Welding Risk And The Law

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Abstract

Welding is the most common and effective form of joining applied to a wide range of materials. All too often there is insufficient understanding of the principles involved in Welding Engineering and too little appreciation of the skills required to make satisfactory welds. Sometimes this can lead to problems in construction projects and occasionally to structural failures. All Professional Engineers need to have an awareness of risk both with respect to avoidance of failure and to the way in which risk is interpreted by the law. An example is described of a structural failure which resulted in a legal case decided on the balance of probabilities.

Welding

Welding is a complex multi disciplinary subject involving the topics of materials science, physics, chemistry, electrical and electronic engineering, mechanical engineering and structural engineering. The successful completion of welds requires a high degree of operator skill. The earliest forms of welding involved heating of materials and beating them together. Nowadays there are many different welding processes, each of which may have particular applications for which it is most suitable. These processes are divided into two main groups:

Fusion welding
Non fusion welding.

Fusion welding processes involve melting of the parent material being joined. They may or may not involve the addition of filler metal. Non fusion processes do not involve melting of the parent material although they may involve heating to temperatures at which the material is softened compared to its condition at normal atmospheric temperatures.

Welded joints

Welded joints can be divided into three main types as follows although there are many different subsidiary types.

Butt welds
T- butt welds
Fillet welds.

Figure 1 shows the simple geometry of these different joint types and also shows the regions of the weld metal, the heat affected zone and the parent material.

The weld metal is material that has been molten at some stage in the joining process. The heat affected zone is the band of the parent material that does not reach the melting temperature but is heated to temperatures such its properties are changed from those of the parent material. In a butt weld the joint is made throughout the full thickness of the material as shown in Figure 1(a) where the two plates 1 and 2 being joined lie in the same plane. In a T-butt weld, the joint is again made throughout the thickness but in this case the plates 1 and 2 are at right angles to each other as shown in Figure 1(b). In a fillet welded joint the end of one plate is joined at an angle to the surface of the other plate as shown in Figure 1(c) but the joint is external to the thickness so that there is no direct connection between the plate 1 and the surface of plate 2. The metallurgical structure and properties of the weld metal and heat affected zone (HAZ) are likely to be different from the parent material and the rapid heating and cooling of the weld will produce locked in residual stresses that are likely to reach a peak magnitude equal to the yield strength of the materials involved. These residual stresses can have significant effects on fracture, buckling, fatigue and stress corrosion behaviour of welded joints. The fatigue strength of welded joints is strongly dependent on the stress concentration effects of the geometry of the joint and is often much worse than plain material without stress concentrations. There are several types of welding defect that can occur and these can also have a major effect on the fracture, fatigue or stress corrosion behaviour of a joint.

An important issue for practical welding purposes is the position in which welding can be carried out. The easiest positions from the point of view of skill required by the welder are the down hand or flat position and the horizontal-vertical position in both of which the molten pool is supported by solid parent material underneath. Welding between plates which are vertical is usually carried out in the upwards direction so that the welder can control and support the size of the weld pool by manipulation of the electrode. In special cases welding can be carried out in the vertically downwards direction but this requires restriction to small weld pools and low heat input. The overhead position is the most difficult for the welder to control the weld pool without it falling out under the action of gravity.

Arc welding processes

Amongst the most important groups of welding processes are the arc welding processes. In these processes the source of heat for welding is an electric arc struck between an electrode and the work piece. In a number of these processes the electrode is consumable, that is it melts under the heat of the electric arc and metal is transferred to the work piece as additional filler metal. It is necessary to protect the liquid metal from the oxygen in the atmosphere otherwise the metal oxidises rapidly and brittle material deposits result. This protection is usually provided by enveloping the arc in a shield of protective gas. The behaviour of the arc depends on the characteristics of the gas shield, the voltage across the arc and the current passed through the arc. In manual metal arc welding (Figure 2) the electrode consists of a wire core surrounded by a coating of flux. The electrodes are supplied in individual lengths of about 300 - 400 mm and gripped in electrode holders manipulated by the skill of the welder to keep a constant gap between the end of the electrode and the work piece to maintain the arc. The wire core melts off and is transferred across the arc by electromagnetic forces whilst the flux coating dissociates to form a gas shield around the arc.

The non metallic constituents float to the top of the molten pool to form a slag that helps protect the cooling metal from the atmosphere and holds the metal in place by surface tension effects until it has solidified.

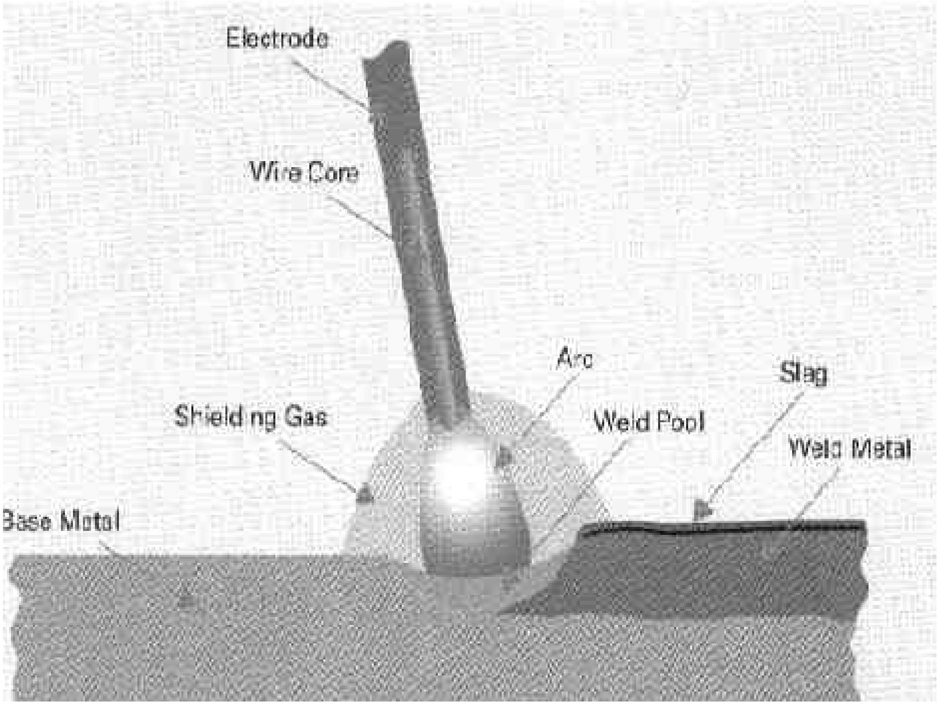

Figure 2 Manual metal arc welding

Improved productivity can be obtained from automatic welding processes when the type of joint is suitable. Submerged arc welding involves the electrode being fed from a continuous reel of bare wire mounted on a mini bogie unit that is driven at constant speed along a predetermined track. To provide the protection from the atmosphere, the arc is struck under a layer of flux that has been deposited on the work piece in front of the electrode from a hopper that is also mounted on the travelling bogie unit. The flux that is not melted to form a slag cover for the completed weld is recovered and recycled by a vacuum unit on the rear of the bogie unit. This process normally operated at high current levels and produces a large molten pool – this in turn limits the process to use in the flat (down hand) or horizontal positions.

Gas shielded welding processes are a group of semi automatic processes that give higher productivity than manual metal arc welding. In these processes the electrode is a continuous reel of wire that is fed through a nozzle with an annular space around it down which a shielding gas is fed from gas bottle supplies. The process is shown in Figure 3. In the original version of this process the shielding gas was inert, either argon or helium, to provide protection of the arc from the atmosphere and this is known as the Metal Inert Gas (MIG) process. The inert gases are expensive however, and for welding of steels a significant development in the 1960s was the use of carbon dioxide as a shielding gas. Carbon dioxide is an active gas and variants on this process are known as Metal Active Gas (MAG) processes. This requires modifications to the chemistry of the welding wire with the addition of elements with an affinity for oxygen to remove the free oxygen from the gas and prevent the formation of metal oxides that would give poor properties to the resulting weld metal.

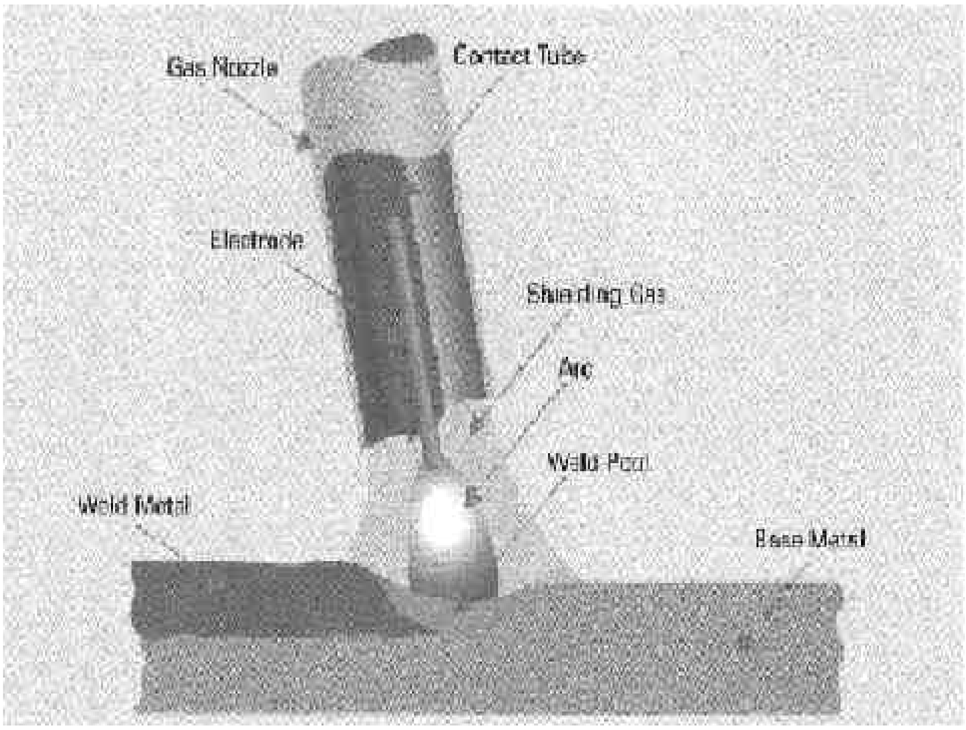

Figure 3 Gas shielded arc welding

The use of robots in welding has developed over the years but there have been some cases where attempts were made to introduce robots without designing the full manufacturing and handling system appropriately. The welding processes initially developed for use with robots were the resistance welding group of processes. In these processes a lap joint is made by clamping two sheets of material together by water cooled copper electrodes and passing a heavy burst of current through the electrodes. Heat is generated at the higher resistance between the sheets at the contact point and by careful control of the time and pressure variables a nugget of molten material can be produced at the interface. Robots for resistance welding have been introduced into production lines for the automotive industry for some years. The use of arc welding robots has also been increasing in recent years where there are repetitive simple geometries and these are invariably based on the MIG/MAG processes. One of the problems with arc welding robots is the need for precise control of the position of the electrode in relation to the work piece to maintain the required arc length. Automatic seam tracking is an extremely tricky problem although this can be done through feed back control of the electrical current and voltage parameters of the process.

The microstructure of the weld metal and the heat affected zone (which will be different from each other) will depend on the chemistry of the materials involved, the peak temperatures and the cooling rates. For arc welding the thermal history in turn depends on the heat input from welding and the heat sink effect of the thicknesses of material being joined.

High Energy Density Welding Processes

Apart from the resistance group of welding processes, another group of fusion processes that does not involve a welding arc is a group known as high energy density processes. These include electron beam, laser and plasma welding. With electron beam welding, a beam of electrons is fired at the surface of material and essentially melts a keyhole into the body of the material. If the beam is traversed along the interface between two close fitting pieces of material the interface can be melted and on solidification the two pieces are joined together by a butt weld. The process can penetrate thicknesses up to 200 mm of steel. The beam of electrons loses much of its energy on collision with air and hence this process usually has to be carried out in a vacuum chamber. It is now possible to do some electron beam welding for thin material out of vacuum by bringing an electron gun in a small chamber close to the material to be welded. Laser welding uses the energy of a beam of coherent light which when brought to a focus can melt through thicknesses of 10 to 20 mm, depending on the power of the laser. Laser welds are sometimes made as lap joints by stitching through the thickness of one section to melt into the second. Plasma welding uses a stream of very high temperature ionised gas to melt material. The high energy density processes usually involve melting an interface and allowing it to solidify again to form a butt weld and hence do not usually involve use of additional filler material. However, there has been some development of hybrid welding processes involving a combination of arc and laser welding. Both laser and plasma processes are also widely used for cutting purposes.

Non Fusion Welding Processes

There are a number of non fusion welding processes. The original blacksmith's process of beating pieces of red hot metal together is essentially a version of pressure welding. The more practical non fusion processes of greatest interest are based on generation of heat by friction. The basic friction welding process involves rotating the end of one component against the end or surface of a second component and after sufficient heat has been generated forcing the two components together. This produces an upset or flash of soft material forced out from the interface whilst a pressure forge weld is formed at the interface. Friction welding is one of the few processes capable of welding together a range of dissimilar materials. For successful fusion welding where the materials melt it is necessary for there to be some degree of mutual solubility between the materials being welded but this is not necessary for friction welding as melting is not involved. Thus friction welding can join together such materials as aluminium and steel.

Friction stir welding is a different process from friction welding. In friction stir welding a rotating hardened steel shaped pin is forced into the interface between two plates of softer material and made to travel along the interface. The rotating pin generates heat by friction and forms a thermo-mechanically mixed zone behind the travelling pin. This process is a way of producing fast defect free welds in aluminium sheets and plates and has become of great interest to the aerospace industry.

Welding of offshore pipelines

An example where welding is a critical operation is in the laying of pipelines for oil and gas on the sea bed. Lengths of pipe of the required diameter and thickness and grade of steel are manufactured in a factory often known as a pipe mill. This is usually done by bending flat plates round into a cylinder and making a longitudinal weld by the submerged arc process to joint the edges and complete the cylinder. Lengths of pipe of the order of 40 ft (~12 metres) are made and each length of pipe is then pressure tested to approximately yield pressure which helps to ensure that the pipe is round and provides a proof test for the welded section.

Offshore pipelines are laid from a lay barge. Lengths of pipe are welded together on the barge and the line is pushed progressively off the end of the barge. To prevent excessively high bending stresses as the line extends off the end of the barge, a sloping ramp is provided at the end known as the ‘stinger’. Once the pipe line reaches the sea bed it is usually laid in a trench that has been cut previously. Since the pipeline is now fixed in position at one end, the barge starts to move progressively as each welded joint is completed to allow the line to continue to pass out from the end over the stinger. Since the manufacture of the pipeline itself requires the completion of circumferential welds between the lengths of pipe supplied to the barge, it is common practice to join pairs of lengths together prior to installing them in the line as this reduces the number of welds to be made in the main production line by half – this step is known as ‘double jointing’. The advantage of this is that it can either be carried out prior to delivery of the pipe to the barge or can be completed on board the barge in parallel to the main ‘firing line’. Completion of the ‘double joints’ can be completed by rotating the pipes under a fixed welding head at the top of the pipe so that the weld is made in the down hand position. This is often done by submerged arc welding giving the advantages of high productivity of automatic welding. For the welds in the firing line however, the pipe cannot be rotated and the welds have to be made ‘in position’ with the welding arc travelling round the circumference of the joint. The welding process most commonly used is an automated form of gas shielded orbital MIG/MAG welding. A set of three or perhaps four welding heads is used – these are mounted on mini tractors that run round tracks clamped around the circumference of the pipe. The heads are set up to start at different positions around the circumference, travelling in the same direction. The weld is made in a series of runs one on top of the other until the original groove preparation has been filled. The welding procedures have to be demonstrated for approval prior to start of work and these test pieces are subject to mechanical and metallurgical tests to confirm their acceptability.

On completion of each production weld, non destructive testing (NDT) has to be carried out and accepted before the weld in question has reach the end of the barge and gone over the end of the stinger. In the past the NDT was usually carried out by radiography in which film on one side of the joint is exposed to X-ray or gamma ray radiation around the perimeter from the other side of the joint. This required the development of the films and checking of them for weld defects to be carried out whilst the next weld was being made. Often the weld would not have cooled out completely and the films would have to be viewed and sentenced before they had dried out completely. In recent years the NDT systems have been changed to automatic ultrasonic testing. In this method a series of computer controlled ultrasonic transducers is mounted around the circumference of the pipe and fired progressively to check for sound reflections from any defects that are present. This is a highly complex technology on which much research effort has been expended to produce commercial systems that can detect and size defects that might be of concern in welds.

One of the potential problems for oil and gas pipelines is the possible presence of ‘sour’ gas containing hydrogen sulphide (H2S) under wet conditions. In simple terms this leads to highly corrosive conditions inside the pipeline and the corrosion reaction leads to the release of hydrogen in atomic form. The presence of the sulphide poisons the reaction and stops the hydrogen atoms recombining as molecules. The hydrogen atoms are of a sufficiently small size that they can be absorbed and diffuse through the solid lattice of steel. The hydrogen atoms tend to diffuse to positions of high stresses such as voids or tips of any cracks where they may recombine as molecules and become locked within the steel lattice. This can lead to the phenomenon of hydrogen embrittlement where in the presence of high tensile stresses and hydrogen, cracking of the steel may occur. Higher strength or harder steels are more susceptible to this problem than lower strength or softer steels. As a result, when sour service is expected, it is normal practice to specify limits on the chemical composition of the steel and on the maximum hardness of both weld metal and heat affected zone. Achievement of these requirements is amongst the results tested in the welding procedure tests.

Risk In Engineering Applications

The dictionary definition of risk is “the chance of loss or injury” [1]. The general public has a basic perception of risk in connection with every day activities. This is usually manifest as a perception of injury or death. The number of deaths from road accidents is slightly less than the number of deaths from accidents in the home for example. If the figures are divided by the current total UK population of 59 million persons, the results give a probability of death per person per year of 5.33 x 10-5 for road accidents and 6.67 x 10-5 for accidents in the home.

There have been two authoritative reports on risk published by the Royal Society in 1983 [2] and 1992 [3]. These reports include some statistics on deaths, a selection of which are shown in Figure 1. The figures are presented as deaths per thousand people per hundred thousand hours activity. The time base for these figures is chosen to approximate an average life of hours at work. It should be noted that the vertical scale in Figure 4 is logarithmic.

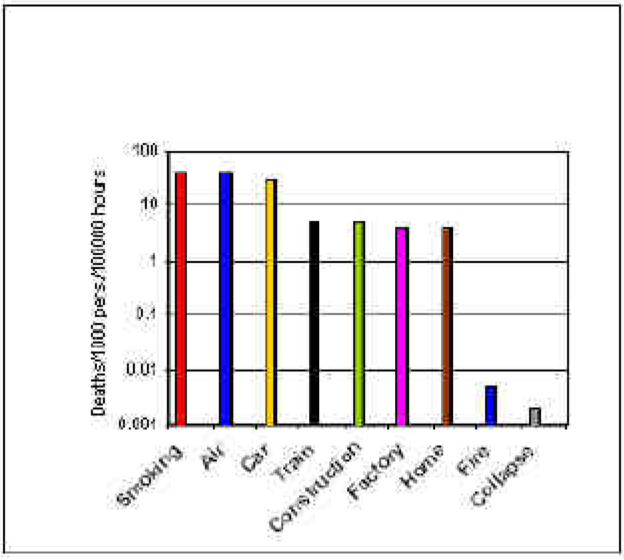

Figure 4 Risk of Death / 1000 People /100000 Hours Activity (3)

Expressed in this way, the risk of death from smoking, travel by air or car are approximately the same and somewhat greater than that from accidents on construction sites, in factories or in the home. It can be seen that on this basis the risk of death from collapse of buildings is over four orders of magnitude lower than the highest level shown in the Figure. However great care is required in interpretation of statistics in this field. It is not clear that the same time denominator of 105 hours activity is applicable to the different activities in this table. Transportation statistics are often quoted as deaths per passenger mile or kilometre, although a more realistic format is considered by some to be deaths per passenger journey.

In the scientific field risk has a more precise definition as follows:
Risk = (Frequency of occurrence of an adverse event x Consequences of the event)

This can also be interpreted as follows:

Risk = (Probability of occurrence of adverse event x Consequences of the event)

All Chartered Engineers are expected to have a basic understanding of the concepts of risk and a guidance document to assist in this has been issued by the Engineering Council [4]. The topic of risk has also been the subject of guidance form the Health and Safety Executive [5]. Figure 4 shows a schematic diagram of frequency of adverse events that cause more than N deaths per year against the number of deaths N (both on logarithmic scales). The lines on the diagram follow the general relationship “Frequency x consequences = constant”. The diagram is divided into zones of intolerable, ALARP and negligible risks. The ALARP region is where action should be taken to reduce the risk to a level As Low As Reasonably Practicable. In the negligible region no action is required and the risk is deemed to be acceptable. In the intolerable region the risk is not acceptable. It should be noted that these concepts do not mean that loss of injuries will not occur – they accept that it is impossible to guarantee freedom from such events but provide methods for ensuring that they are so infrequent that the public is prepared to accept the situation.

Civil and Structural Engineers put these concepts into practice by the use of design codes which include safety margins against failure. Modern codes are based on the concepts of Limit State Design in which the effects due to loading are multiplied up by partial factors so that they represent extreme upper bounds whilst the resistance effects are divided by partial factors so that they represent extreme lower bounds.

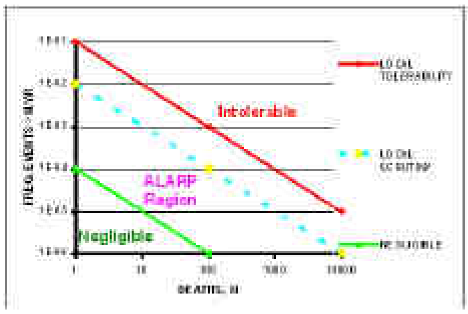

Figure 4 Societal Risk Tolerability [5]

The partial factors are calibrated to give a target notional probability of failure for the assumed scatter in material properties and uncertainty in determination of loading effects. The target probability of failure is chosen to be sufficiently remote for the potential consequences of failure that the risk is acceptable.

Engineering and The Law

Unfortunately the incidence of litigation in cases of problems in engineering is becoming much more common. In such cases there is a crucial role for the Expert Witness. Although Experts may be appointed by individual parties in a dispute and will advise their clients on the technical aspects of the case, when it comes to formal reports and evidence the Expert is required to give an independent opinion for the benefit of the Court. The Expert Witness is required to sign a declaration in any Reports to the effect that his/her primary duty in furnishing written reports and giving evidence is to assist the Court and that this takes priority over any duties they may owe to the party or parties by whom they have been engaged, and that they have complied with this. Any Expert who strays outside his/her field of expertise will soon be exposed by the barristers involved for one party or the other and if an Expert fails to give impartial evidence he/she will probably be publicly reprimanded by the Judge with adverse comments recorded in the judgement.

Although in engineering applications, designs are arranged so that there is a very remote probability of failure, decisions in law are based on ‘the balance of probabilities’. An interesting example of the distinction between these concepts arose in a recent case concerning the failure of a welded sub sea pipeline. The line failed after a period of some three months in service by leakage through short through thickness longitudinal cracks which developed at six of the circumferential welds within an overall length of the line containing some 144 individual pipes and welds. The mechanism of failure was hydrogen induced stress corrosion cracking and it was found that this cracking developed in two stages. The first stage was initial cracking in the weld metal at the root of the weld where the welds had too high a hardness level. These cracks occurred in the root bead of a few welds with a typical size of the order of 3 mm transverse to the weld and were confined to the weld metal which was not sufficient to cause leakage or failure. In the six cases where leaks occurred, the cracks extended through the heat affected zone, into the pipe material and through the wall thickness of the pipe to cause leakage. After extensive investigations it was discovered that at least one of the two pipes at each of the six joints that developed leaks did not comply with the specified requirements for the chemistry of the steel, in particular with respect to the requirement for a maximum value of 0.40 for carbon equivalent. However, the test certificates gave values of carbon equivalent which were in conformity with the specification. The steel maker, a foreign company, eventually admitted that the test certificates had been changed for cases where the values of carbon equivalent had been found not to comply to indicate that they did. The litigation was brought on the grounds that the deceit of the steel maker in issuing fraudulent test certificates had led directly to the failure of the pipe line. The operating company claimed for the replacement costs for a new pipe line and consequential costs for loss of use of the line whilst a replacement was installed. The total claimed was about £200 million. Although the steel maker had admitted the deceit, his defence was that the failure was caused by faulty welding procedures approved by the operator and that as a result of this the line had been doomed to fail even if the material had all complied with the specification requirement of 0.40 maximum carbon equivalent.

The case was heard over a two week period in the High Court in London. The Judge and the barristers had to seek to understand highly complex technical material concerning steel manufacture, welding, fracture mechanics, corrosion behaviour, risk and probability of failure applied to structural integrity assessment. A relatively unusual fracture mechanics test, the double cantilever beam test, was used to assess the resistance of samples of the pipeline steel with different levels of carbon equivalent over the range approximately 0.36 to 0.45 immersed in a standard corrosion test liquid commonly used for corrosion testing. The results showed that the resistance to hydrogen induced stress corrosion cracking decreased progressively with increase in carbon equivalent. This led on to the need for detailed fracture mechanics analyses to provide the relationship between stress levels, sizes of initial stage one cracks and resistance of the steel pipes to crack extension.

The technical experts appointed by the two sides had submitted their initial reports, responses to reports by others and a first supplemental report each before the opening of the hearing. In his first supplemental report one of the Experts for the Defence claimed that the combination of highest likely stress levels and largest initial stage one cracks with the lowest material resistance to crack extension did not give an adequate safety margin for normal code design or safety assessment requirements. The Experts for the Claimant responded that the issue was not whether there were adequate safety margins for normal design, but whether, on the balance of probabilities, the failures that had occurred had been due to steel material not complying with the specification requirements for carbon equivalent. On the first day, the defence submitted a further report attempting to carry out a probabilistic analysis to prove that, on the balance of probabilities, there would be failures in material that did comply with the specification. Further supplemental reports were submitted by both sides over the next few days, much to the annoyance of the Judge.

There was an inherent problem about any attempt to carry out a detailed probabilistic analysis and this was the values of carbon equivalent that could be ascribed to any particular pipes in the line. The only information available was the analysis taken from the ladle at the melting stage and the analyses of two particular pipes taken to represent the product analysis of pipes from that cast. Apart from the problem of changes to records by the steel maker, there is inherent variability in the chemical analyses of a batch of pipes taken from a particular cast. Furthermore there were inherent variations in the welding procedures used and scatter in the relationship between carbon equivalent and resistance to crack extension. There was also uncertainty about the actual environment in the pipeline compared to that used for the fracture mechanics crack extension tests.

The detailed technical arguments involved the following specific points:

The actual yield strength of the weld metal
The level of residual stress in the circumferential direction and the effects of proof testing of the pipeline on the residual stresses
The shape and range of sizes of initial (stage one) cracks that might form at the root of the weld.
The probability of cracks of different sizes being present in welds made between pipes of different carbon equivalent level.
The probability of initial cracks extending to cause failure in pipes of different carbon equivalent.

Apart from the detailed technical submissions, the Claimants' Experts made four general submissions as follows:

Based on sound metallurgical principles it would be expected that both the hardness level and the size of the hardest zone at the root of the weld metal would tend to increase with increasing carbon equivalent levels in the pipe material due to dilution effects from the pipe into the weld metal.
The lack of firm data was such that any fracture mechanics analyses should be regarded as indicative of general trends of behaviour rather than exact relationships.
The uncertainties in the data were such that no confidence could be placed in any attempted probabilistic analyses.
It was inappropriate to use assessment codes intended to demonstrate fitness for purpose as a basis for deciding whether failure had been caused by particular circumstances or not.

In addition to their attempts to produce probabilistic arguments to support the 'doomed to fail' argument, the Defence Experts sought to discredit the welding procedures used as having been out of control on the lay barge and claimed that if there was insufficient evidence to make a probabilistic case, the argument that the failure had been due to the high carbon equivalent of the pipe material could not be supported either.

The Judge found in favour of the Claimants. He accepted virtually all the technical arguments from the Claimants' Experts and rejected those of the Defendants. He also accepted the four general points of principle put forward by the Claimants and rejected the responses of the Defendants. He therefore awarded damages and costs to the Claimants.

The Defendants sought leave to appeal and were eventually given such leave. The Appeal hearing took place over three days but collapsed when the Defence was unable to respond to the requirement that the Burden of Proof for the 'Doomed to Fail' case lay with them. Damages were eventually set at £108 million.

Concluding Remarks

Welding is a highly complex technical field and is all too often little understood by general engineers. There are many different welding processes and many different problems with different materials. It is most important that appropriately experienced and qualified engineers are involved in any major project where welding is an important part.
Risk is a concept that should be understood by all professional Engineers. The concepts of material variability and uncertainties in parameters are inherent to design. The way in which these need to be considered in minimising the risk of failure is of paramount importance.
In the unfortunate circumstances of litigation occurring on Engineering projects, it is essential for Expert witnesses to stay within their field of expertise and obey fully their obligations to inform and advise the Court in an impartial manner. The Law is often concerned with the balance of probabilities rather than the occurrence of extreme events but Courts are well able to take on the challenge of highly complex detailed technical arguments and arrive at judgements based on such understandings.

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