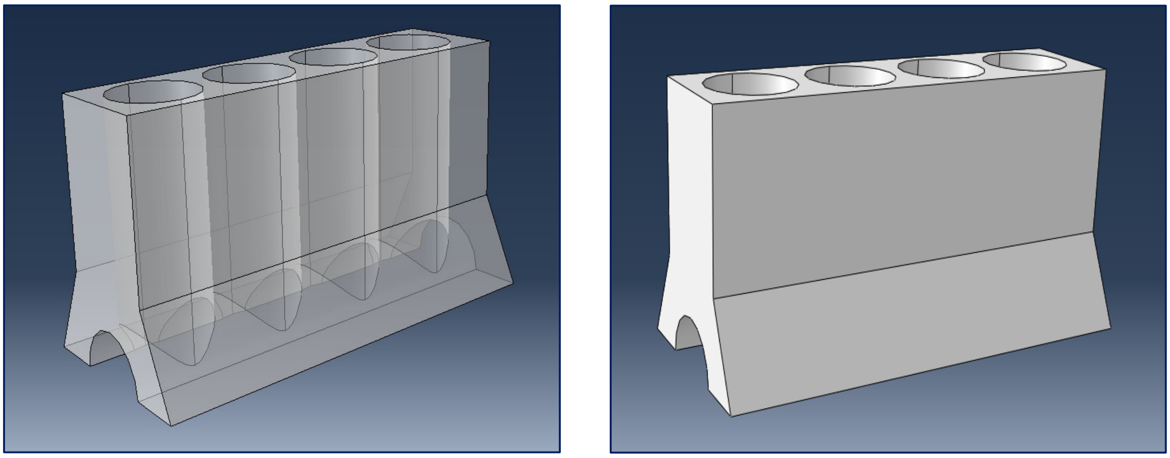
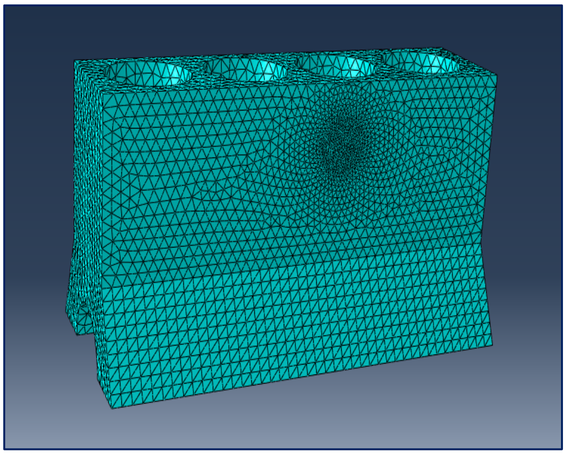


Fig. 5.17. Cylinders Block Model

5.3.2. Mesh Generation



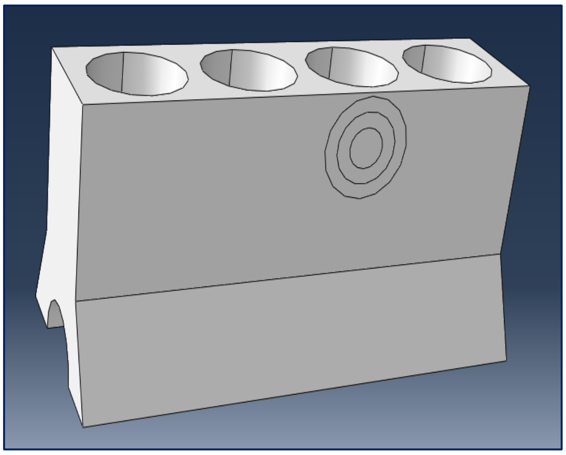


Fig. 5.18. Cylinders Block meshed **Fig. 5.19.** Preparing the Meshing

5.3.3. Boundary Condition Configuration

The base of the engine block was supposed to be embed, so all displacements and rotations in the three axes are removed. In the second boundary condition all the Engine Block is fixed except in the Y-axis direction which is allowed the global Cartesian coordinate system. The coordinate systems are marked in the figures bellow. The application of equivalent stress as loads will be sort of outgoing pressure equal to 50Mpa in the outer all of the cylinder block. Results of the deformations that will appear in the structure are shown in the figure 5.18.

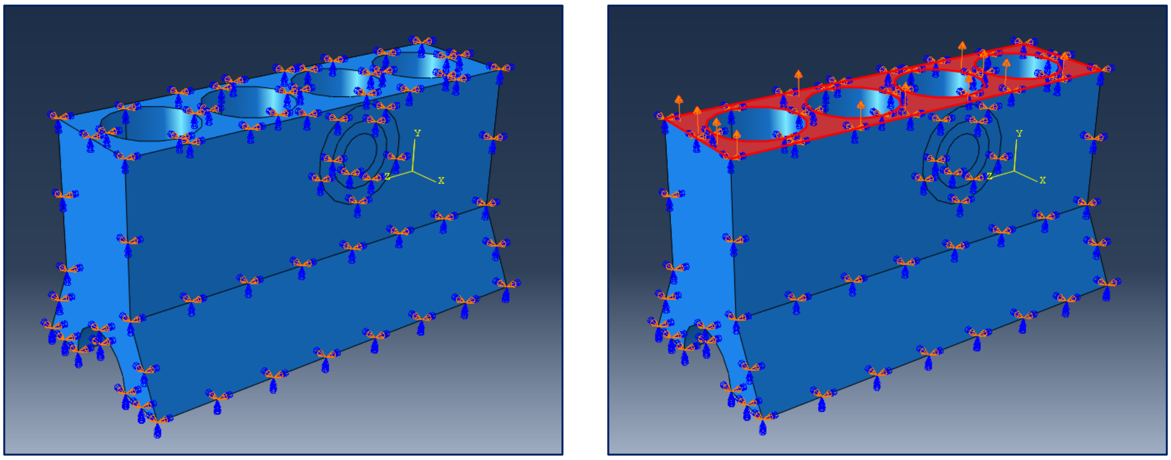


Fig. 5.20. Configuration of Boundary Conditions

5.3.4. Results and Discussions

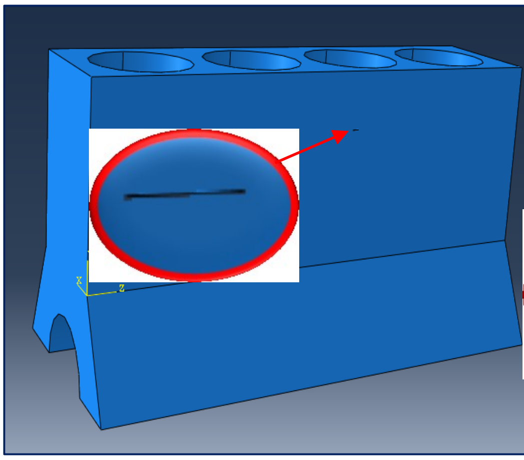


Fig. 5.21. Zoom in the Micro Crack

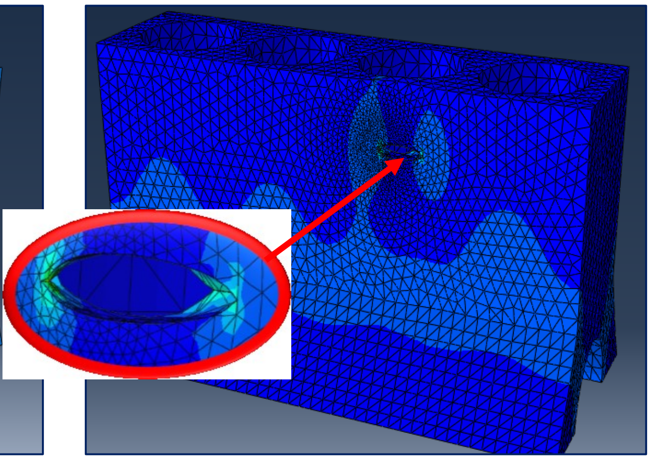


Fig. 5.22. Zoom in The Final Crack

After the application of the XFEM methods using the results from the simulation of pressure, it can be seen (Fig. 5.22) that the stress generated from the high pressure of explosion has created micro crack. The micro crack has grown (Fig. 5.22.) because of the cyclic pressure.

5.4. Conclusion

Fatigue crack growth describes the mechanism of failure process in a material or component as a result of cyclic mechanical loading. To ensure safety, the prediction of fatigue crack growth is an important issue that has to be solved using computational techniques. Because of the three-dimensional geometry and complex loading conditions, the analytical solutions for the prediction of fatigue crack growth are limited in predicting the damage and failure. They are mostly applicable to simple geometries and may not consider the complex stress level developed in service environments. For this reason, the finite element method (FEM) is the numerical tool recommended to solve the problems of fracture mechanics.

CHAPTER 6.

Final Conclusions and Perspectives

6.1. Final Conclusions

Inspections using Non-Destructive Examination (NDE) in which no portion of the completed weld is destroyed, are made during and after the manufacturing cycle to ensure that parts meet specifications. Weld integrity inspections may also be required in addition to the Non-Destructive Testing (NDT) to verify the weld quality.

Intended weld repairs must be evaluated as to whether the discontinuity should be removed because repairs can cause new problems in a weld:

- Repairing a completed weld could cause instability of the reworked area.
- Repairs can be made to correct dimensional problems, surface defects, and internal defects. Internal defects are generally found by radiographic and ultrasonic testing.

In some cases, a discontinuity can be left in a weld without affecting the weld that's why all Non-Destructive Testing, required for final acceptance of the weld, must be completed after the weld repair is done, before commissioning the welded structure and during its service life.
By following a maintenance plan based on quality assurance, we will guarantee:

- The quality of the welded structure;
- Its reliability;
- Its response to requirements and its service life.

The use of numerical methods such as the finite element method, through computer tools and mechanical simulation software, by highlighting the working conditions, one could:

- Predict the presence of defects in a structure;
- Its growth over time;
- The life of the structure.

6.2. Perspectives

Many different adaptations, tests, and experiments have been left for the future due to lack of time:

- The experiments with real data (which are usually very time consuming, requiring even days to finish a single run);
- Optimization of welding processes;
- Use of XFEM technique to predict defects in welded structures;
- Develop and transform the maintenance plan into reliability based management plan and implement it in companies as model.

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ANNEX A

Welding: ISO/TR 25901-1:2016(en)	
Welding	Joining process in which two or more parts are united producing a continuity in the nature of the workpiece material(s) by means of heat or pressure or both, and with or without the use of filler material Note: Welding processes may be used also for surfacing and remelting
Fusion welding	Welding involving localized melting without the application of external force in which the fusion surface(s) has (have) to be melted with or without addition of filler material
Weld	Result of welding The weld includes the weld metal and the heat-affected zone.
Parent material **Base material**	Material to be joined, or surfaced, by welding, braze welding or brazing.
Parent material thickness **Material thickness**	Nominal thickness of the materials to be welded
Manual welding	Welding in which the electrode holder, gun, torch or blowpipe is manipulated by hand
Mechanized welding	Fully mechanized welding Welding where the required welding parameters are maintained by mechanical or electronic means Note: Manual adjustment of welding parameters by the welding operator during welding is possible.
Automatic welding	Welding in which all operations are performed without welding operator intervention during the process.
Robotic welding	Welding that is performed and controlled by robotic equipment.
Characterization of welds	
Weld metal	All metal melted during welding and retained in the weld
Heat-affected zone **HAZ**	Portion of non-melted parent metal whose microstructure has been affected
Weld zone	Zone containing the weld metal and the heat-affected zones
Deposited metal	Filler metal that has been added during welding
Fusion line	Interface between the weld metal and the non-melted parent metal as determined on the cross section of a weld

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Fusion zone	In the weld metal, part of the parent metal that has been melted, as determined on the cross section of a weld
All-weld metal	Weld metal consisting of deposited metal without dilution
Weld pool **Molten pool**	Pool of liquid metal formed during fusion welding Note: In electroslag welding, the term includes the slag bath.
As welded	Condition of the weld after welding prior to any subsequent thermal, mechanical, or chemical treatments Note: For alloys that may undergo natural ageing (e.g. some aluminium alloys), the as welded condition lasts only for a limited period of time.
Ferrite number FN	Arbitrary standardized value designating the ferrite content of nominally austenitic or austenitic-ferritic (duplex) type stainless steel weld metal based on its magnetic properties
Metallurgical deviation	<Welding> changes in the mechanical properties and/or metallurgical structure of the weld metal or heat-affected zone compared to the properties of the parent metal
Dilution	Mixing of melted parent metal and deposited metal expressed as a ratio of the melted parent metal to the total melted mass
Dilution rate	Dilution expressed as a percentage
Residual welding stress	Stress remaining in a metal part or structure as a result of welding
Strength weld	Weld designed to withstand stress
Joint efficiency	Ratio of strength of a joint to the strength of the parent metal, expressed as a percentage
	Imperfections
Imperfection	Discontinuity in the weld or a deviation from the intended geometry Note: Imperfections are cracks, lack of penetration, porosity, slag inclusions.
Internal imperfection	Imperfection that is not open to a surface or not directly accessible
Systematic imperfection	Imperfections that are repeatedly distributed in the weld (2.1.1.3) over the weld lengths to be examined
Projected area	Area where imperfections distributed along the volume of the weld under consideration are imaged two-dimensionally
Hot crack(s)	Material separations occurring at high temperatures along the grain boundaries (dendrite boundaries) when the level of strain and the strain rate exceed a certain level Note: Small cracks visible only at magnifications greater than 50×, are often described as microcracks.
Solidification crack	Hot crack formed during solidification from the liquid phase of weld metals

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	Note: It usually extends up to the surface of the weld metal, but sometimes can be subsurface.
Liquation crack	Hot crack formed by liquation in the heat-affected zone of the parent material or in multirun welds where weld metal is reheated by subsequent runs
Ductility dip crack	Hot crack formed during welding by a reduction in hot ductility Note: As with a liquation crack, it can occur in the heat-affected zone of the parent material (2.1.1.5) or in multirun welds.
Cold crack(s)	Local rupture (intergranular or transgranular) appearing in a weld as a result of a critical combination of microstructure, stress and hydrogen content
	Type of joints
Joint	Junction of workpieces or the edges of workpieces that are to be joined or have been joined
Welded joint	Assembly that is produced by welding together two or more parts
Multiple joint	Type of joint where three or more parts meet at any required angles to each other
Parallel joint	Type of joint where the parts lie parallel to each other EXAMPLE: In explosive cladding.
Butt joint	Type of joint where the parts lie in the same plane and against one another at an angle of 135° to 180°
T-joint	Angle joint where the parts meet each other forming a T-shape
Lap joint	Type of joint where the parts lie parallel to each other (0° to 5°) and overlap each other
Angle joint	Type of joint where one part meets the other at an acute angle greater than 5° but not more than 90° Note: For a fillet weld, the angle is over 5° and less than 45°. Note: For a butt weld, the angle is between 45° to 90° inclusive.
Corner joint	Type of joint where two parts meet at their edges at an angle between 30° and 135° to each other
Edge joint	Type of joint where two parts meet at their edges at an angle of 0° to 30°
Cross joint	Type of joint where two parts lie crossing over each other EXAMPLE: Wires that cross over each other.
Cruciform joint	Type of joint where two parts lying in the same plane each meet, at right angles, a third part lying between them
Homogeneous joint	Welded joint in which the weld metal and parent material have no significant differences in mechanical properties and/or chemical composition Note: A welded joint made of similar parent materials without filler metal is considered homogeneous.

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Heterogeneous joint	Welded joint in which the weld metal and parent material have significant differences in mechanical properties and/or chemical composition
Dissimilar material joint	Welded joint in which the parent materials have significant differences in mechanical properties and/or chemical composition Note: Manual adjustment of welding parameters by the welding operator during welding is not possible.