Effect of Multiple Repair Welds on High Strength Low Alloy (HSLA) Steel

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Certificate

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Dedicated To

My parents, wife, siblings, affectionate teachers, colleagues, friends and all those who have ever prayed for me.

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Abstract

Present study presents the results of multiple weld repairs made in the same area to evaluate and analyze its effects on the microstructural and mechanical performance of quench and tempered A24303 steel. The welding was performed by Tungsten Inert Gas (TIG) welding using H18CrMoA filler rod and five repairs were carried out. Specimens of different repair work were then characterized to find out the variations in microstructure, mechanical properties and corrosion behaviour.

Mechanical performance was evaluated by tensile testing, charpy impact testing, bend testing and hardness testing. Microstructural features were analyzed with optical microscopy. Compositional analysis using spark emission spectroscopy and energy dispersive spectroscopy (EDS) of the samples were conducted and correlated with the mechanical and microstructural findings to substantiate the test results.

It has been revealed that tensile strength is dropped marginally during increased number of repairs. Overall slight increase in percent elongation was observed. An increase in the impact strength was also observed with increasing number of repairs with a varying rate. Variation in chemical composition and and microstructures was also observed with repairs. Corrosion resistance of the samples was decreased with the increased repairs.

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List of Abbreviations

GTAW	Gas Tungsten Arc Welding
HAZ	Heat Affected Zone
PWHT	Post Weld Heat Treatment
HSLA	High Strength Low Alloy
COD	Crack Opening Displacement
WPS	Welding Procedure Specification
ASME	American Society of Mechanical Engineers
API	American Petroleum Institute
SMAW	Shielded Metal Arc Welding
YS	Yield Strength
UTS	Ultimate Tensile Strength
AWS	American Welding Society
ASTM	American Society for Testing and Materials
EDS	Energy Dispersive Spectroscopy
SEM	Scanning Electron Microscope
ASM	American Society of Materials
NDT	Non-destructive Testing

1. Introduction

1.1 Welding

Welding is considered to be the most widely used metal joining process in the industries and is defined as “a process in which two or more than two pieces of metal are joined together by the application of pressure, heat or both in combination”. Welding is essentially used in manufacturing of almost every product. However, this process consumes major portion of the product cost and creates difficulties in production.

There are many points which explain this statement. First of all, welding is a multidisciplinary process. This means that multiple disciplines (such as mechanics, materials engineering, physics, chemistry, and electronics) will be needed for problem solving. Therefore usually a very high level training with profound knowledge is required to an engineer to bring these disciplines together and apply them effectively in the variety of processes.

Secondly, welding problems usually occur after reaching far into the manufacturing process, where the cost of the scrapped has become too high. Thirdly, a very large percentage of product failures occur at joints because they are mostly located at the areas of high stress and are considered the weak areas of that product. However careful attention to the welding process can bring great rewards like product reliability, safety and economy [1, 2].

1.2 Development in Welding Technology

The earliest welding technology is traced as back as 1000 BC when the forge welding was utilized in the manufacturing of weapons. First time the use of electric fusion process was reported in 1782 in Germany by G. Lichtenberg [4]. However, most of the references confirm that electric arc welding process was developed in the late nineteenth century. A brief summary of the developments in welding processes is shown in Table 1.1 [5, 6].

Before going into the details of welding processes, let’s first go through the schematic presentation of the basic welding processes Fig. 1.1. According to this welding is mainly categorized in two types based on technique.

Table 1.1: History of development of welding

1801	Discovery of electric arc by Sir Humphrey Devy
1860-1865	Wilde first intentionally joined metal by electric welding in early 1860 and was granted a patent in 1865 for his work
1885	De Meritens obtained patent of electric arc welding process in England using carbon electrode
1886	E. Thomson obtained a patent on resistance
1887	Benardos, a Russian scientist, got first patent of electric arc welding for slightly different equipment then by De Meritens
1891	Another Russian N. Slavianoff replaced carbon electrode with a metal electrode and obtained a patent on metal arc welding
1908-1940	Kjellberg, a Swedish, got a patent for coated welding electrode Development in joining process continued and major welding process including oxyacetylene, MMAW (manual metal arc welding), GTAW (gas tungsten arc welding), and GMAW (gas metal arc welding) processes were successfully implemented
1960	Advanced welding types such as Electron Beam, Laser and Ultrasonic welding were developed during 1950-1960
2000	Most recent development is magnetic pulse welding introduced

1.2.1 Pressure Welding

Welding process in which external force is applied to cause plastic deformation of both facing surfaces, without addition of filler metal. Usually the facing surfaces are heated in order to facilitate bonding.

1.2.2 Fusion Welding

Welding process in which facing surfaces are melted and joined without application of external force. Usually, but not necessarily, filler metal in molten form is added [1]. One of the major and most widely used welding processes is discussed as under.

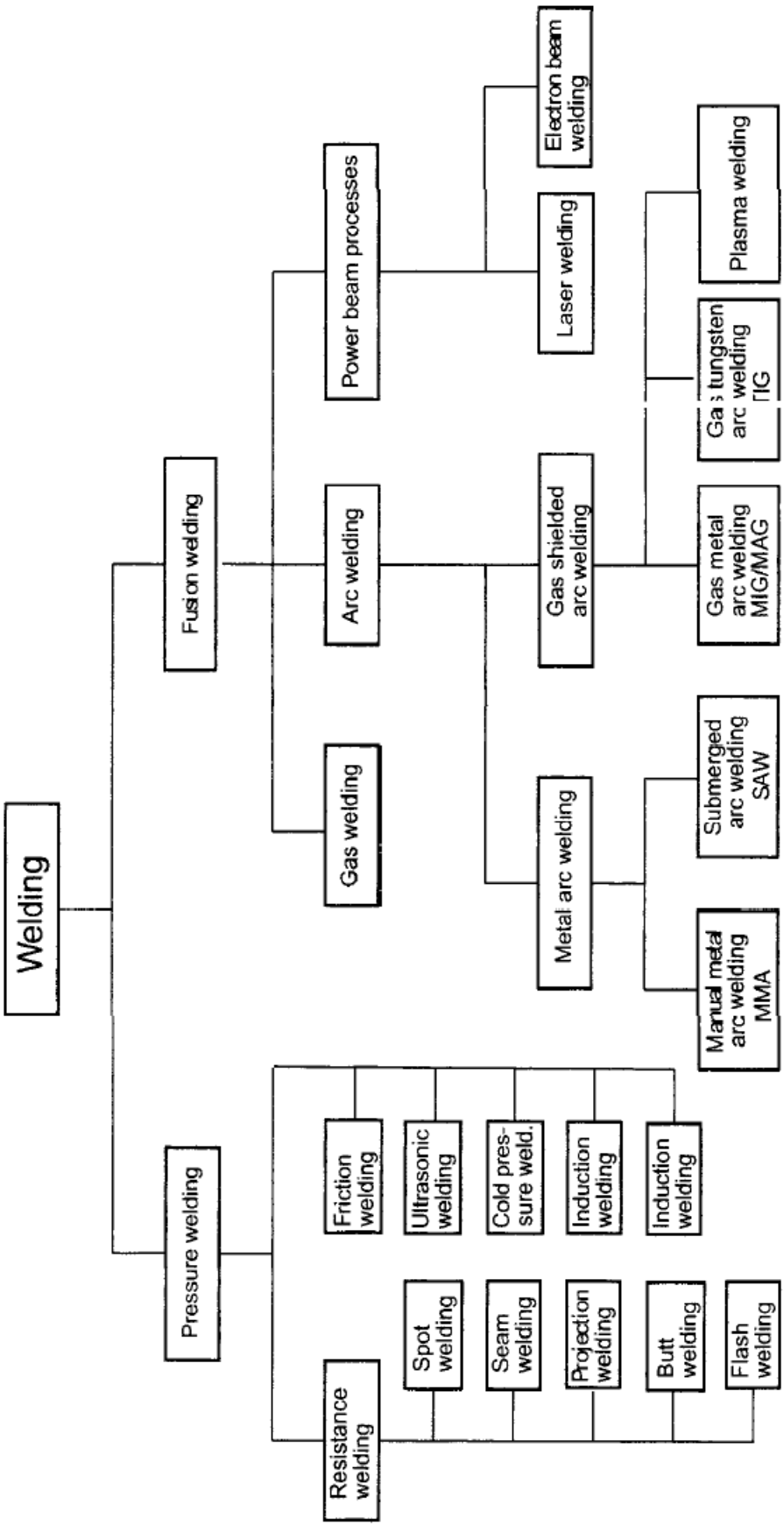


Fig. 1.1: Schematic presentation of Welding Processes [3]

1.3 Gas Tungsten Arc Welding

In GTAW, alternatively called TIG welding, metals are joined by melting them with the help of an arc produced between non-consumable tungsten electrode with or without filler wire as shown in Fig. 1.2b. The torch carrying tungsten electrode connects with a cylinder having shielding gas and with a power supply (Fig. 1.2a). To prevent overheating, a copper tube connected with water cooling system is in contact with the tungsten electrode (Fig 1.2b).

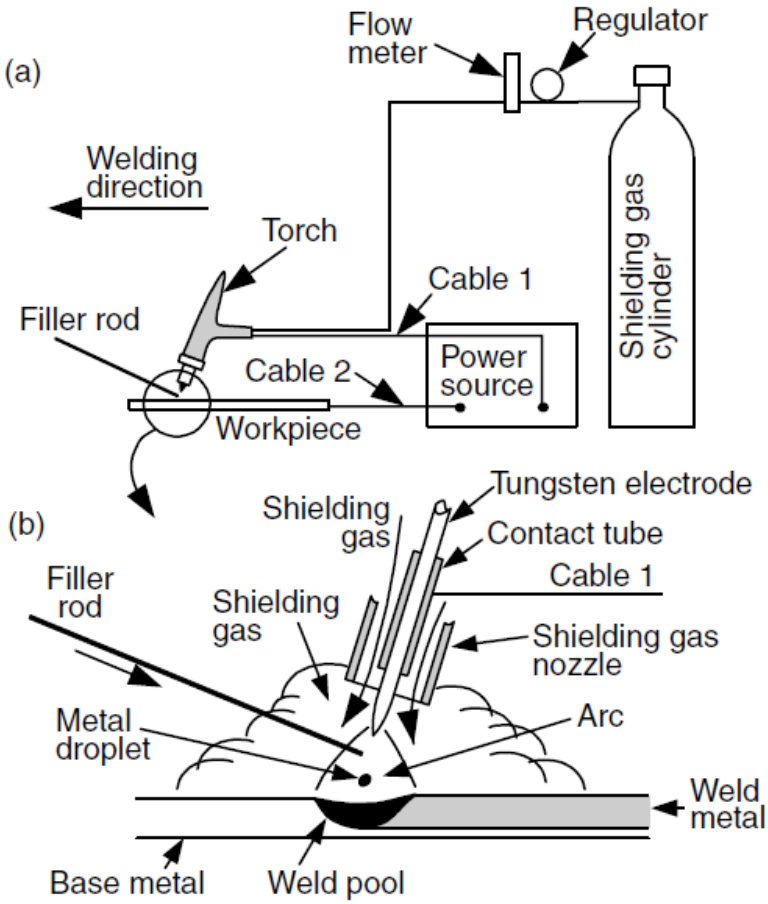


Fig. 1.2: Schematic presentation of GTAW processes [7]

The work piece is also connected to the power supply using a separate cable. A nozzle attached with torch body is used to direct shielding gas towards the weld pool to guard against weld pool-air interaction. Small quantity of inert gas like argon may be used alongside shielding gas for added protection.

1.4 Welding Joint Types and Geometry

Joint types are selected on the basis of welding method and plate thickness. An ideal joint volume provides the required structural strength and quality without an unnecessarily large joint volume. The welding cost also increases with the size of the joint, and the higher heat input will also cause problems with impact strength and distortion. The basics of joint geometry are also shown below in Fig. 1.3 [3].

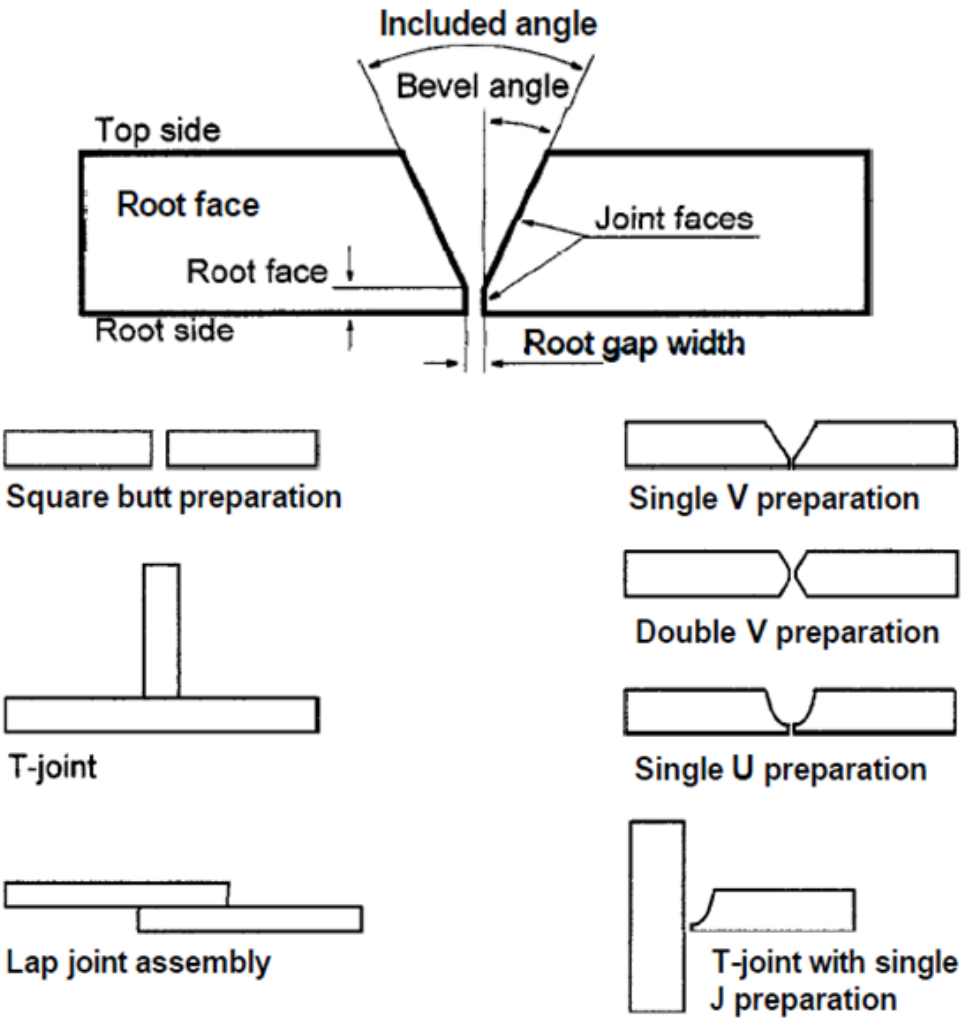


Fig. 1.3: Schematic presentation of joint geometry and joint types

1.5 Features of the Weld

Features of the weld are defined as under and are also shown in Fig. 1.4.

1.5.1 Base metal

Metal pieces required to be joined or surfaced by welding.

1.5.2 Filler metal

Metal, other than base metal used in welding.

1.5.3 Weld metal

All metal (either base or filler) melted and retained in the weld.

1.5.4 Heat-affected zone (HAZ):

The zone around a weld or thermally cut area which does not melt but gets metallurgically affected by welding heat or thermal energy.

1.5.5 Fusion line

The line that separates HAZ from weld metal in a fusion weld is called fusion line.

1.5.6 Weld zone

A zone including HAZ and the weld metal is called weld zone.

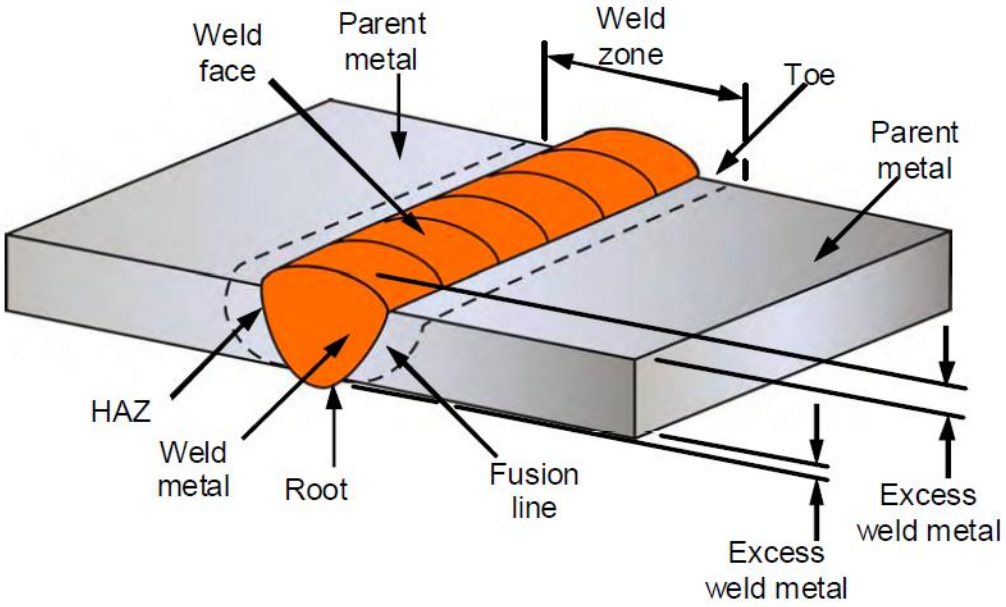


Fig. 1.4: Schematic presentation of features of welded joint [8]

1.5.7 Weld face

The exposed side of the weld metal surface where the welding has been carried out.

1.5.8 Root

Opposite side of the weld face is called root of the weld.

1.5.9 Toe

The border line between the base metal and weld face is called weld toe. It is a significant weld feature with regards to stress concentration. Moreover, cracks of various types including cold cracks and fatigue cracks are usually found to be initiated at the toe area. If the toe blends well with the surface of base metal, stress concentration can be reduced.

1.5.10 Excess weld metal

Weld metal lying outside the plane joining the toes [8].

1.6 Heat Input

Heat input is a relative measure of the energy transferred during welding. In arc welding, energy is transferred from the welding electrode to the base metal by an electric arc. When the welder starts the arc, both the base metal and the filler metal are melted to make the weld. This melting is possible because an adequate amount of power (energy transferred per unit time) is supplied to the electrode. Heat input is a relative measure of the energy transferred per unit length of the weld. It is an important characteristic because, like preheat and inter pass temperature; it influences the cooling rate (Fig. 1.5), which ultimately affects the mechanical properties and metallurgical structure of the weld and the HAZ consequently [9]. Heat input is typically calculated as follows:

$$H = \frac{E \times I \times 60}{S}$$

Where; H: Heat input (kJ/mm)

E: Arc voltage (volts)

I: Current (amps)

S: Travel speed (mm/min)

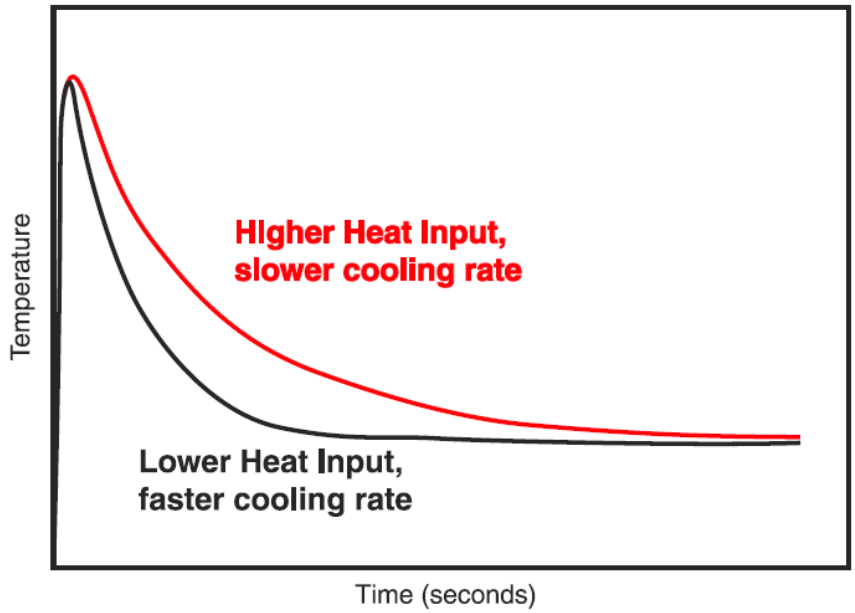


Fig. 1.5: Schematic presentation of heat input during welding [9].

Effect of Heat Input

The welding heat input has a great influence on the properties of weldments. As shown in Fig. 1.5, the effect of heat input on the cooling rate and cooling rate is primary factor that determines the final metallurgical structure of the weld [10, 11]. The cross sectional area of a weld is generally proportional to the amount of heat input. If more energy is supplied to the arc, more filler material and base metal will be melted and thus a larger weld bead will form. The most important characteristic of heat input is that it affects the cooling rate in the welds and thereby affects the microstructure of the weld metal. A change in microstructure directly affects the mechanical properties of weld. Therefore, the control of heat input is very important in arc welding process in terms of quality control [9].

1.7 Welded Structure

The heat produced by welding arc is used to melt the base as well as filler metal and make the welded joint. The accompanying thermal gradients cause distinct metallurgical areas to form in and along the weld joint. In a single pass weld these areas can be simplified as:

a. Weld is the melted base metal and filler metal

b. Heat Affected Zone (HAZ) is the portion of the base metal that has not melted but where the temperature was raised high enough to change the material microstructure and mechanical properties
c. Unaffected base metal, as shown in Fig. 1.6 [8].

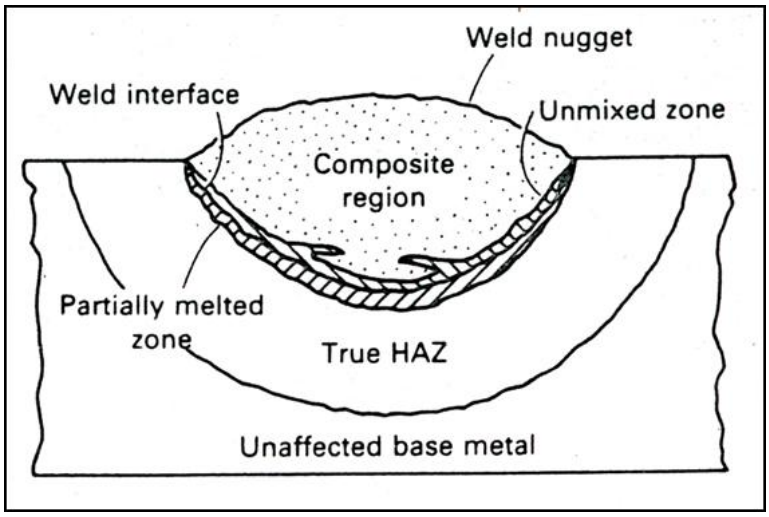


Fig. 1.6: Schematic presentation of the weld zones [9].

In a multipass weld, the situation is further complicated by the thermal gradients caused by the subsequent weld passes on the microstructures of the previous weld beads. The micro-structural changes of the underlying weld beads depend on the welding process and parameters used (thermal cycles). Depending on the base material's composition, special welding procedures may be needed to maintain the integrity of the weld and surrounding area to prevent various defects from occurring such as cracking from a microstructure that has become too hard and brittle [12].

1.8 Welding defects

The presence of surface or internal defects can degrade the performance of a weld that may appear to be sound. Typical welding defects are as follow:

a. Porosity
b. Undercut
c. Overlap
d. Lack of penetration
e. Lack of fusion
f. Shrinkage voids
g. Crater cracking

h. Melt-through or burn-through

i. Inclusions due to entrapped slag or tungsten electrode pieces [13]

1.9 Detection of Defects

Certain Non-destructive testing (NDT) methods are employed to detect the external and intrinsic defects of weldments. Visual, ultrasonic, radiographic, magnetic particle and liquid penetrate testing are widely used methods for the examination / qualification of weldments. These methods have relative advantages and limitations vis-à-vis their application for the inspection of welds.

Radiographic Testing - General

In radiographic testing techniques, a radiation beam is passed through a welded object. On the other end of the object, after passing through, this radiation is captured on some type of media that measures the comparative strength of radiation beams falling on its surface. Generally, this media is a radiographic film. Penetrating radiation or high energy electromagnetic radiations are termed as X-rays or gamma-rays. Typical X-ray machine is shown in Fig. 1.7.

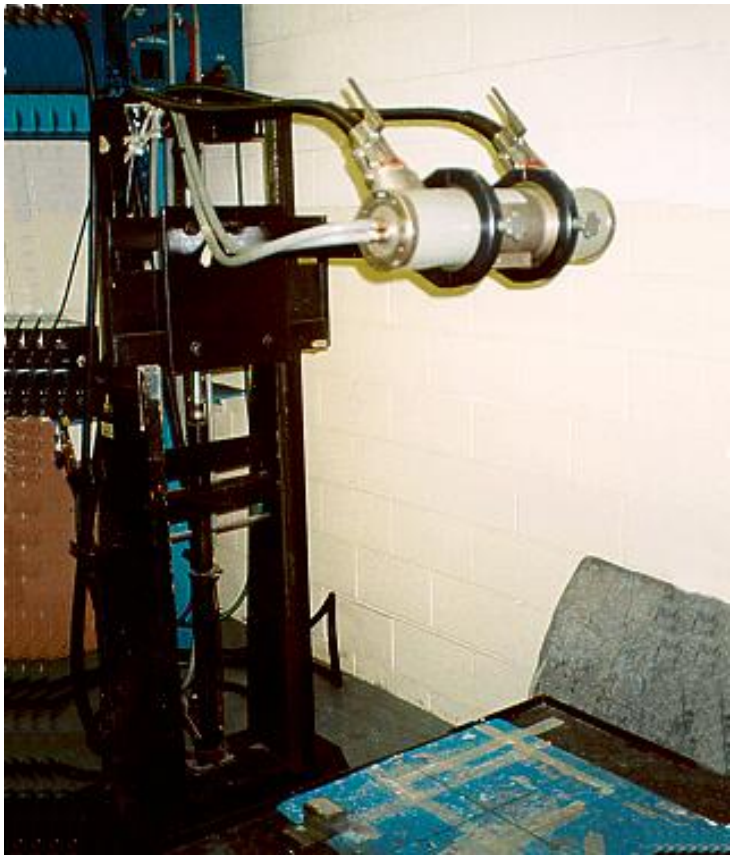


Fig. 1.7: A typical X-ray machine for radiography of weldments [14]

Radiography of Welds

Radiographic techniques can easily detect a range of weld defects including a variety of gas porosities, cracks parallel to ray, root defects and slag inclusions. When a ray passes through the thickness of an object and encounters a change in density and thickness, because of the defect, the absorbed radiation and scattering is substantially different compared to parent object which makes the defect detectable. However, planar flaws like lack of sidewall fusion, lack of inter-pass fusion or in-plane cracks are unlikely to be detected by radiography since there may be little to no difference in the through thickness [14]. Few typical welding defects are also shown on radiographic film in Fig. 1.8.

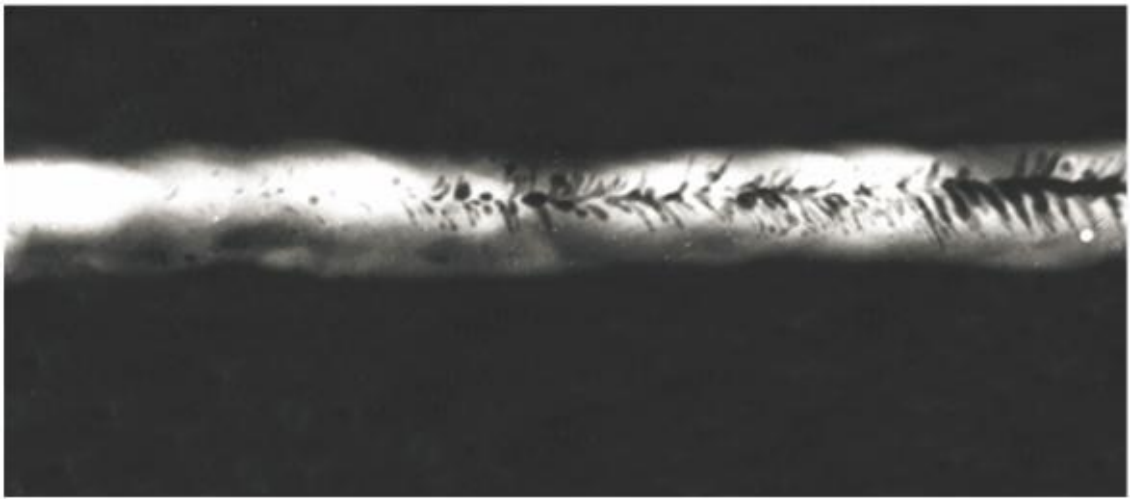


Fig. 1.8: A typical X-ray machine for radiography of weldments [14]

1.10 Destructive Testing

Test coupons, made for qualification of welding procedure, are required by all international welding standards to undergo non-destructive as well as destructive testing. In a destructive test, a variety of test samples are made by destructing a welded joint.

Destructive tests are subdivided as follows:

a. Quantitative Tests; for measurement of a mechanical property
b. Qualitative tests; for assessment of joint quality

Tests for measurement of mechanical property such as impact strength, hardness or tensile strength are quantitative because they measure a quantity of a property. Qualitative testing such as fracture, macroscopic examination and bending is

used to ensure that a joint demonstrates good quality and is defect free i.e. having no surface cracks or fissures etc.

Material manufacturers use a variety of tests to ensure that forgings, rods, plates etc, demonstrate certain minimum values of a property typical of a specific grade. The minimum value of a property of a specific grade is then used by a designer as design basis and the optimum design is one in which properties of welded area are assumed to be equivalent of base metal. The purpose of mechanical testing performed for the qualification of welding procedure is to ensure that the properties of welded area meet the design criteria.

1.11 Tensile Test

For the qualification of welding procedure, tensile testing is required to ensure that welded joint strength meets design requirement. Before the test, dimensional measurements of the samples are accurately taken. These samples are held in the machine jaws and an incremental tensile load is applied until their fracture. Measurement of Yield (Re) is made by attaching an extensometer along sample's length which measures the extension in gauge length with incremental load, as shown in Fig. 1.9.

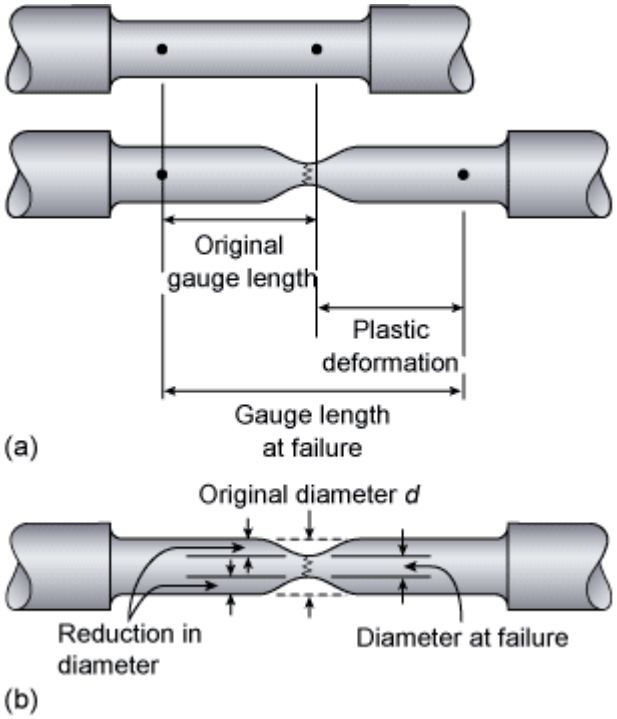


Fig. 1.9: Tensile specimen showing change in length and diameter after plastic deformation [14]

The calculation of tensile strength (Rm) is made by taking load at the point of sample fracture and dividing it by the measured area of sample cross section. Tensile ductility can be measured by following approaches:

a. Percent elongation in gauge length
b. Percent reduction in fracture point area

Acceptance Criteria

Test Sample is acceptable even if it breaks from welded portion if its tensile strength is higher as against the lowest tensile strength of the particular grade of material as specified in the relevant standard. Generally, if a test sample breaks beyond weld zone above 90 ~ 95% of bare minimum tensile strength of the base metal, test results are acceptable. Tensile tests of weldments are also regularly carried out to ensure whether electrodes and/or filler wires are appropriate for tensile properties as specified in relevant standard or not.

1.12 Impact Tests

Charpy Impact test is a widely accepted technique to determine the amount of energy absorbed by a V notched test sample before fracture. When a standard impact test sample encounters an impact load, crack is initiated at the V notch which propagates through the sample material. The energy which is absorbed during testing is actually consumed in crack initiation and propagation. Designers have to make sure that the product material used has enough toughness to avoid material fracture from possible in-service impact loads.

A full sized standard test sample having standardized dimensions is shown below. Specimens are obtained from welded sample plates having a notch at the centre of the weld as shown below.

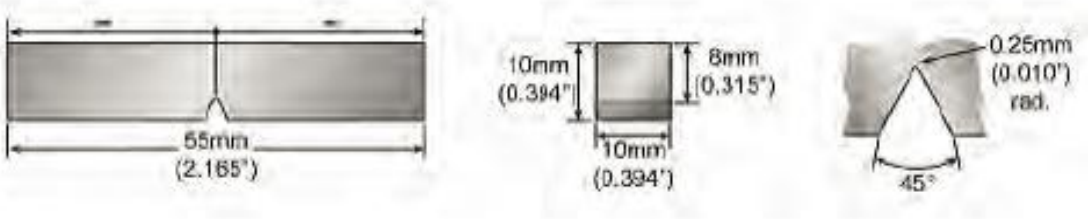
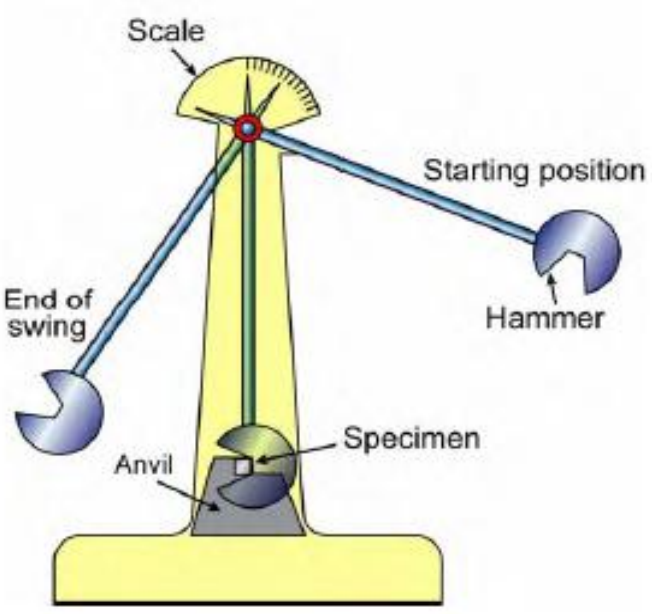
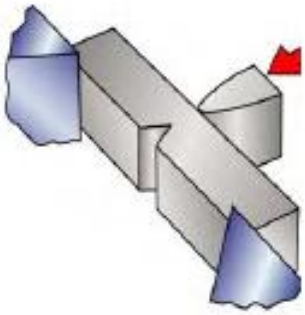


Fig. 1.10: Impact specimen showing notch geometry [14]

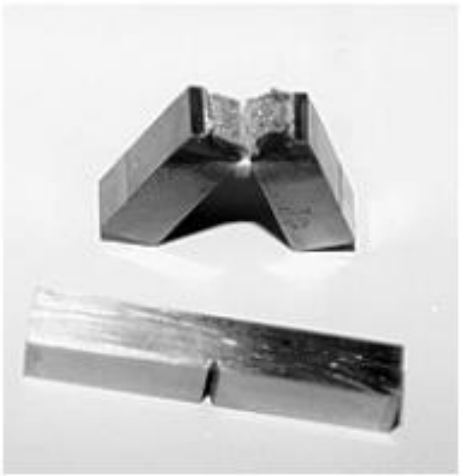
Test specimens are mounted on anvil of impact testing machine in such a way that V notch is exactly opposite to the point where the hammer strikes the sample after release from a height to deliver an impact load. The machine has a graduated scale that shows absorbed energy. The absorbed energy is basically the difference in potential energy of the hammer before and after striking the sample as noted by the difference of hammer position on the scale. Impact test specimens are taken in triplicate as the results for weldments are not as particularly precise as they are for solid metals.



Impact testing machine



Impact specimen on the anvil showing the hammer position at point of impact.



Charpy V notch test pieces before and after testing

Fig. 1.11: Charpy impact testing machine with V-notch specimen before and after test [14]

Acceptance Criteria

An average of a set of test results, usually 3 or 5, is calculated. This average value is then checked against the value specified either in a relevant standard or by customer to verify whether the result meets the specified requirements. Moreover, test samples are examined for any supplementary information regarding its characteristics of toughness which can be useful and worth reporting.

a. Percent crystalline – percentage of crystalline form on the surface of fracture demonstrates a brittle fracture; a complete brittle fracture is concluded if it has full crystalline appearance.
b. Lateral expansion – a more enlarged width just opposite to notch side of the specimen, shown below, indicates that sample is more tough.

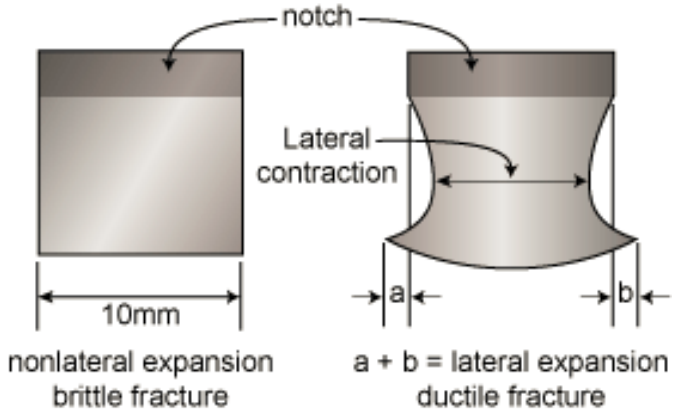


Fig. 1.12: Graphical representation of brittle and ductile fracture in impact test specimen [14]

A clean fracture, whereby the surface of fracture on both sides of the impact sample is totally flat with very less to no transverse strain, indicates severe brittleness. However a test sample which may have a minor crack but with significant transverse strain and without fracture indicates high energy absorption.

1.13 Hardness Testing

Hardness is a property whereby a material resists plastic deformation. It can be measured by resistance of material to indentation on a specific scale using a particular indenter. Steel weldments having hardness more than a specific value can be prone to crack formation, not only in fabrication but also during service. Testing for the qualification of welding for particular types of steels and their applications requires

hardness testing to make sure that no region has exceeded the upper limit of hardness specified for the application.

Following three methods are generally used for testing hardness:

a. Brinell test using a ball type indenter.
b. Rockwell test using either a steel ball or a diamond cone as an indenter.
c. Vickers test using a diamond pyramid with square base as an indenter as shown in Fig. 1.14.

A standardized load is applied to produce an indentation. Indentation size is measured which is used to calculate hardness value of the sample as shown in Fig. 1.13. Smaller the indentation, harder will be the metal. Brinell and Vickers hardness test techniques are appropriate for macroscopic assessment on welded test samples. Typically hardness for the base metal, the weld metal and across the HAZ is measured using a specific indenter.

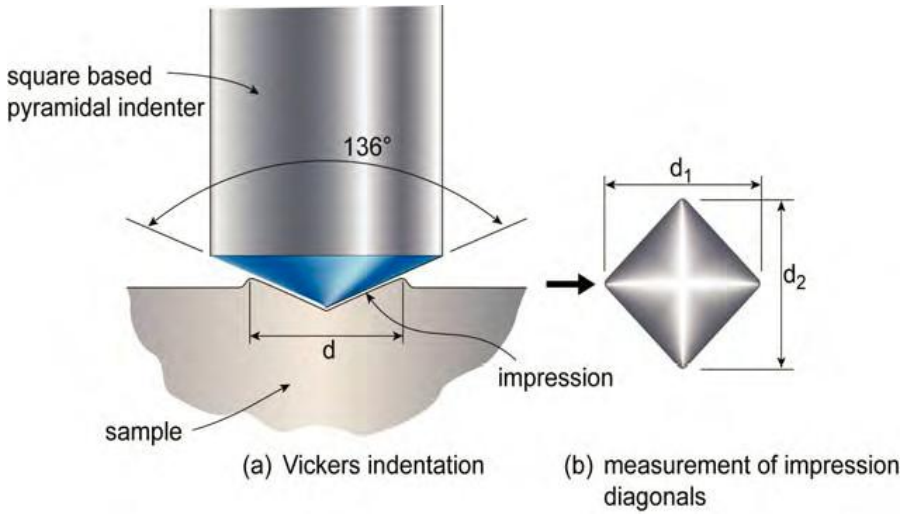


Fig. 1.13: Vickers hardness testing indenter and impression [14].

The Brinell hardness test is typically used for measurement of base metal hardness as the indentation produced by this test is too large for accurate measurement of HAZ hardness. A hardness test using a Vickers tester is demonstrated in Fig. 1.14.

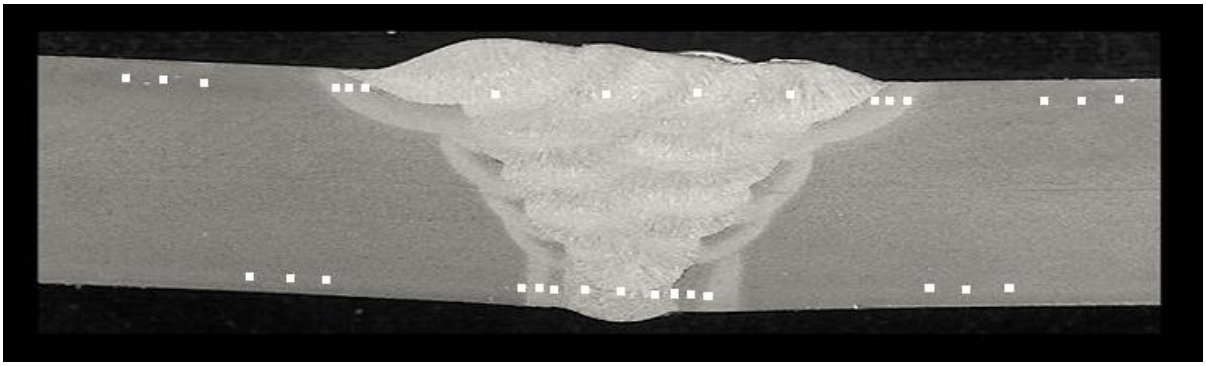


Fig. 1.14: A typical hardness survey of weldments using Vickers hardness test [14].

1.14 Bend Testing

Bend testing samples are routinely taken from test coupons for qualification of welding. A simple method is used for bending a test sample in order to verify that the joint exhibits ductility to some extent and is free from flaws. The test does not involve measurement of ductility however if the sample endures bending load with no sign of fracture, the results is assumed as satisfactory.

There are four types of bending samples:

1.14.1 Face

Sample is drawn such that its axis is perpendicular to the butt weld and is bent in a way that weld face is on the outer side implying that the face is under tension.

1.14.2 Root

Sample is drawn such that its axis is perpendicular to the butt weld and is bent in a way that weld root is on the outer side implying that the root is under tension.

1.14.3 Side

A transverse piece (~10mm) is drawn as a test sample out of full thickness from butt weld which is bent so as to test full thickness of joint thereby having the side of the sample in tension.

1.14.4 Longitudinal bend

Sample is drawn such that its axis is parallel to butt weld longitudinal axis; A 12mm thick sample is used to test root or face of the weld in tension.

Generally guided bend tests are carried out for qualification of welder and welding procedures. In guided test, the specimen is bent around a former having a specific diameter thereby uniformly controlling the imposed strain. The former diameter for a guided test is determined by material type under test, the expected ductility after the welding and post welding heat treatment (PWHT) performed. The test method specified in the standard includes minimum bend angle, typically between 40° ~ 180° which the specimen must experience.

Acceptance criteria

The outer side of bend tests specimen should demonstrate soundness i.e. it is free of cracks and without significant cavities and fissures. However, some standards allow small scale problems, usually less than 3mm in length [14].

1.15 High Strength Low Alloy Steel (HSLA)

HSLA is a superior alloy steel with regards to mechanical properties and corrosion resistance as compared to carbon steel. Carbon content of HSLA, which is typically between 0.05 ~ 0.30 %, contributes to better weldability and formability. HSLA has a maximum of 2.0% manganese as well as small quantities of nickel, copper, chromium, titanium, nitrogen, vanadium, niobium, calcium, zirconium, Molybdenum and rare earth elements.

Titanium, Copper, niobium and vanadium are added to increase strength. These elements are added to change the microstructure of carbon steels, which is usually an aggregate of ferrite and pearlite. The structure after change becomes a very fine dispersion of alloy carbides in a pure ferrite matrix. This increases the material's strength by refining the grain size, which in case of ferrite increases yield strength by 50% after every halving of the mean grain diameter. Precipitation strengthening also increases the strength but to lesser extent. Their yield strengths are usually between 250 ~ 590 MPa. Because of their higher strength and toughness, HSLA steels consume around 25 to 30% more power during forming as compared to plain carbon steels.

Silicon, copper, chromium, nickel and phosphorus are added to increase corrosion resistance. Calcium, zirconium and rare earth elements are added as a purpose of increasing formability by sulphide inclusion shape control. Formability and

impact strength can vary significantly when tested in longitudinal and transverse to the grain flow direction.

HSLA steels are usually 20 to 30% lighter than carbon steels with the same strength. HSLA steels are also more resistant to corrosion than most of the carbon steels. Density of the HSLA steels is usually around 7.8 g/cm^3 [15, 16].

2. Literature Review

Welding is one of the major manufacturing processes in fabrication of several engineering structures. Fusion welding processes involves partial heating of the base metal above melting temperature followed by cooling to room temperature, with or without filler metal. In this cycle the chance of welding defects (which can greatly affect the performance and longevity of the weldments) cannot be ruled out.

Efforts are made to minimize the welding defects by controlling the process variables of any specific welding technique. Despite all attempts, defects are observed after welding and are repaired mostly with the same process parameters as in the normal welding. When a defect is detected in a weld by means of some non-destructive test (e.g., radiography), it is first removed by some mechanical means and inspected to verify the effective removal of the defect in order to re-weld as per a qualified welding procedure (WPS).

2.1 Definition of Repair

As per ASME Sec IX 'repair' is defined as; a weldment in which a flaw is mechanically removed and repair welding is performed before the weld joint is presented to final visual inspection. Examples of such repairs are areas of removal of incomplete fusion, porosity etc., where sufficient metal is mechanically removed and localized addition of weld metal is made in order to make the surface geometry suitable as the normal welding is [17].

2.2 Limitation of Welding Standards

In the qualification of weldments in accordance with Mil-Std-2035 [18], API 1104 [19] and ASME Section IX [17] which are applicable standards to the welding steels, the requirements to make weld repairs in areas previously repaired, indicate that the weld repair should be carried out with a qualified procedure; however, these standards do not limit the number of times of repair that can be applied to an area previously repaired. However there are few standards (Mil-Std-2219A [20], GB 3323, DNV-OS-F101 [21], QJ 1842, IPS-C-PI-270(2) [22] and GB50236-98 [23] etc.,) found, in which the allowed number of weld repairs in weldments are limited to two. One such example is DNV-OS-F101 states "Weld seams may only be repaired two

times in the same area" [22]. According to GB 50236-98 standard, "no more than two repair welds should be performed in the same area" [23].

2.3 History of Work

In past, various studies are carried out to address the welding performance using different techniques and processes. Some investigators studied the effect of heating and cooling (through various heat treatments and welding techniques) on oxide film, micro structures, fatigue and creep behaviour of 316L stainless steel [24 ~ 35]. Some other investigations, particularly in weld repairs (which cause repeated heating and cooling of material), focused on studying the distribution or effect of residual stresses, and most of these studies are based on simulation by finite element analysis [36 ~ 47].

As mentioned earlier, repeated heating and cooling during repair welding not only induces residual stresses but also affects the structural integrity of weldments in terms of its mechanical performance, metallurgical structure and corrosion resistance. A very limited work is found relating to repeated heating and cooling during weld repairs that evaluate changes or effect on the performance of the welds in as welded or annealed states and even the work which is found pertains to carbon steel or stainless steel [48 ~ 50]. It is pertinent to mention here that literally no data available to study the effect of multiple repairs on high strength low alloy (HSLA) steel after subsequent heat treatment (i.e., quenching and tempering) and this was the main driving force to carry out this study. However, some of the similar work done in past is referenced as under.

Lai et al [51] studied the fracture resistance of welds in the heat affected zone (HAZ) of a mild steel plate JIS-3123 after the welds were repaired up to three times, by means of crack opening displacement tests (COD) (as described in the ASTM E-399 standard). Their study mentioned that, the apparent lowering in fracture resistance of weld repair was caused not due to the micro-structural change in the heat affected zone, but was more likely occurred by introduction of defects in the repair.

Mc Gaughy et al [52, 53] evaluated the effects of shielded metal arc welding (SMAW) repairs on the hardness, fracture toughness and residual stress distribution of girth welds of an API 5L X65 steel. The weld repairs were carried out by employing SMAW process and by using E8010-G consumable filler rod. The results indicated

that the stress levels increased as the depth of the repair increased. The grain size measurements indicated that weld repair generally produced larger grains in the HAZ as compared to the normal welding (without repair) condition. This could be the reason for the reduction in toughness found in the HAZ. However, the effect of third and fourth repairs in the same area was not reported.

Vega et al. [54] studied the effect of multiple repairs in the same area on seamless API X52 micro alloyed steel pipe and concluded that a fourth weld repair was also possible. The mechanical properties (Tensile, Hardness and Impact energy) satisfied the requirements of the different standards; however their investigation did not cover the corrosion studies.

Jiang et al. [55] studied the repair weld effect on residual stress distribution in a stainless steel clad plate by employing finite element technique. They showed that transverse stresses are in inverse relation with heat input, while a small change in longitudinal stresses was revealed. A decrease in residual stresses was observed with the increase in welding layers. They investigated that as the number of repairs is increased, the fusion zone becomes thicker, and the content of short ferrite also increases, which leads to some voids in the third and fourth repair welds. It was reported that massive ferrite is generated in the fusion zone of the sample with four repairs due to diffusion of Cr element to the fusion zone. Based on the data including micro-structural evidences, residual stress results and hardness profile, it was proposed that the clad plate cannot be repaired more than 2 times.

Lin et al [56] investigated effect of repeated repair welding on micro-structural, impact strength and corrosion properties of AISI 304L stainless steel. The study was conducted by fabricating only two weld repair specimens, one specimen repaired just one time (designated as WD-1) and one specimen repaired five times (designated as WD-5). The results of the study showed that increasing number of repair welds have no significant effect on the impact strength; however, the fracture characteristics were affected. Furthermore, increasing number of repair welds caused uniform and pitting corrosion in the stainless steel.

Silva et al [57] evaluated the effect of welding heat input on the microstructure, hardness and corrosion resistance of AISI 316L austenitic stainless steel plate with AWS E309MoL-16 weld metal. Their investigation revealed that the corrosion rate reduced as the heat input increased.

Ali et al studied and evaluated changes in the mechanical, micro structural and the corrosion properties of stainless steel 316L under multiple repair welding (SMAW) using E316L filler metal. Base metal and welded samples with different conditions of shielded metal arc welding repairs were studied by looking in the chemical composition of the phases, micro structural changes, grain size and the effect on the mechanical and corrosion properties. Hardness of the heat affected zone decreased as the number of repairs increased. A slight decrease in yield strength (YS) and the ultimate tensile strength (UTS) was observed with repair welding however values of YS and UTS were not less than the values of base metal. Significant reduction in impact strength with the number of weld repairs was observed. The sensitivity of HAZ to pitting corrosion was increased by increasing the number of welding repair [58].

Gas tungsten arc welding (GTAW) of HSLA steel was conducted by Honggang Donget al. with different welding heat inputs, and its influence on Vickers hardness, microstructure and impact toughness of heat affected zone (HAZ) was studied. The microstructure in HAZ with low welding heat input mainly consisted of martensite, and the micro-hardness of coarse grain HAZ was measured higher than that of fine grain zone. The results show that increasing the welding heat input could suppress the formation of martensite and reduce the micro-hardness of HAZ. However, the impact toughness of HAZ was not improved with the increase of welding heat input [59].

2.4 Motivation

In view of aforementioned references, it is pretty much clear that up to date, exactly no work to study the effect of multiple weld repairs on microstructure, mechanical properties and corrosion resistance of HSLA steel (after quenching and tempering) has been performed. The purpose of focusing on HSLA is due to its excellent mechanical properties, weld-ability and wide use in various fields, especially in the manufacturing of pressure vessels. Welding of HSLA steels is indispensable in the manufacturing of these large scale structures [60]. In large fabrication facilities, the volume of repairs is also not less than the manufacturing process. So it is necessary to pay more attention to the influence of heat input and repeated heating and cooling during multiple repair welds on various physical chemical and mechanical

properties of steel. Therefore the purpose of this study is to evaluate changes in different attributes of HSLA steel after multiple weld repairs.

In this study, this will be investigated by conducting several weld repairs (up to repair 5) on HSLA steel sheet, followed by post weld heat treatment (PWHT) i.e., low temperature annealing to relieve welding stresses after every repair time. Radiography is performed on each welded plate to ensure that the samples are free from welding defects. The existence of welding defects can affect the results of mechanical testing and hence can affect the results for this reason this variable is also precluded. After radiography, samples for each type of testing will be retrieved from the qualified portion of the welded plates. All these samples will then be subjected to testing after quenching and tempering.

The quantitative comparative analysis on the basis of results obtained, will be presented to analyze the effect of repeated repairs on the weld performance of HSLA steel. The effect will be analyzed by performing chemical composition, mechanical testing (which includes tensile, impact, bend and hardness tests), corrosion resistance and micro-structural analysis.

3. Experimental Work

3.1 Material Information

A hot rolled HSLA steel sheet of 3.8 mm (qualified in terms of surface quality, mechanical properties, chemical composition, heat treated state and the properties after quenching and tempering as per requirement of GB 5067-85) was selected for experimental work. Material was A24303 and the percentage composition is shown in Table 3.1.

Before cutting the sheet for welding samples, macro etching was performed to reveal the direction of the grain flow i.e., the rolling direction of the sheet using in accordance with ASTM E 340-00 (Standard Test Method for Macro-etching Metals and Alloys). Samples were etched chemically with 10 ml HCl solution with 100 ml water. In order to get the welding samples in a direction parallel to the rolling direction, all the sheets were cut in a direction perpendicular to the rolling direction.

Table 3.1: Chemical composition of A24303 (HSLA) steel [61].

Composition of Elements (%)								
	C	Mn	Si	Cr	Ni	P	S	Cu
Actual	0.3	1.05	1.08	1.01	0.15	0.019	0.0030	0.021
Standard	0.28~0.34	0.8~1.1	0.9~1.20	0.8~1.1	$\leq$ 0.30	$\leq$ 0.025	$\leq$ 0.025	$\leq$ 0.030

The characteristic of exhibiting different strength and ductility values with respect to the direction of working is referred to as mechanical anisotropy. Due to directionality/anisotropy, all materials show difference in mechanical properties in different directions. Strength and ductility are almost always greater in the direction parallel to that of working and is exploited in the design of wrought products [62].

Since the index values (heat treated) of A24303 steel as per GB/T 3077-1999 are in longitudinal direction as mentioned in Table 3.2; that is why samples for evaluation of repair welds were selected in longitudinal direction. Furthermore engineering products are always designed and manufactured in such a way that the best directional properties are in their maximum stress direction.

Table 3.2: Mechanical properties of A24303 (HSLA) steel in quenched and tempered state [63].

Material	Mechanical Properties					
	Tensile Strength (MPa)	Yield Strength (MPa)	Elongation (%)	Reduction in Area (%)	Impact Strength (J/cm^2)	Hardness (HRC)
A24303	$\geq$ 1080	$\geq$ 835	$\geq$ 10	$\geq$ 45	$\geq$ 49	$\geq$ 38

3.2 Welding and Multiple Repairs

After revealing the flow direction of grains, sheet was marked with rolling direction on it and four plates of (1500 x 120 x 3.8 mm) were cut through it. Out of four similar sized sheets, two are shown in Fig 3.1. It is pertinent to mention here that the sheet before cutting was also subjected to ultrasonic testing for detection of intrinsic defects (if any). Presence of an internal defect may affect the mechanical properties and hence may lead the results to disqualification. Therefore this factor is also ruled out so that only the effect of repair cycles during welding may be analyzed.

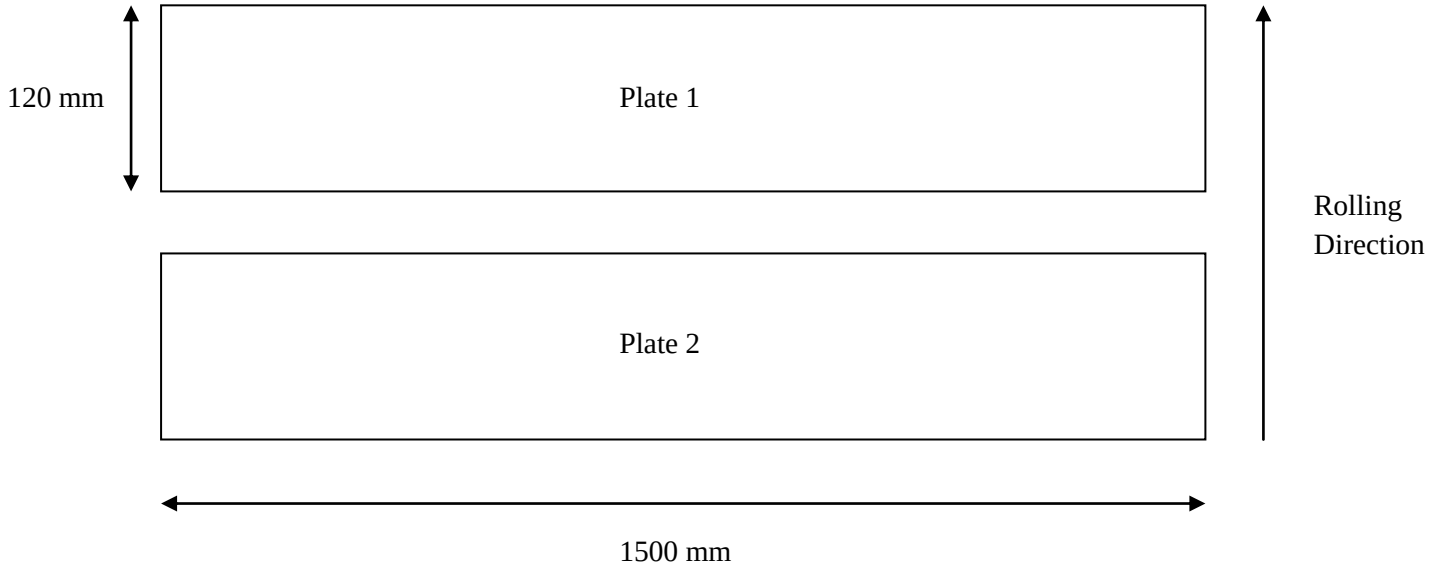


Fig. 3.1: Sketch of welding sheets for welding samples.

Single V butt joint as shown in Fig. 3.2 was machined out on planar machine. Mechanical cleaning through sand blasting with subsequent chemical cleaning of joint was carried out in order to lessen the chances of defects during welding. Afterwards the plates were welded in accordance with an approved welding procedure specifications (WPS) using automatic GTAW in which Argon was used as shielding gas.

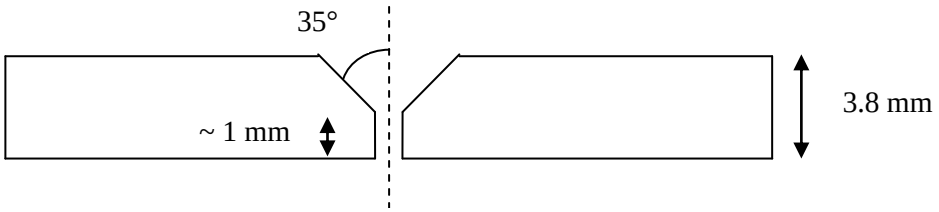


Fig. 3.2: Sketch of weld joint.

Compositions of filler wire along with welding parameters are as below in Table 3.3 and Table 3.4 respectively. Welding procedure specifications (WPS) in light of ASME Sec IX were fixed and followed for all the welded plates so that variations in these may not cause change in mechanical or any other properties after testing.

Table 3.3: Chemical composition of H18CrMoA welding wire [64].

Composition of Elements (%)									
	C	Mn	Si	Cr	Mo	Ni	P	S	Cu
Actual	0.19	0.55	0.28	1.03	0.22	0.23	0.023	0.009	0.08
Standard	0.15~0.22	0.4~0.7	0.15~0.35	0.8~1.1	0.15~0.25	≤0.3	≤0.03	≤0.025	≤0.2

Table 3.4: Welding Parameters [65].

Wire Diameter (mm)	Electrode Diameter (mm)	Wire Feed Rate (m/hr)	Welding Speed (m/hr)	Arc Voltage (V)	Current (A)	Gas Flow Rate (L/min)	Polarity
1.6	4	10	12 ~ 14	13 ~ 15	180 ~ 210	10 ~ 12	DCEN

After welding, the weld was inspected visually and visual defects like undercut, lack of penetration, under fill, crater etc (if any) were removed. The joint was inspected dimensionally for weld width, front reinforcement height and root penetration. All these dimensions were conformed according to the stipulated values and are also shown in Fig. 3.3.

After welding, visual and dimensional inspection welded sheet was subjected to post weld heat treatment (PWHT) i.e., stress relief annealing in order to relief the stresses produced during welding using following annealing cycle Table 3.5 as per relevant standard.

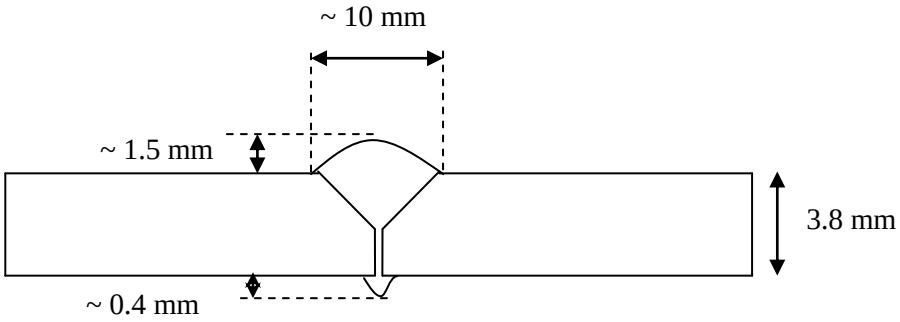


Fig. 3.3: Sketch showing dimensions of weldment.

As per previous practice all these variables (like stress relief annealing temperature, holding time and furnace atmosphere) were kept fixed for all the welded plates so that effect of repair times can only be analyzed.

Table 3.5: Post weld heat treatment (PWHT) cycle [66].

Loading Temperature (°C)	Heating Temperature (°C)	Heating Time (hr)	Cooling Temp (°C)	Cooling medium
640 $\pm$ 10	640 $\pm$ 10	1	250	Furnace Cool

The welded plate after PWHT was undergone through radiography to check the weld for intrinsic defects. Non-destructive testing (radiography) at this stage was employed to make sure that the welded plate is free of defects. If a plate with some welding defects is processed further, the defects will degrade the mechanical properties during testing and hence the effect of repair times cannot be studied purely. Therefore all the process variables right from the beginning to the finishing process (welding joint geometry, welding parameters and PWHT) were fixed for every welded plate.

After welding, NDT and PWHT, a portion of 500 mm length was cut off from the welded plate as shown in Fig. 3.4 and was punched as ‘0R’ which means as-welded or normal welding or without any repair. The remaining portion (1000 mm in length) of the plate was subjected to planar machine for removal of weld bead. Whole weld bead was removed leaving 1 mm weld metal of root pass. After removing the weld metal, remaining plate was welded again to make it repair - I plate with subsequent PWHT.

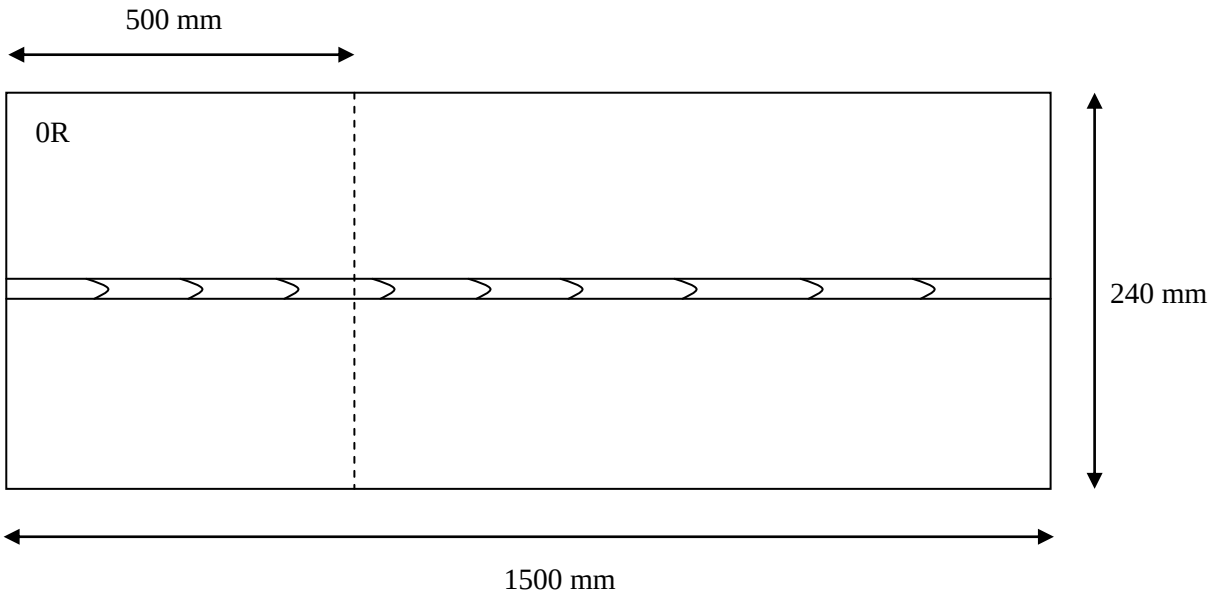


Fig. 3.4: Sketch showing cutting of welded sheet (500 mm length) after 1st time welding i.e., no repair or 0R.

Radiography was also performed to make sure that the weldment is free from welding defects. As mentioned earlier, if the welded sheet with some welding defect is subjected to testing, defects will influenced the results of mechanical properties and hence the whole study will become erroneous. It is restated that all the parameters of welding and stress relieve annealing were kept constant during repair-I welding. After carrying out repair - I welding, PWHT and NDT the next portion of 500 mm length was cut through shear machine as shown in Fig. 3.5 and was also engraved 1R.

Same procedure as before was opted for remaining 500 mm length welded sheet. Weld was first removed through planer machine, re-welded (second time repaired) and subjected to PWHT. After stress relieve annealing the welded sheet was checked for intrinsic defects through radiography and found qualified (free of defects) and finally engraved with 2R as shown in Fig. 3.6.

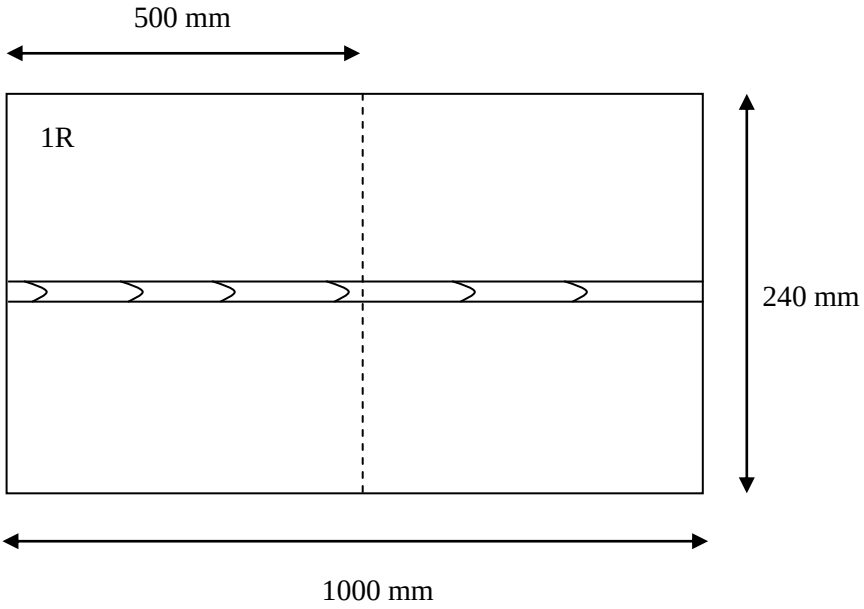


Fig. 3.5: Sketch showing cutting of welded sheet (500 mm length) after second time welding or first time repair i.e., 1R.

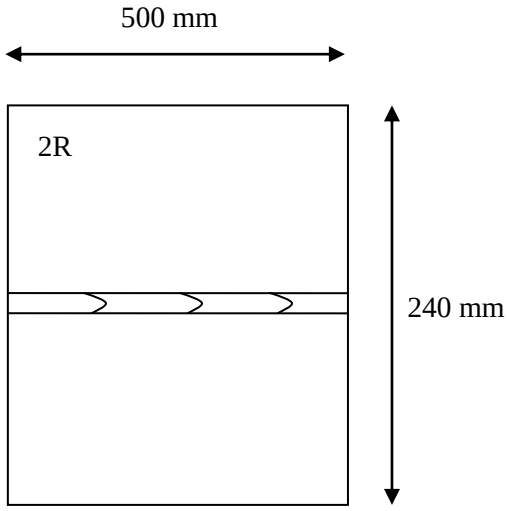


Fig. 3.6: Sketch showing left over welded sheet of 500 mm length after third time welding or second time repair i.e., 2R.

So far, three samples were prepared with no repair, one time repair and two times repair i.e., N, 1R and 2R. As stated earlier, four sheets each of size (1500 x 120 x 3.8 mm) was cut. Two sheets, out of these four were welded to make 0R, 1R and 2R test samples. Remaining two sheets of same dimensions were also welded to make R-3, R-4 and R-5 samples. Joint design, welding process / parameters, filler wire and PWHT were kept constant during processing of these samples. Joint design was prepared as per Fig. 3.2, filler wire and welding parameters were as per Table 3.3 and

3.4 respectively. After welding, it was subjected to PWHT and the parameters were as per Table 3.5 as in previous plate.

After welding and PWHT, weld bead was removed, re-welded and again subjected to PWHT for stress relieving and hence one time repair on this plate was completed. After that whole procedure right from removal of weld till PWHT was repeated for second time repair and for third time repair as well. After carrying out third weld repair and PWHT, weldment was tested for its intrinsic defects through radiography to confirm that the plate is defect free and then a portion of 500 mm length was cut through shear machine and was engraved as 3R as shown in Fig. 3.7.

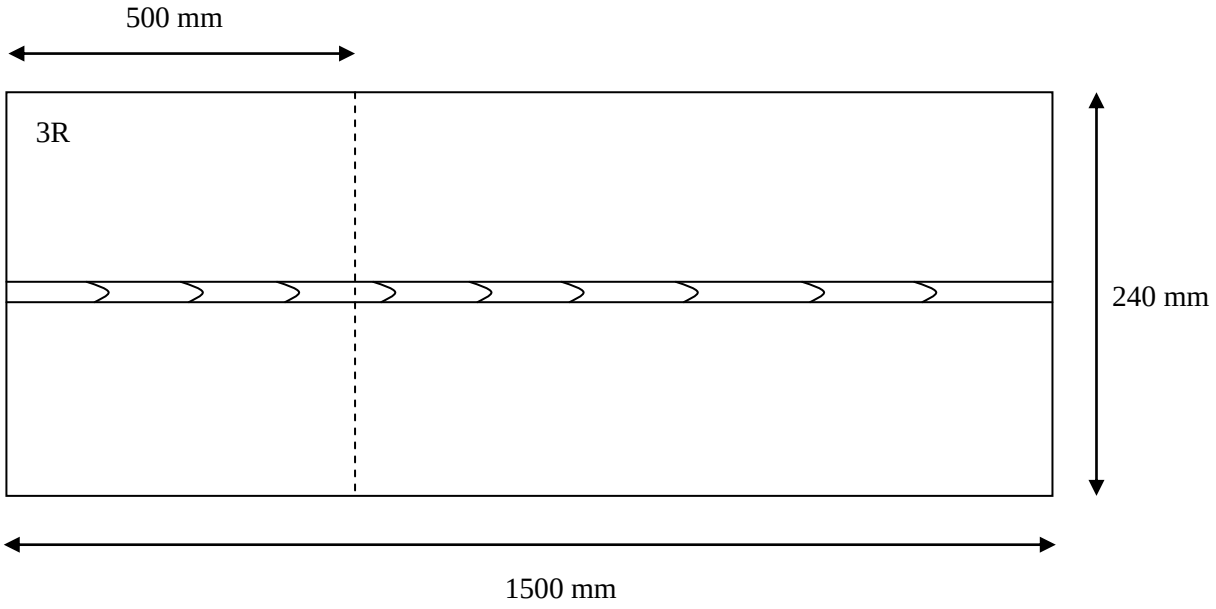


Fig. 3.7: Sketch showing cutting of welded sheet (500 mm length) after fourth time welding or third time repair i.e., 3R.

As per previous plate, the remaining portion (1000 mm in length) of the plate was subjected to planar machine for removal of weld bead. Whole weld bead was removed leaving 1 mm weld metal of root pass. After removing the weld metal, remaining plate was welded again to make it repair - 4 plate with subsequent PWHT. After carrying out fourth time weld repair and PWHT, weldment was tested for its intrinsic defects through radiography to confirm that the plate is defect free and then a portion of 500 mm length was cut through shear machine and was engraved as 4R as shown in Fig. 3.8.

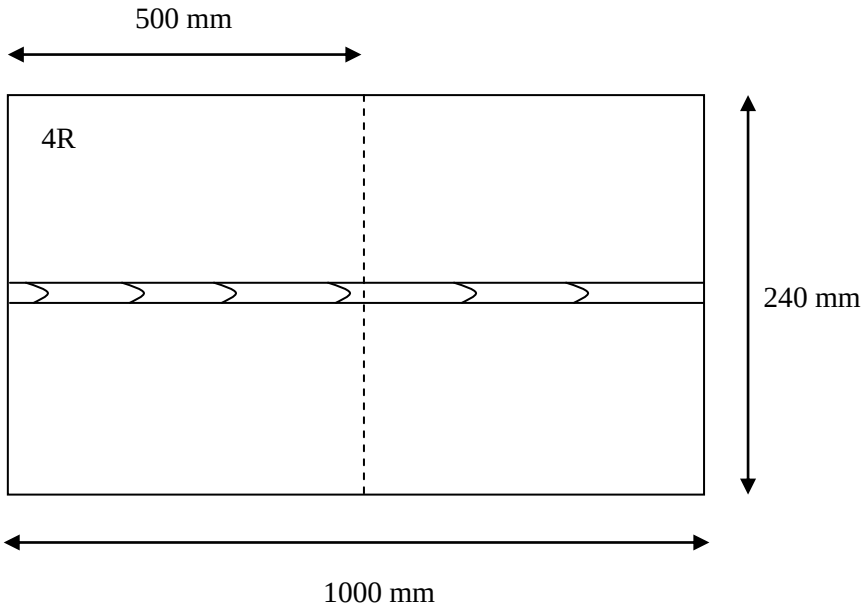


Fig. 3.8: Sketch showing cutting of welded sheet (500 mm length) after fifth time welding or fourth time repair i.e., 4R.

Similarly, weld bead of remaining (500 mm length) welded sheet was again removed through planer machine and re-welded fifth time and then subjected to PWHT. After stress relieve annealing the welded sheet was checked for intrinsic defects through radiography and found qualified (free of defects) and finally engraved with 5R as shown in Fig. 3.9.

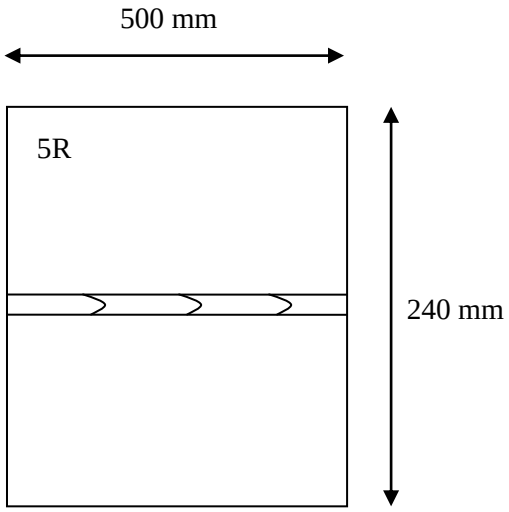


Fig. 3.9: Sketch showing left over welded sheet of 500 mm length after third time welding or fifth time repair i.e., 5R.

3.3 Heat Treatment

Once all the six plates (N, 0R, 1R, 2R, 3R, 4R, 5R) were welded for their respective repair time, stress relieve annealed, tested for their intrinsic defects through radiography and cut in equal length were than subjected to quenching and tempering. Since austenitizing temperature of A24303 alloy is quiet high therefore there are substantial chances of de-carburization at that temperature. De-carburization can significantly reduce the hardness at the surface and thus during mechanical testing may deteriorate / deviate the results.

In this way the true analysis of the results obtained from samples of various repair times cannot be carried out. In order to cater this, a heat resistant paint was used for the protection of samples from de-carburization at high temperature. Heat treatment (quenching and tempering) parameters are shown in Table 3.6.

Table 3.6: Heat treatment parameters (quenching and tempering) cycle [67].

Loading Temperature (°C)	Heating Temperature (°C)	Holding Time (min)	Cooling Temp (°C)	Cooling medium	Tempering Temp (°C)	Holding Time (min)	Cooling medium
650 $\pm$ 10	890 $\pm$ 10	60	60	oil	480 $\pm$ 20	80	Ambient temp

3.4 Testing of Samples

After heat treatment, the blanks for testing samples were cut through cutting disc on milling machine. The cutting map of the sample blanks from which the final samples for mechanical testing were to be machined is shown in Fig. 3.10. Sufficient allowance on length and width of the final samples (which are to be machined) was kept in sample blanks so that final samples can be machined out easily. It is pertinent to mention here that samples were cut in transverse direction of the weld and hence they were parallel to the rolling direction of the material.

The respective quantity of sample blanks cut through each plate for various kind of testing is mentioned below. 18 x samples were cut through each plate and thus making 102 samples from all 6 x plates of each repair time.

a.	Tensile test	5 samples from each repaired plate
b.	Impact test	5 samples from each repaired plate
c.	Guided bend test	5 samples from each repaired plate
d.	Hardness survey	2 samples from each repaired plate
e.	Chem comp, Metallography & Corrosion	1 sample from each repaired plate

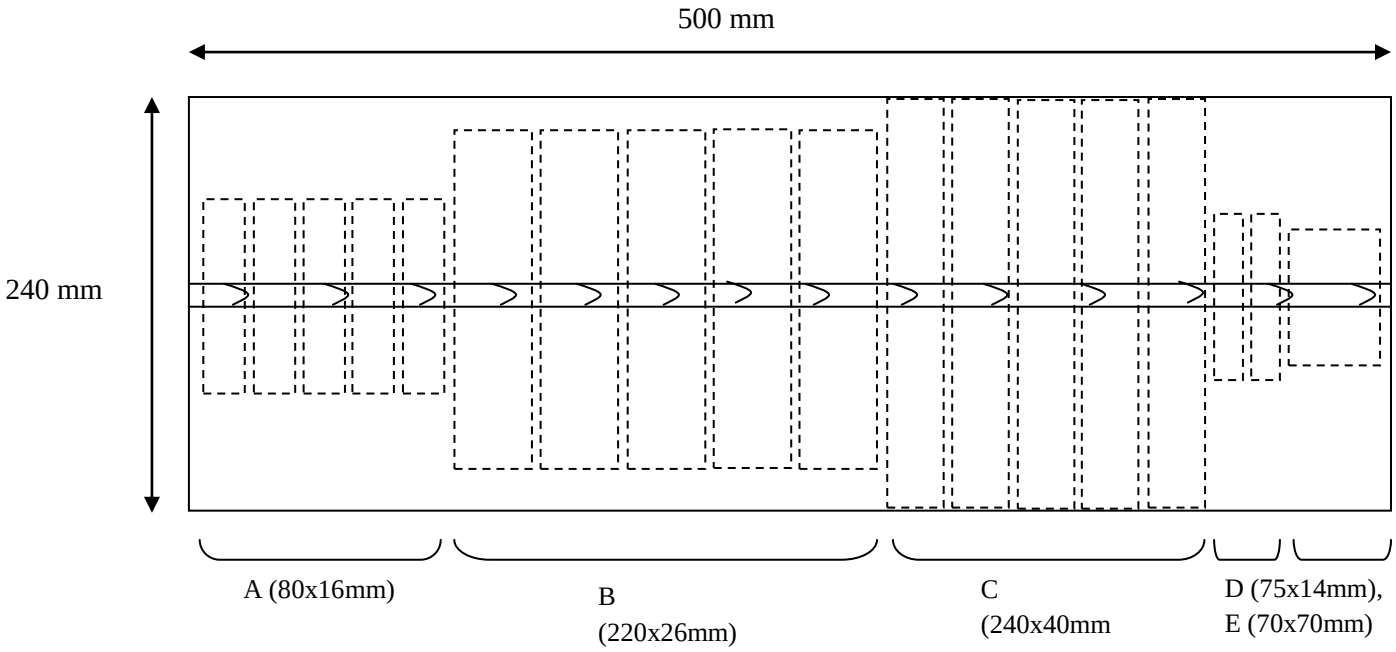


Fig. 3.10: Map of the sample blanks cut in rectangular shapes through each welded plate. A: 5 x blanks for impact testing samples, B: 5 x blanks for tensile testing samples, C: 5 x blanks for guided bend test samples, D: 2 x blanks for hardness profile samples, E: 1 x sample for metallography, elemental analysis and corrosion testing.

3.4.1 Tensile Testing

After cutting 5 x sample blanks for tensile testing from each welded sheet, these were machined in standard sizes (i.e., 200 mm x 20 mm x 3.8 mm) according to the requirements of ASTM E 8/E 8M – 11 (Standard Test Methods for Tension Testing of Metallic Materials). The detailed dimensions were prepared according to rectangular test specimens (standard sheet type) and are mentioned in Fig. 3.11.

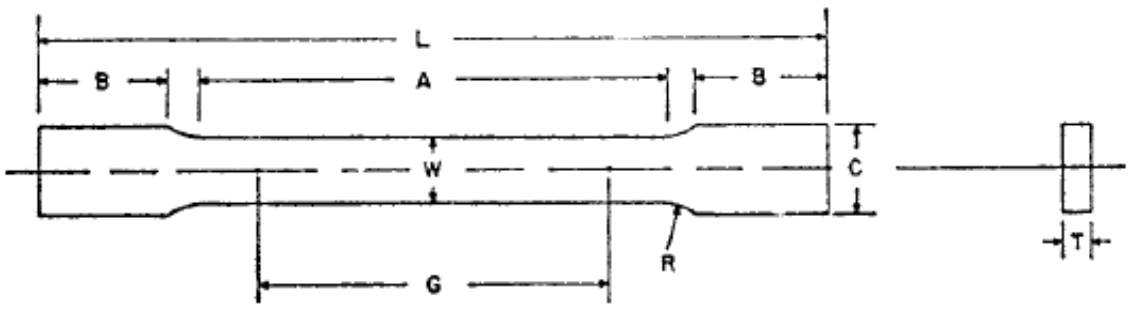


Fig. 3.11: Sketch of the rectangular tensile specimen (standard sheet type) as per ASTM E 8/ E 8M – 11. G: gage length 50 mm, W: width 12.5 mm, T: thickness 13.8 mm, R: radius of fillet 12.5 mm, L: overall length 200 mm, A: length of reduced section 57, B: length of grip section 50.

Testing was performed at room temperature. The extension rate or strain rate was 0.5 mm/min during tension and the machine used was Hydraulic Universal Testing Machine (WE-100) shown in Fig. 3.12. The testing was basically performed to study the effect of multiple repairs on UTS and elongation of the weldments.

Fig. 3.12: Hydraulic universal testing machine WE-100.

3.4.2 Impact Testing

Impact testing relate specifically to the behaviour of metal when subjected to a single application of a force resulting in multi axial stresses associated with a notch, coupled with high rates of loading and in some cases with high or low temperatures. The results of impact tests on notched specimens, when correlated with service experience, have been found to predict the probability of brittle fracture.

In order to study the aforementioned phenomenon, impact testing of the samples cut from repaired plates was also carried out. Already cut 5 x sample blanks for impact testing from each welded sheet were machined in standard sizes (i.e., 55 mm x 10 mm x 3.8 mm) according to the requirements of ASTM E 23-12c (Standard Test Methods for Notched Bar Impact Testing of Metallic Materials). Testing was performed using charpy impact testing machine and V - notched samples were prepared as per Fig. 3.13.

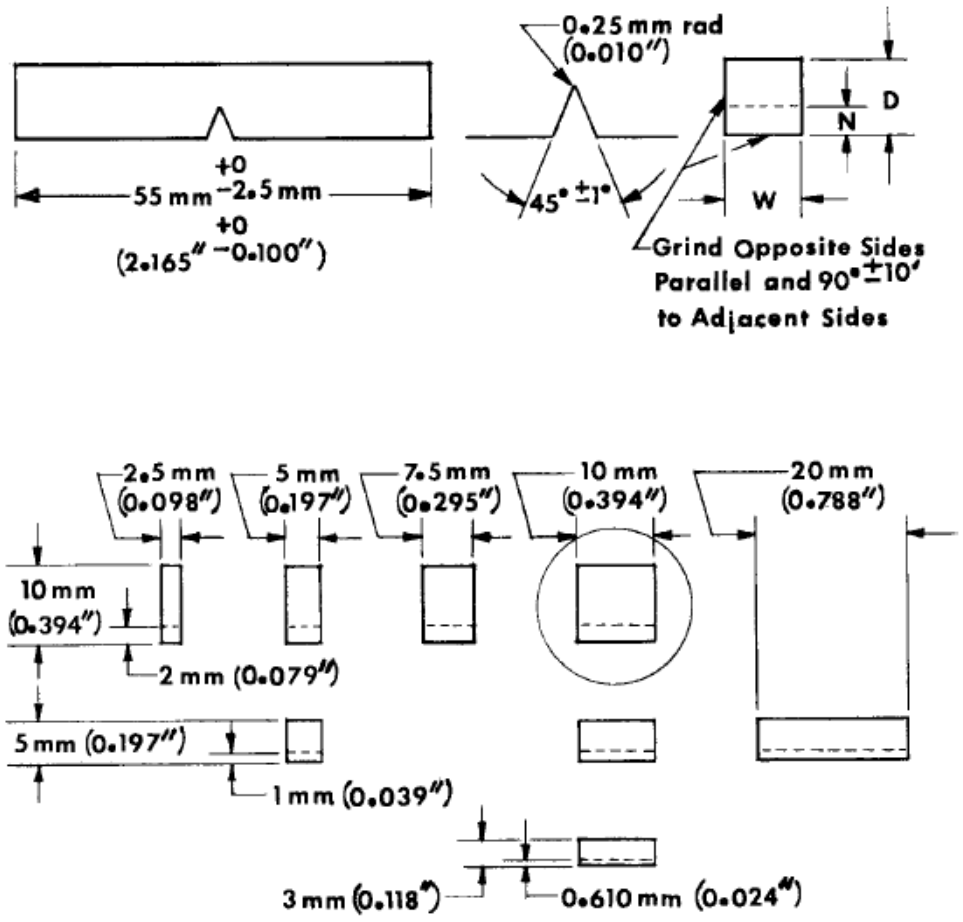


Fig. 3.13: Sketch of the charpy (simple beam) sub size (Type A) impact test specimen as per ASTM E 23-12c.

3.4.3 Guided Bend Testing

Guided bend test is carried out to determine soundness and ductility in welds as evidenced by their ability to resist cracking during bending. In order to perform this, 5x rectangular samples (240 mm x 38 mm x 3.8 mm) from each repair weld plate were machined out and tested to evaluate the quality of welds. Weld reinforcement was removed from the surface of the specimen as shown in dotted line in Fig. 3.14. Testing was performed on Hydraulic Universal Testing Machine (WE-100) in accordance with E 190-92 Reapproved 2003 (Standard Test Method for Guided Bend Test for Ductility of Welds) 40° jig (angle referenced from design specifications).

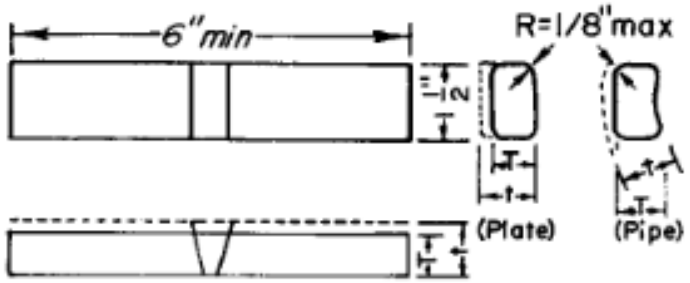


Fig. 3.14: Sketch of the transverse root bend specimen for plate as per ASTM E 190 - 92.

Transverse root bending was performed in which weld is transverse to the longitudinal axis of the specimen which is bent so that the weld root surface becomes the convex surface of the bent specimen. The specimen is forced into the die by a plunger having the shape necessary to produce the desired contour. After unloading the convex surface is examined for cracks or other open defects.

3.4.4 Hardness Testing

The samples for hardness measurement were retrieved from welded samples in such a way that portion from each base metal, HAZ and weld metal was included. After mounting in Bakelite samples were ground using emery papers up to 1000 grit Nos. The specimen should be so prepared or mounted that the surface is normal to the axis of the indenter within $\pm$ 1° of angle. The surface of the specimen should be so prepared that the ends of the diagonals are clearly defined and can be read with precision of $\pm$ 0.0005 mm.

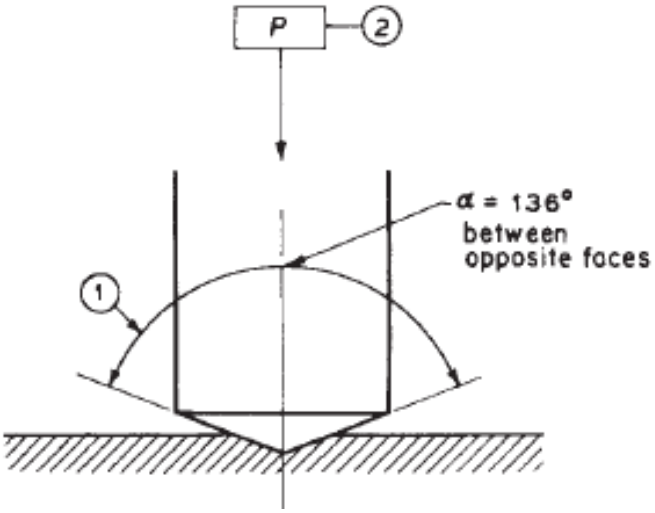


Fig. 3.15: Sketch of the square based diamond pyramid indenter.

Square based diamond pyramid with a face angle of 136° (as shown in Fig. 3.15) is used with applied forces of 5 kgf in accordance with ASTM E 92-82 Reapproved 2003 (Standard Test Method for Vickers Hardness of Metallic Materials). Three indents on each portion (starting from one end) were taken and Vickers hardness numbers were recorded (directly from the screen of Digital Vickers Hardness Tester) on two samples from each repair weld.

3.4.5 Metallography

Metallography was also performed to study the effect of multiple repairs on structure of steel after quenching and tempering. For this purpose the specimens for microstructural analyses were retrieved in such a way that all three zones i.e., base metal, HAZ and weld bead were included. These samples were mounted afterwards in Bakelite for handling during grinding and polishing. These were then ground mechanically using emery paper of grit Nos. 120, 240, 400, 600, 800, 1000, 1200, and 2000 before final polishing with diamond paste of 3 microns as per ASTM E 3-11 (Standard Guide for Preparation of Metallographic Specimens).

Since the samples were of HSLA steel therefore a commonly used etchant (Nital) for iron, carbon, alloyed steels, and cast iron which may also reveal alpha grain boundaries and constituents is used. Samples were etched chemically with Nital having composition of 2 ml HNO_3 and 98 ml ethanol as per ASM Vol. 9 (Metallography and Microstructures) up to 60 s. The surface of each specimen (base

metal, HAZ and weld bead) was then examined using optical microscope and metallographs at 500x were taken.

3.4.6 Elemental Analysis

Since the welding is a high temperature process in which oxidation of various alloying elements takes place according to their nature. Therefore it was certain that the due to multiple repairs on same plate, composition of few elements will change and hence this change may affect the physical, chemical and mechanical properties of the alloy.

In order to study this effect chemical composition on fusion line (the area between weld bead and base metal) and weld bead was determined using energy dispersive spectroscopy (EDS) on SEM in accordance with ASTM 1508 – 98 Reapproved 2003 (Standard Guide for Quantitative Analysis by Energy Dispersive Spectroscopy). SEM was preferred over mass emission spectroscopy because of the width of fusion line. For this purpose, samples were mounted in Bakelite and their surface was prepared according to the requirements of ASTM E 3 – 11 (Standard Guide for Preparation of Metallographic Specimens) for compositional analysis at SEM.

3.4.7 Corrosion Testing

Corrosion test of each repaired sample was carried out to study the effect of weld repairs on corrosion resistance of weldment (including HAZ and adjacent base metal) after quenching and tempering. For this purpose six samples (one from each repair time i.e., 0R, 1R, 2R, 3R, 4R, 5R) were machined out in square form (17 mm x 17 mm x 3.8 mm) from each plate, also shown in Fig. 3.16. Corrosion samples were machined in such a way that the weld bead was in center of the sample with equal size of HAZ on both sides.

Since the corrosion rate on weld bead, HAZ and base metal is considered to be different (as weld bead and HAZ are affected more than base metal due to heating cycles of welding during repairs) therefore it was mandatory to keep weld bead in center and to have equal portion of HAZ and base metal on each side. That is how the factor effecting overall corrosion rate of the sample was eradicated.

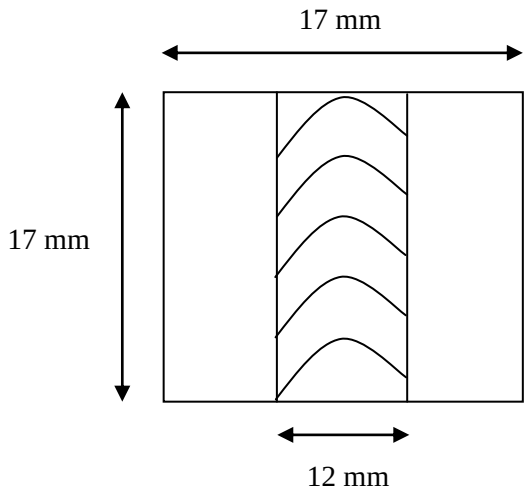


Fig. 3.16: Sketch of corrosion sample of welded plate for salt spray test.

Samples were prepared according to the requirements of ASTM G 1 – 03 (Standard Practice for Preparing, Cleaning and Evaluating Corrosion Test Specimens). Each sample was inspected dimensionally to calculate the area and also each sample was weighed to calculate the weight loss after performing the test. Identification mark was also engraved on each sample. Samples were first cleaned mechanically for any scale formed during quenching and tempering and then with organic solvent to remove any grease oil or contaminations. After cleaning mechanically and chemically samples were tested for corrosion rate in a salt spray chamber. Procedure and conditions required for salt spray chamber were in accordance with ASTM B 117 – 03 (Standard Practice for Operating Salt Spray (Fog) Apparatus).

The apparatus for salt spray (fog) exposure consists of a fog chamber, a salt solution reservoir, conditioned compressed air, atomizing nozzles, specimen supports, heating in the chamber and all the controls [68]. Salt solution prepared for the test was 5 + 1 parts by mass of sodium chloride in 95 parts of water. The specifications of water and salt were conforming to the requirements of ASTM B 117 – 03. Temperature in the salt spray chamber was maintained at 35 °C and the duration of test was 48 hrs.

After removing the samples from the chamber, each sample was rinsed in running tap water to remove the salt and then chemically cleaned for 10 min at 20 ~ 25 °C. The chemical solution used for this purpose was made by mixing 100 ml of hydrochloric acid with 1000 ml reagent grade water and also 10 g of hexa-methylene tetramine. After cleaning corrosion products each sample was dried and the weight was measured and recorded to calculate the weight loss.

4. Results and Discussions

Results of the various tests (to analyse the effect of repairs) performed are shown and discussed below in this chapter.

4.1 Ultimate Tensile Strength

As mentioned in previous chapter that tensile testing was performed to check the strength and ductility of material under uni-axial tensile stress. This information is usually useful for design under certain circumstances. The results of tension test of specimens machined to standardized dimensions from selected portion of the welded plate may not fully represent the strength and ductility properties of the entire weldment or its in-service behaviour in different environments however, this test is considered satisfactory for acceptance testing of weldments [69].

The tensile strength results obtained from tensile testing are shown in Table 4.1. Since five samples were taken and tested from each repair time therefore average of the tensile strength along with standard deviation is plotted as shown Fig. 4.1, which shows the variation in ultimate tensile strength as a function of number of repairs. Figure shows that average tensile strength increases slightly after first repair and got maximum value of 1188 MPa.

Table 4.1: Tensile strength values of 5 x samples from each repair time, their averages and standard deviation.

Sample No.	Ultimate Tensile Strength (MPa)					
	0R	1R	2R	3R	4R	5R
1	1179	1186	1194	1175	1174	1163
2	1180	1199	1180	1199	1170	1176
3	1187	1180	1178	1164	1201	1159
4	1186	1190	1195	1194	1162	1168
5	1188	1187	1190	1196	1178	1156
Average	1184	1188.4	1187.4	1185.6	1177	1164.4
Standard Deviation	3.7	6.2	7.0	13.6	13.1	7.0

After second repair, tensile strength decreases gradually and so in the third, fourth and fifth repairs. Tensile strength value of 3R is approximately equal to the sample having no repair i.e., 0R. Maximum difference of tensile strength observed in this study is about 24 MPa which show a marginal effect of multiple repairs on the tensile strength performance of the heat treated A24303 welded steel.

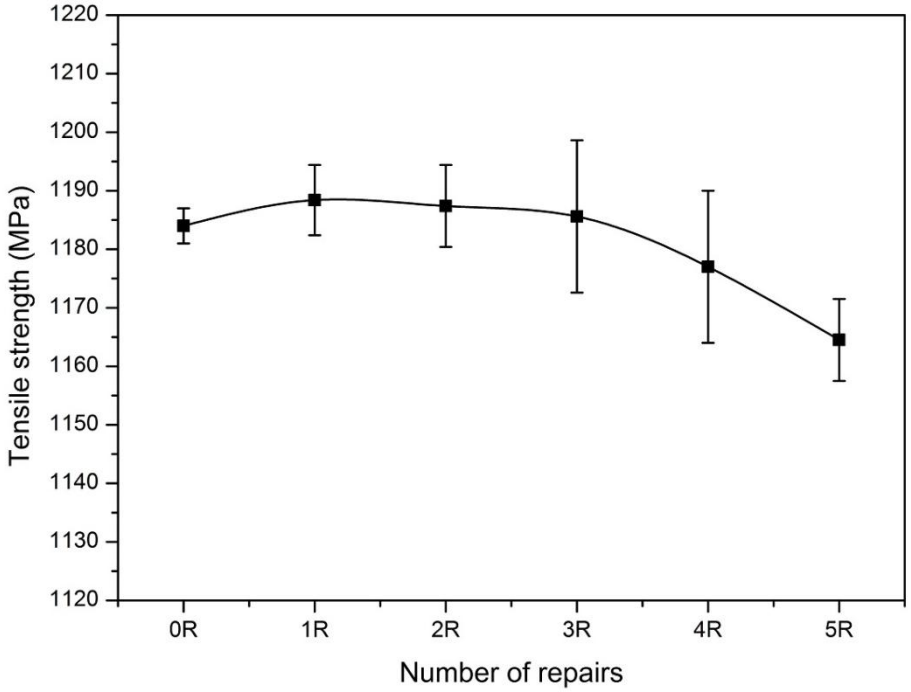


Fig. 4.1: Plot of average tensile strength against repair times.

The obtained corresponding polynomial equation for the variation of tensile strength as a function of number of repairs is as follow:

$$\sigma b = - 2.060R^2 + 10.59R + 1175 \quad (1)$$

Where σb is tensile strength and R represents repair number. The slight variation in the UTS as shown in Fig. 4.1 can be attributed to the contribution of the changes in grain size of HAZ with multiple repairs, the drop in manganese and silicone contents or the decrease in hardness with increasing repairs.

4.2 Elongation

The change in elongation as a function of number of repairs is presented in Table 4.2 and their average values along with standard deviation in Fig. 4.2. Variation in elongation of the samples follows approximately the same trend as generally observed in steels against tensile strength values. The elongation decreases in initial

repair work and then it starts increasing in second, third, fourth and fifth repairs. The reason for this trend can also be attributed to same mechanisms which are believed to be responsible for variation in tensile strength.

Table 4.2: Elongation (%) values of 5 x samples from each repair time, their averages along with standard deviation.

Sample No.	Elongation (%)					
	0R	1R	2R	3R	4R	5R
1	10	9	9	9	10	12
2	11	9	10	10	10	10
3	12	10	10	11	12	13
4	11	10	11	12	11	12
5	10	11	10	10	11	11
Average	10.8	9.8	10	10.4	10.8	11.6
Standard Deviation	0.7	0.7	0.6	1.0	0.7	1.0

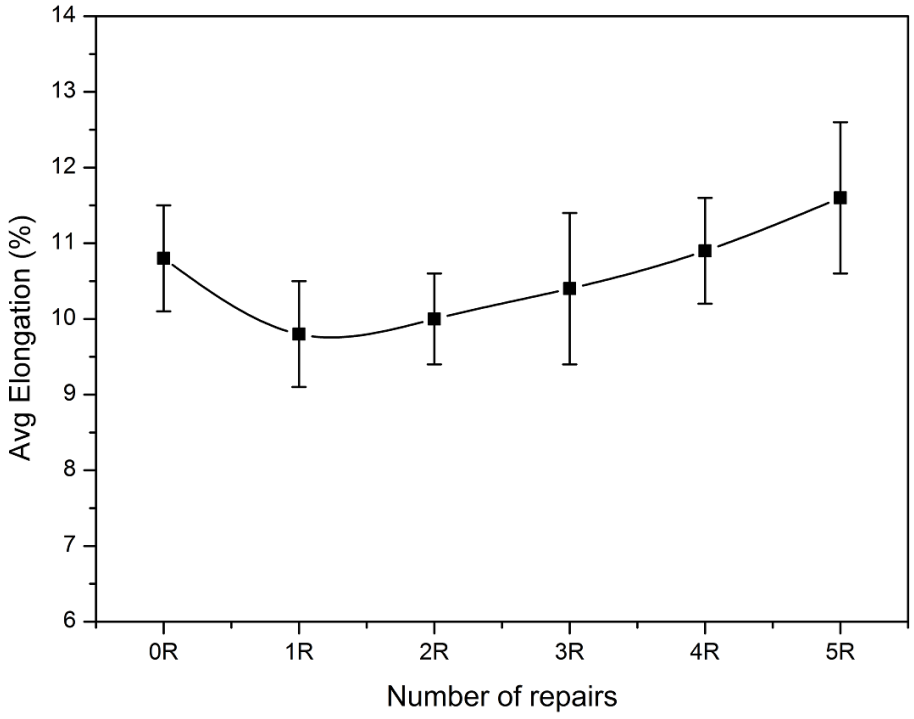


Fig. 4.2: Plot of average elongation (%) values against repair times.

Variation of elongation as a function of number of repairs observed in this study follows following relationship:

$\delta = 0.175R^2 - 1.013R + 11.46$

Where δ is percentage elongation and R represents repair number.

4.3 Impact Toughness

Charpy impact test was performed to measure the impact toughness of the welded plate for each weld repair. Impact strength results of the 5 x samples, their averages and standard deviation are shown in Table 4.3 for each repaired plate. The average values of impact strength calculated for each one of the weld repaired plate along with standard deviation are also plotted as in Fig. 4.3.

Table 4.3: Impact toughness values of 5 x samples from each repair time, their averages and standard deviation.

Sample No.	Impact Strength (J/cm^2)					
	0R	1R	2R	3R	4R	5R
1	93	121	121	130	135	142
2	98	115	125	130	144	140
3	98	122	122	133	142	140
4	102	120	123	125	145	141
5	116	119	122	138	143	152
Average	101.4	119.4	122.6	131.2	141.8	143
Standard Deviation	7.8	2.4	1.3	4.2	3.5	4.5

Variation of impact strength as a function of number of repairs observed in this study follows following relationship:

Impact Strength (J/cm^2) = $- 0.8R^2 + 13.777R + 90.08$

Where R represents repair number.

An increase in the impact strength has been observed with increasing number of repairs. However, after 2R, this increase is sharp up till repair 4. Amount of energy absorbed after 2R has then increased and the highest value of absorbed energy belongs to 5R which is 143 J/cm^2.

The increase in impact value from 4R to 5R is very slight. Increased number of weld repairs leads to increase in impact strength in this particular study conducted on

steel in hardened and tempered state. This behaviour can be attributed to the drop in manganese and silicone contents [70, 71], drop in hardness and strength.

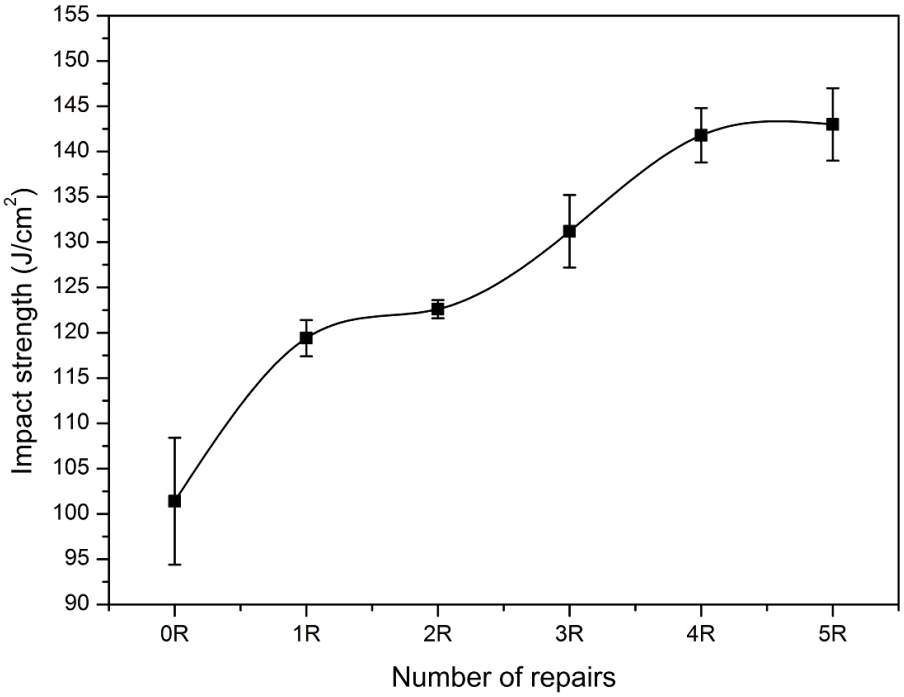


Fig. 4.3: Plot of average impact strength (J/cm^2) values against repair times.

4.4 Hardness Profile

Micro hardness (HV) test results for 2 x samples are reported in Table 4.4 and are also plotted against distance from the weld centre in Fig. 4.4. Indents for hardness were taken on base metal, HAZ and weld bead on both sides of the weld bead. Base metal hardness of all samples is very close to each other with a maximum difference of approximately 25 HV only. The maximum hardness in HAZ is observed in 1R. Furthermore 1R is also second highest in weld bead, followed by 2R, 3R, 4R and 5R in descending order. Overall maximum hardness of 1R samples in HAZ also complies with tensile results which found maximum in 1R among all cases.

In HAZ, results are quite different from welded zone. In this zone maximum hardness is observed in 1R, whereas minimum values are reported in 5R, while hardness values of other samples lies in between 1R and 5R, but still the trend is not linear. In the welded zone, the hardness results are very linear with number of weld repairs. The maximum hardness value is observed in 0R, then it drops as the number of repairs increases and minimum value is observed in 5R.

Table 4.4: Average hardness (Vickers) values of 2 x samples in base metal, HAZ and weld bead

Area	Average Hardness (HV)					
	0R	1R	2R	3R	4R	5R
Base metal	375.5	387	395	368	375.5	382
	374	385	391	368.5	373	380
	369	383	393	365	372	378
HAZ	365	376	385	366.5	344.5	342.5
	362	380.5	360	365	348	347.5
	364	378	363	363	348.5	345
Weld bead	370	364	366	326	319	312
	372	360	354	321.5	317.5	315
	371	366	358	324	319.5	307
	373	357	355	319.5	318	317.5
	369	366	365	327	320	311
HAZ	363	379	361	362	350	346
	362	381	360	365.5	349	348
	364	377.5	385	366	347	342.5
Base metal	368	383.5	392	363	372	378.5
	373	384.5	390	366	373	381
	375	387.5	394	368	374	382

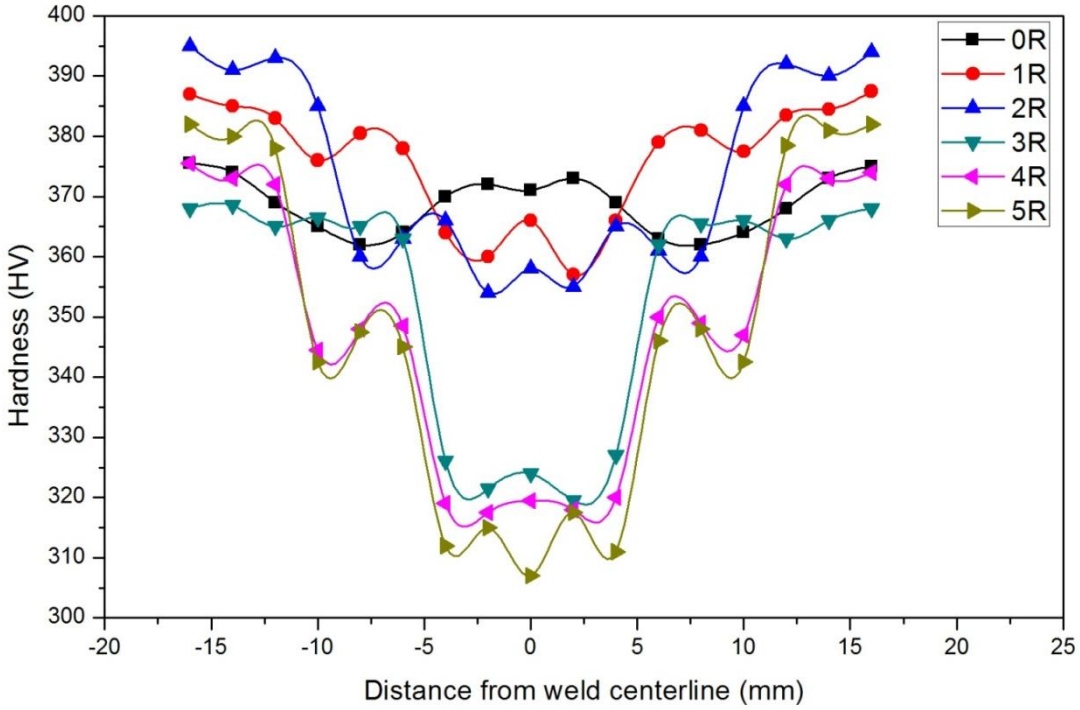


Fig. 4.4: Plot of average hardness (Vickers) values of 2 x samples against distance from the weld center line.

4.5 Elemental Analysis

Drop in hardness as shown before, is attributed to change in chemical composition of weld regions due to the depletion of certain alloying elements with the increased number of repairs as illustrated in Fig. 4.5 ~ 4.7. The results of chemical compositions of weld bead and fusion line taken through SEM (EDS) are also shown in Table 4.5 for each repair welded plate.

Table 4.5: Elemental analysis of weld bead and fusion line

Repair State	Fusion line				Weld Bead				
		Elements (% age)							
	Si	Cr	Mn	Fe & other elements	C	Si	Cr	Mn	Fe & other elements
0R	0.99	0.88	0.77	Bal	0.28	0.76	0.89	0.50	Bal
1R	0.78	0.84	0.73		0.29	0.64	0.89	0.43	
2R	0.84	0.86	0.39		0.27	0.60	0.88	0.18	
3R	0.94	0.91	0.37		0.26	0.54	0.91	0.10	
4R	0.92	0.91	0.33		0.25	0.48	0.93	0.08	
5R	0.85	0.89	0.17		0.25	0.44	0.91	0.07	

Chromium contents in the weld regions and fusion zones are scattered somewhat around the 0.88 % which are in the composition range of A24303. However, a significant drop in the manganese contents have been observed with increased number of repairs. Manganese contributes to strength and hardness as well as it has strong effect on hardenability of the steels [72]. Lowering of manganese contents in the weld bead is likely to be due to ‘Mn’ emission during welding being more vulnerable in evaporating than any other alloying element [73].

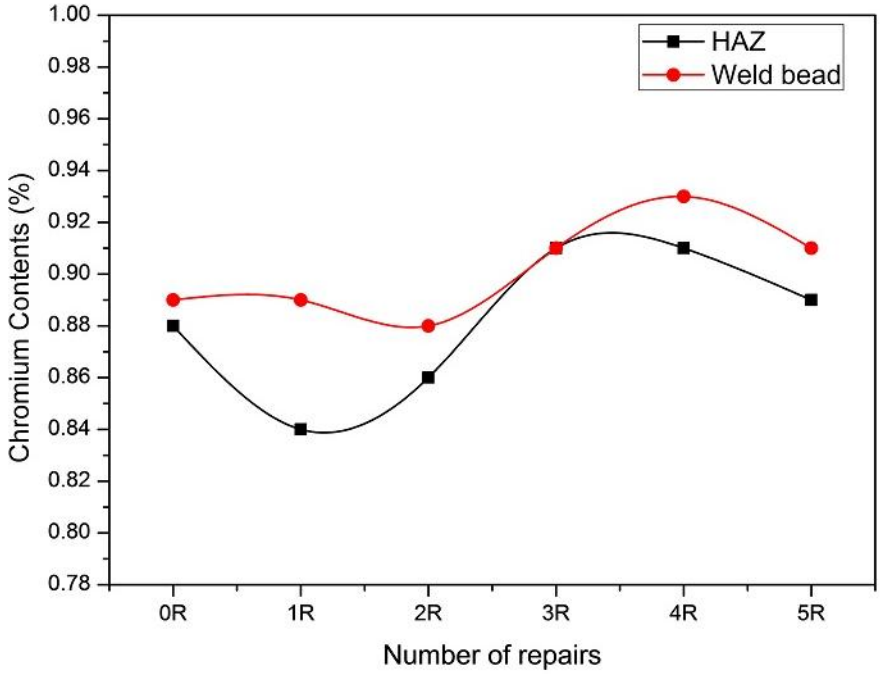


Fig. 4.5: Plot of variation in Chromium contents (%) of weld bead and fusion line against number of repairs.

Moreover, depletion of Mn in the fusion zone sharing less content in weld bead dilution may also be responsible for less Mn percentage in the sample with increasing number of repairs. It can be seen in the Fig. 4.6 that manganese contents have dropped to about 0.07% in weld bead which may also promote internal porosity and cracking in the weld bead (although not observed in this study).

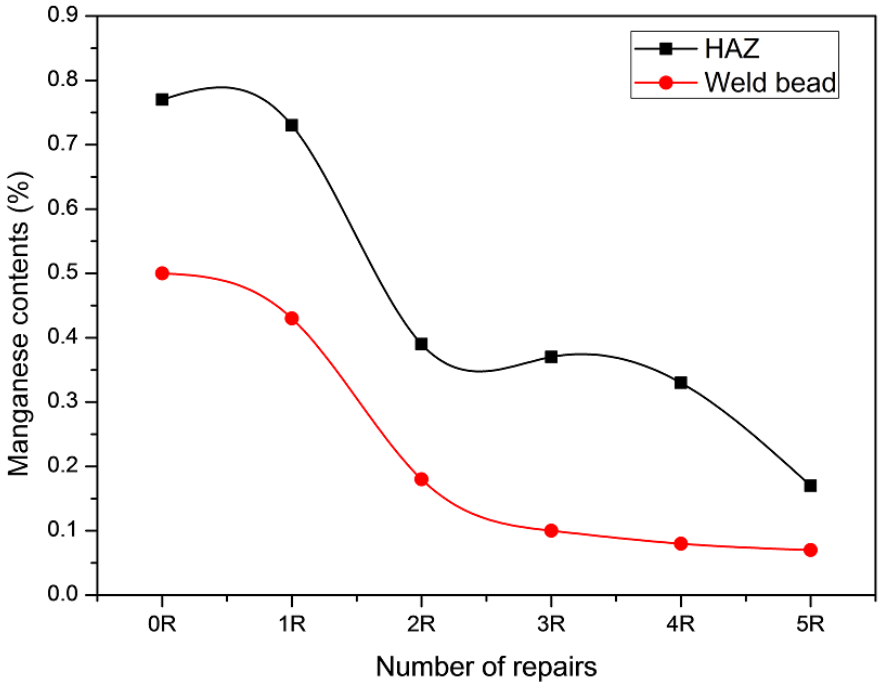


Fig. 4.6: Plot of variation in Manganese contents (%) of weld bead and fusion line against number of repairs.

Silicon contents in the HAZ are either within or very close to the compositional rage of A24303. However, silicon in the welded region drops with a low rate in subsequent repairs. Silicon improves strength and considered to increase hardness of steels but to a lesser extent than manganese. Drop of silicon contents in increasing repairs may be partially responsible for the less hardness in the weld regions in higher repairs.

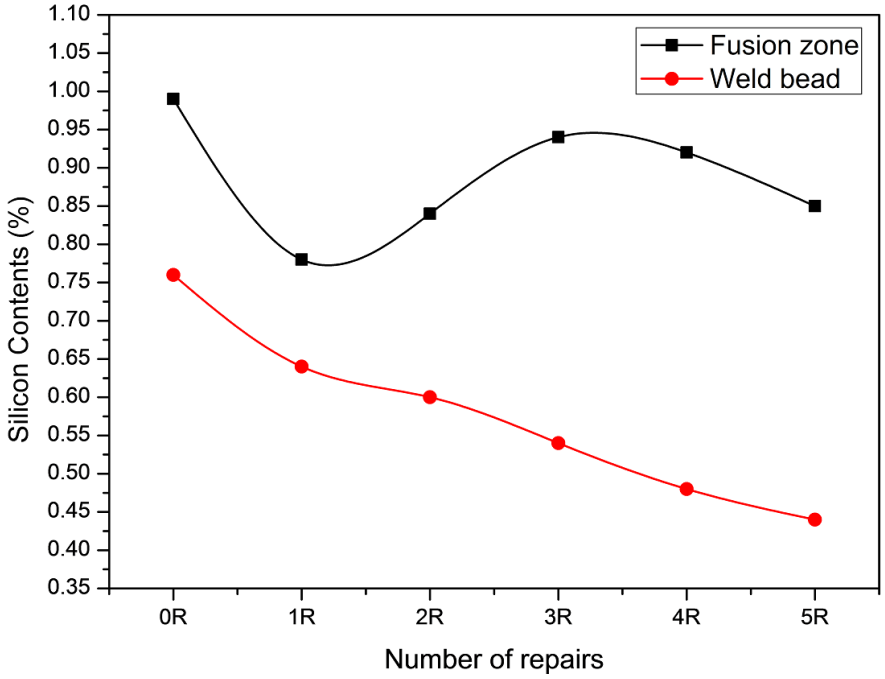


Fig. 4.7: Plot of variation in Silicon contents (%) of weld bead and fusion line against number of repairs.

4.6 (%) Drop in Hardness

Percentage drop of hardness from maximum value in the base metal to minimum value in the HAZ or weld bead for different number of repairs is shown in Table 4.6 and is plotted in Fig. 4.8. The purpose of analysing drop of hardness is to study the gradient or variation in mechanical properties within the sample. The equation for calculating percentage drop is as under.

$$\text{Drop (\%) in a welded sample } (H_d) = \frac{\text{Max hardness value} - \text{Min hardness value}}{\text{Max hardness value}} \text{x}100$$

Table 4.6: Drop in hardness (%) in each welded sample.

Sample No.	Max Hardness Value (HV)	Min Hardness Value (HV)	Drop in hardness (%) 'H_d'
0R	375.5	362	3.6
1R	387	357	7.7
2R	395	354	10.3
3R	368	319.5	13.2
4R	375.5	317.5	15.4
5R	382	307	19.6

The minimum and maximum percent drop of hardness is approximately 4 % and 20 % in 0R and 5R respectively. Fig. 8 shows that percent drop of hardness increases almost linearly with the number of repairs. The corresponding linear equation obtained is as follows:

H_d (%) = 3.028R + 4.061

Where H_d is percentage drop in hardness and R represents repair number.

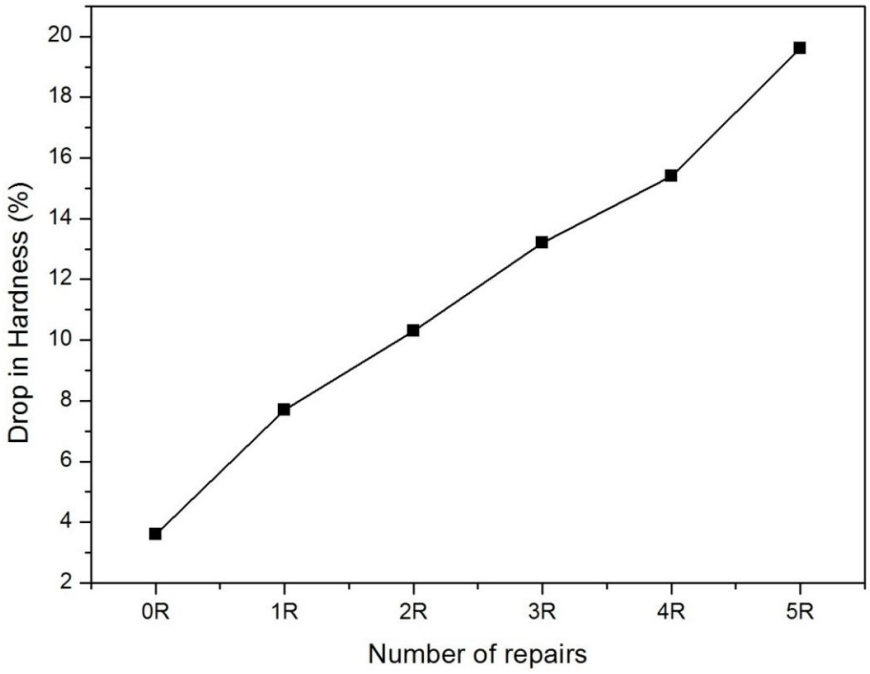


Fig. 4.8: Plot of percent drop in hardness (Vickers) values from maximum value in base metal and minimum value in HAZ.

4.7 Microstructure

Fig. 4.9 (a, b, c, d, e and f) presents optical microscope images of the base metal regions of the 0R, 1R, 2R, 3R, 4Rand 5R specimens respectively. Since all samples were heat treated after welding with same parameters, their microstructures in the base metal regions are almost same consisting tempered martensite with a few traces of retained austenite in certain areas. This also shows the execution of proper heat treatment on all samples heat treated together.

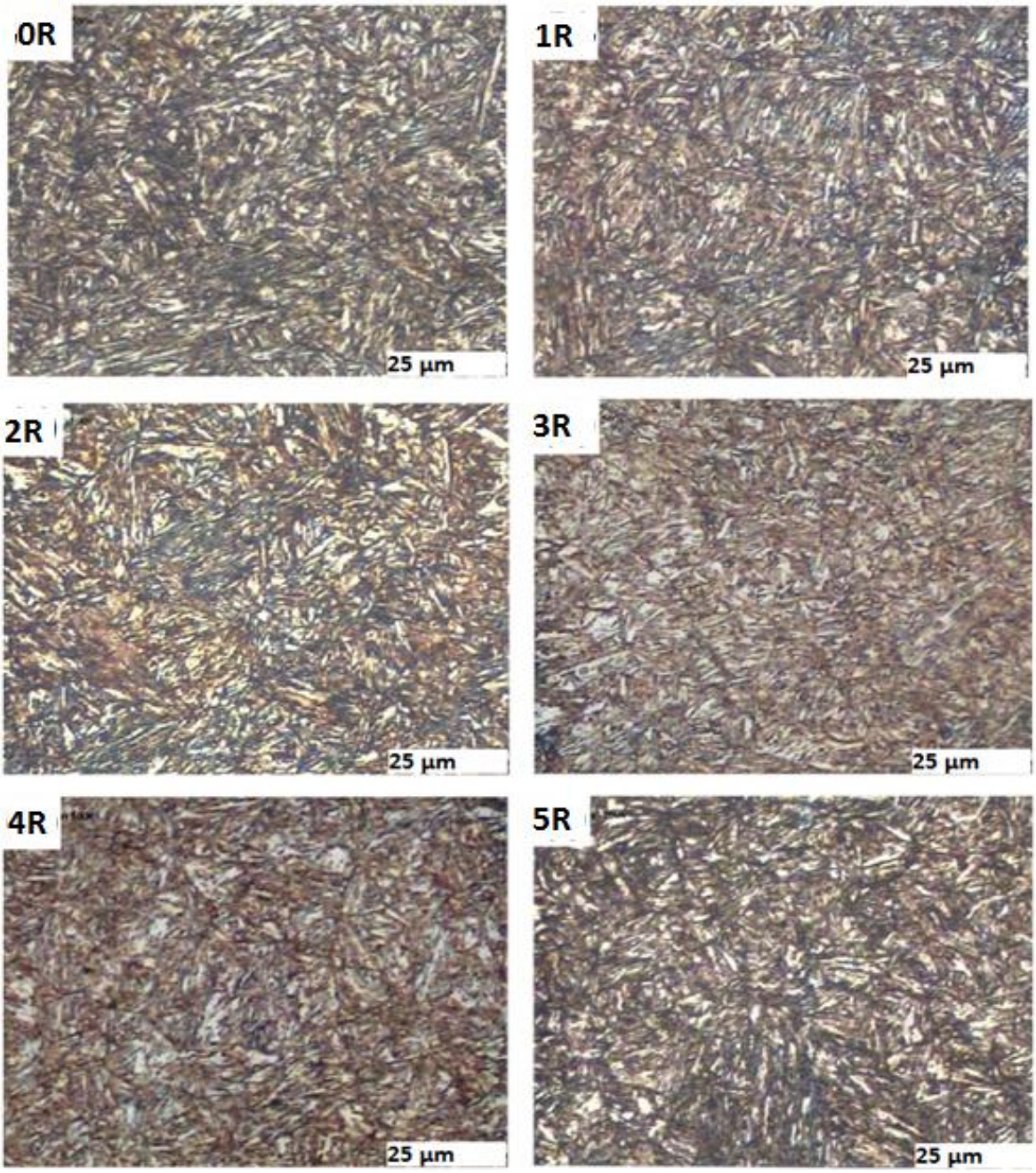


Fig. 4.9: Metallographs (500x from metallurgical microscope) a, b, c, d, e and f showing base metal portion of the samples 0R, 1R, 2R, 3R, 4R and 5R respectively.

Fig. 4.10 (a, b, c, d, e and f) shows the micrographs of HAZ of the 0R, 1R, 2R, 3R, 4R and 5R repair welded samples respectively. The microstructure in all cases has predominantly tempered martensite of lathy morphology. However, certain traces of irregularly shaped ferrite with some second phase (cementite) are also present in the microstructure. It is likely to be due to change in chemical composition of this region as discussed earlier. Manganese plays an important role in decreasing the critical cooling rate during hardening and vice versa [74]. Therefore the decrease in 'Mn'

contents is shifting the nose of CCT curve to the left, resulting in formation of ferrite and cementite in the microstructure.

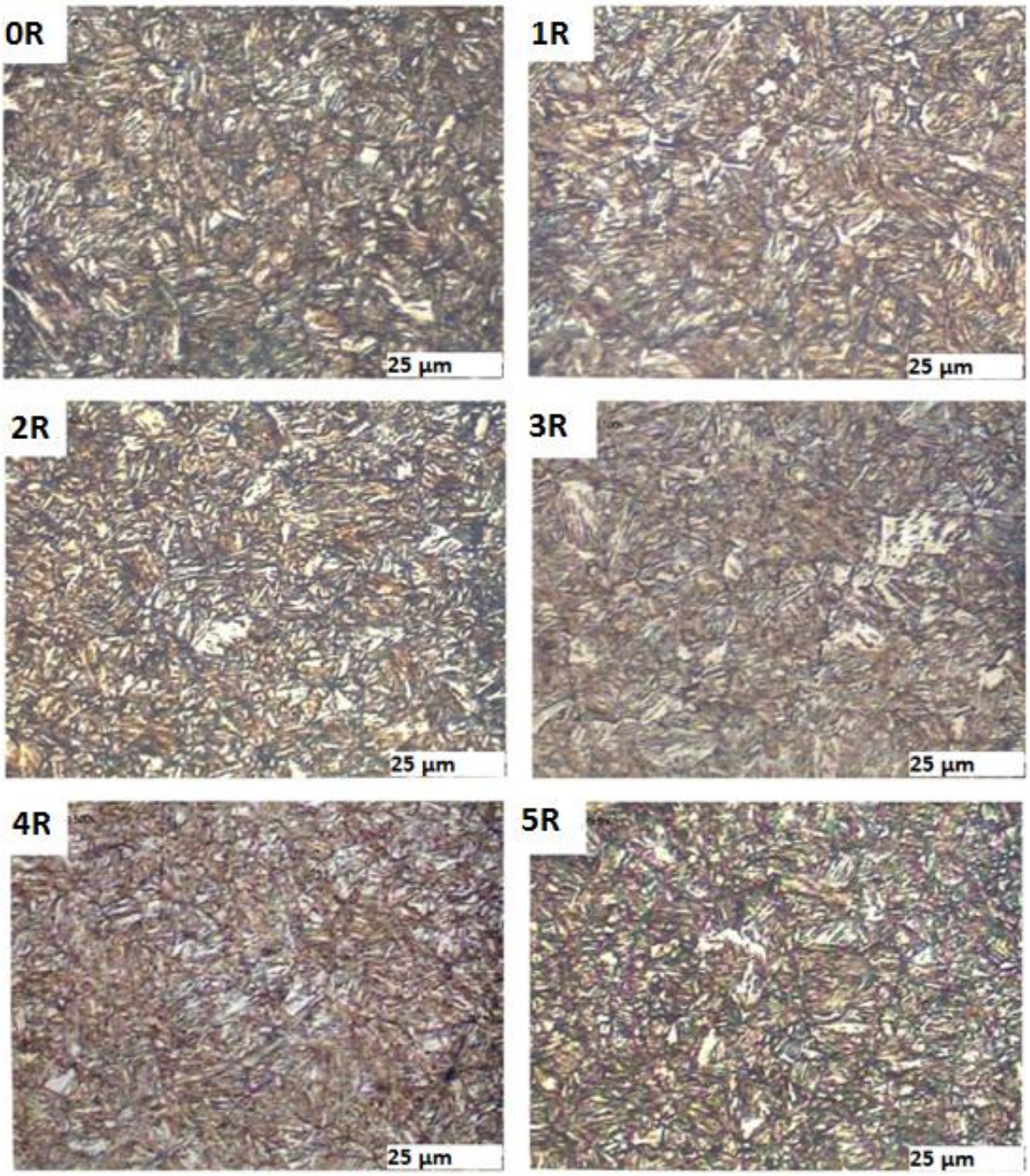


Fig. 4.10: Metallographs (500x from metallurgical microscope) a, b, c, d, e and f showing HAZ portion of the samples 0R, 1R, 2R, 3R, 4R and 5R respectively.

Fig. 4.11 (a, b, c, d, e and f) shows the microstructure of the weld zone of the 0R, 1R, 2R, 3R, 4Rand 5R respectively. These micrographs show interesting results in which along with tempered martensite, a significant proportion of ferrite with some second phase (cementite) and traces of Widmanstatten structure are also present in the

microstructure. With the increasing weld repairs, the proportion of martensite is decreased due to other two phases. It also contributed towards loss of hardness in the weld region with the increasing number of weld repairs discussed in the hardness profile of the samples.

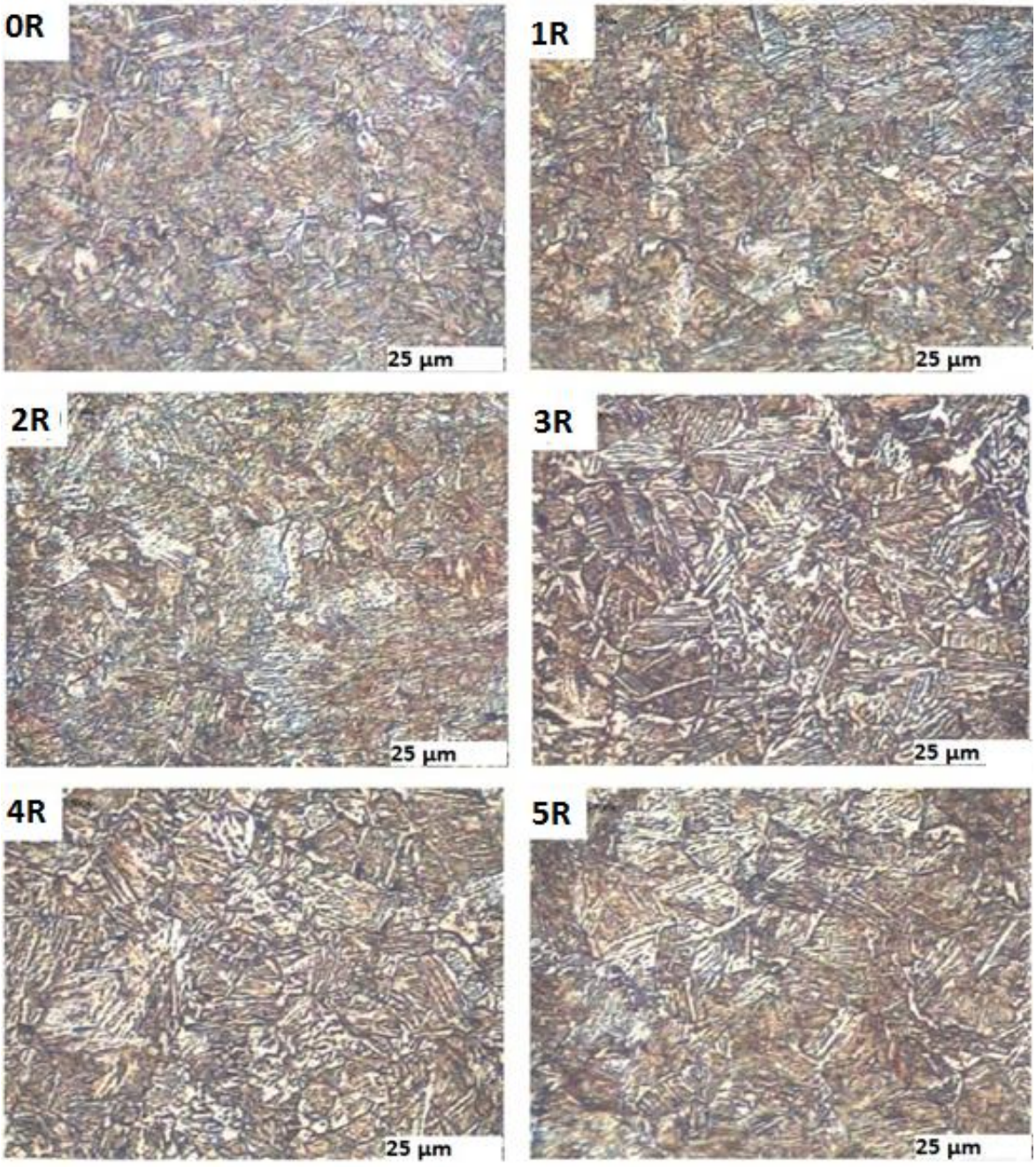


Fig. 4.11: Metallographs (500x from metallurgical microscope) a, b, c, d, e and f showing weld bead portion of the samples 0R, 1R, 2R, 3R, 4R and 5R respectively.

4.8 Corrosion Rate

As discussed in previous chapter, salt spray test was also carried out to study the effect of multiple repair welds on corrosion resistance of weldment. 1 x sample from all the repaired plates was processed and the results obtained are as under in Table 4.7 and are also plotted as Fig. 4.12. As clear from the results, mass loss increases with increasing the number of repairs if the weldment is subjected to corrosive environments.

The mass loss was initially 0.028 gm and reached up to 0.042 gm while going from sample having no repair to the sample repaired five times. This increasing mass loss is actually increasing the corrosion rate and obviously decreasing the corrosion resistance of the weldment during stringent environments. Corrosion rate was calculated in mills per year (mpy) from the following formula. The results of the corrosion rate are also calculated and shown in Table 4.7. 26 % increase in corrosion rate is observed between the sample having '0' repair and 5 times repaired. The change in corrosion rate is due to the compositional gradient between base metal, HAZ and weld metal which results the condition favouring the galvanic corrosion [75].

$$\text{Corrosion Rate 'mpy'} = \left(\frac{K \times W}{A \times T \times D}\right)$$

Table 4.7: Salt spray test results in terms of corrosion rate (mpy) of each welded sample.

Sample No.	Initial Mass (g)	Final Mass (g)	Mass Loss 'W' (g)	Total Surface Area 'A' (cm^2)	Exposure Time 'T' (hrs)	Density 'D' (g/cm^3)	Constant 'K'	Corrosion Rate (mpy)
0R	8.520	8.492	0.028	9.33	48	7.86	3.45×10^6	27.44
1R	8.807	8.774	0.033	9.78				30.85
2R	10.294	10.258	0.036	10.22				32.21
3R	8.466	8.432	0.034	9.55				32.55
4R	9.202	9.166	0.036	10.00				32.91
5R	10.490	10.448	0.042	10.44				36.78

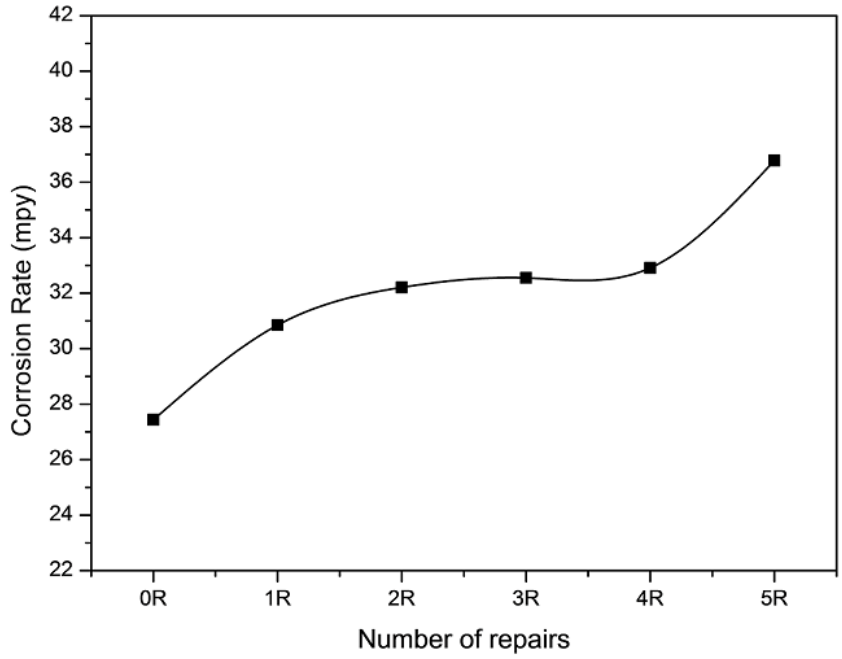


Fig. 4.12: Plot of corrosion rate (mpy) against number of repairs.

4.9 Conclusion

Mechanical, corrosion, compositional and micro-structural evaluation of HSLA steel (A24303) with five weld repairs in the same area were studied. Tensile, impact, hardness and bend testing were carried out to analyze the mechanical performance of the steel after different weld repairs. Variations in all mechanical properties have been observed but properties (except hardness) were within the range as stipulated in the material's relevant standard. However hardness, compositional gradient in the weld and HAZ, microstructure and corrosion behaviour of the different repair welded samples were considerably changed as the number of repairs were increased.

According to the results obtained; tensile, impact and bend tests satisfied the requirements of the relevant standards and up to five weld repairs are possible in A24303 steel because, even after fifth repair, these mechanical properties meet the minimum requirements of relevant standard i.e., GB/T 3077. But this statement can only be considered valid if the material, welding wire, welding technique, welding parameters and other processes like heat treatment processes as mentioned in experimental work are kept same. However, if the material has to put into a service where hardness, corrosion resistance and microstructure are important then this study

supports those standards indicating that weld repairs should not be exceeded two times in the same area.

5. References

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