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The Origin and Evolution of Welding Principles: A Guide for the Understanding of Welding Engineering for Mechanical Engineers

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Abstract: Mechanical engineers require a good, accurate and comprehensive understanding of what welding and welding engineering actually is because many of them are very much involved with the manufacture of welded fabrications. The article provides the mechanical engineer with the subtleties from required thinking, in order to understand, as a whole, the philosophy of welding engineering. In this article/paper, welding, welding engineering and welding principles are explained derived from the origin of welding action, how and why this action came about and further, how it has evolved into the empirical science and technology it is today. There will be an explanation of the role of welding rituals that became the backbone of the methodology. Certain facts regarding welding will be proven in front of the reader, e.g. what is the subtle difference between "welding and welding engineering", and how do we bring about the welding action? Further, it will be brought home to the mechanical engineer that there must be a "Common Objective", what is it? The paper will go on to establish some definitions, facts and aspects of welding? Proceeding along as the thought process develops, the article analyses for the mechanical engineer in the various instants of argument, how a particular welding principle came about and should be observed. Further, it will be shown how the welding facts and principles, affect and influence welded fabrication behavior in industry. All of this information and facts are to aid the mechanical engineer to understand welding engineering principles, the article / paper is a guide and is written in that style to teach what is an Empirical Science, already established by the author.

Keywords: Welding the Atom Bonding Phenomenon, Welding Engineering Principles, Weld Material and Physical Condition, Weld Procedures and Welder Qualification, Welding Codes, Specifications and Standards

1. Introduction

In order to identify the origin and then follow the evolution of welding engineering and its principles, it is necessary to examine aspects of the history of progress made by human beings into civilization. This is because everything that has arisen in welding is derived from this feature of evolution.

2. Investigation and Discussion

2.1. What Motivated the Need for Welding

Thousands of years ago, pre-civilization, evolution had produced various versions of the human species, all of which essentially existed in the hunter gatherer mode, a more nomadic type of existence. The most important requirement to maintain this mode of living was the ability to develop and manufacture tools, tools that could be weaponized and then employed to catch and kill prey for food. There was therefore a need for suitable materials that could be made into tools for this latter purpose. Prior to about 10,000 years ago, [1] Chapter 2 and 3, tools were made with some degree of success, from varieties of "stone", e.g. "Flint", see Figure 1. In fact, when it was discovered that food, i.e. wheat, [1] Chapter 2, could be cultivated in a localized position, these stone tools could do and successfully carry out the necessary work of clearing land area where the settlements could be built, these human actions were the beginnings of civilization. The major limitations of stone tools, however, were in the size and shapes that could be developed and their durability in performance. At about 10,000 years ago and onwards, [1] Chapter 4, metals started to be discovered, metals such as Gold, Copper, Tin, Lead and later came Iron, because this latter metal was the most difficult metal to extract from its source. The properties and performance of metal would ultimately be found by human beings to be very different and superior in most aspects of usefulness when compared to stone, for making tools, weapons and other objects, see Figure 2. However, metals at this point in history did initially suffer from the same limitations as stone, i.e. in their ability to be developed into the desired size and shape for manufactured objects --- this was a perennial problem for a little while at least, shall we say! --- We must now at this point ask some fundamental questions.

Figure 1. *Stone material tools adapted into weapons.*

Figure 2. *Early forged Iron metal made into arrowed headed weapons.*

Question: At this point in history, thousands of years ago, did mankind know anything about the nature of materials and indeed science?

Answer: Well, the reality was that the knowledge base was virtually non- existent. Human beings would not have a concept of what the exact nature of anything was at all.

Question: Accepting that many years ago there existed this dearth in mans' knowledge of the world around him how was it that any developments were made in the manufacture of tools or objects, in stone and or metals?

Answer: The only way open to man would be by saying to himself --- "If I do this action on whatever stone or metals are, then I shall observe an effect and learn from it to my advantage". Today we now know that these actions and effect are the sound basis of "Empirical Science", a discovery by man of staggering importance. It would be a natural thing for mankind to employ this thinking process, as it was evolution of the body and brain at work.

We must respect humans whatever species that were around thousands of years ago. They were just as intelligent as present day humans, it was just the knowledge base was barren, obviously not their fault. Consequently, it follows that early man about 10,000 years ago, [1] Chapter 4 and [2] started and tried to develop size and shape in the materials available, the quest would be to achieve greater functionality from tools and objects. It was soon realized, quite obviously, that objects in stone could not be increased in size and or changed in shape by any development techniques, such as bashing pieces together, as an advantage simply did not happen nor work out in a satisfactory manner. However, under particular conditions man soon found out that by employing the "Empirical Science" principle, metals were found to be malleable, tough, strong and ductile to such an extent the size and shape of metal pieces can be increased and developed readily when compared to stone. --- This was a major breakthrough in the science of metallurgy as we now know of it today.

It was soon realized, when manipulating metals in various ways, by using the principle of "Empirical Science", certain courses of actions when strictly adhered to, delivered a consistent and desired effect. For example, when metals could be made liquid by heating, then by pouring into a clay mold, allowed to cool and solidify, an increase and change in the size and shape of an object could be achieved, e.g. the production of what we today know as an ingot. The ingot could then undergo further change from hitting action i.e. mechanical working, which today we term as "forging" but in reality it is "forge welding". Archaeologists typically find ornaments, jewelry and tooling from this period in time, in metals such as Gold, Silver, Tin and Lead, [1] Chapter 4, as these metals could be readily found native in the pure form and melted and or easily smelted from the ore. Smelting from an ore and then casting was found to be more difficult and the only way in the pursuit of the metal Iron, therefore, usage of Iron was delayed somewhat, relative to the other known metals of the time, [1] Chapter 4. (To remind readers here, mankind really did not know at this point in time what metals consisted of and why they would be different in properties and performance to stone, this fact must always be kept in mind when trying to understand what was going on).

Question: Why was iron pursued by mankind?

Answer: Compared to the other metals discovered at the time, Iron had superior mechanical properties. It was a very desirable material to possess as it offered greatly increased functionality, [2].

We must now try and appreciate the difficult problems presented to mankind derived from extracting Iron from the ore by smelting, [1] Chapter 4. Due to the smelting difficulty, options needed to be explored to find other manufacturing techniques that would change the size and shape of pieces of Iron. Iron was mainly found as the ore or a sand type of material but only in solid metal form as a meteorite, [1] Chapter 4. Again, derived from action and effect (trial and error), it was discovered that by simply hammering pieces of Iron (meteorite) together the desired changes in the sizes of pieces could be achieved, i.e. by forging, [1] Chapter 4. Trying and doing the forging action with Iron at ambient temperature had no satisfactory result, i.e. no joining took place between pieces, however, if the solid source of iron was heated in a fire / furnace and then these pieces were hammered together, the joining effect was achieved, today we call this action "blacksmithing" but it is "forge welding". In general, and by chance therefore, especially working with Iron in this way, rapid progress was made in our expertise in the joining action derived from "forging". Over the centuries, Iron was eventually smelted in small blooms and even in Roman times these pieces could be forge welded into much larger pieces, remarkably to a weight of 40 Kg as a lintel, as an example of what became possible, see Figure 3. For a successful result, however, there had to be strict adherence to a certain course of actions, these actions were and have become known as "rituals" of forging, today we term these rituals as "weld procedures", [1] Chapter 4.

Figure 3. *Roman hypocaust lintel over 1 metre long and weighing some 40 Kg fabricated by forge welding a number of smaller 'blooms' of Iron by repeated heating and hammering.*

2.2. An Explanation of Welding Action Is Required

Question: We must now ask what was and is actually happening during the forging action on metals?

Answer: In order to answer the latter question we need first to call upon our current knowledge base of science to determine what is meant by the word "welding".

Welding fact: Welding is the action of bonding by the atoms that constitute the mating parts of a joint. This is an indisputable fact of science, as to contest it one has to prove atoms do not exist, anyone attempting to disprove this fact will not be successful, or ask yourself, do you feel lucky?

For illustration of "welding", see Figure 4. The figure shows gold metal atoms, the black dots, that bond one side of a piece of gold foil to the other, this simulates and illustrates the situation that has to be brought about in a joint being welded. Early man would obviously not know this fact about required atom behavior and also would not realize what had been discovered by action and effect, accurately, i.e. trial and error. Despite the ignorance of the time, mankind had now developed what has become to be known as the first welding process, namely "forge welding".

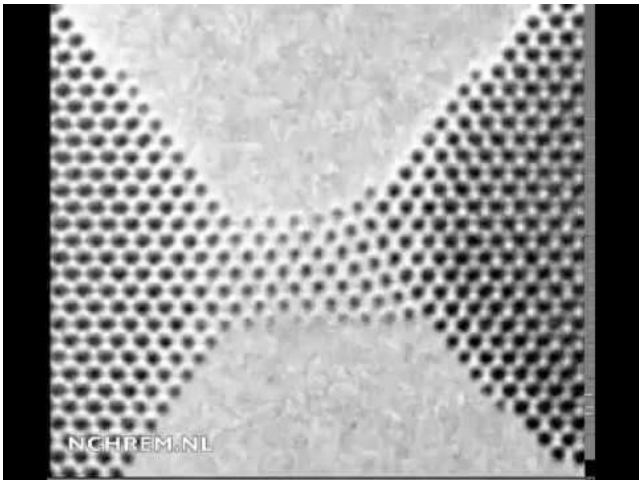

Figure 4. *Electron micrograph of how atoms (the black dots) bond one side of gold foil to the other side, this simulates and illustrates how a weld is formed between two component parts of a joint.*

2.3. How Was Welding Action to Be Physically Brought About

The energy delivery systems, i.e. the welding processes and their procedures! What initiated therefore the discovery of the forge welding process, i.e. in reality to encourage atom bonding, was the desire to join pieces of metal, predominantly to facilitate greater functionality of tools and objects manufactured. It was, and at this point in time the first welding development, the origin of welding engineering and hence one of the main principles.

Welding principle: One must initiate atom bonding between components of a joint.

Welding principle: The discovery of the effect of forging on metals by action and effect (trial and error) meant that it had been established that welding engineering was " Empirical Science based only " and we now know that this fact remains true to this current day. --- Another staggering discovery of great industrial importance.

Welding principle: It should be noticed that welding of metals requires the application of heat to elevate the temperature of the metal pieces/components to be joined. We now know that this requirement is because the atoms in a piece and or pieces of metal forming a joint do require a supply of energy to be able to bond.

The early use of the forge welding process had to be mainly in accordance with a spoken "ritual", as there was no other effective way of maintaining and preserving the knowledge base and practical techniques involved. An important example of using a "ritual" would be the Japanese Samurai sword maker, [1] Chapter 4, and see Figure 5. This ritual would require finding the appropriate starting material, which was Iron sand and charcoal, heating it in a furnace, recovering the smelted slab at the bottom of the furnace and then repeatedly hammering pieces of the iron slabs one on top of the other. This forging sequence of operations would be ultimately completed with a quenching of the hot forged metal iron piece. By selecting slabs from different parts of the furnace and the repeated forging action ritual, a composite and layered metallurgical structure of relatively soft Iron inside the sword and a harder Iron structure at the surface of the sword, was achieved. At the end of each stage of piece build up, in size and shape, the forger would and still does to this day make a religious type of remark, this remark would indicate a certain stage in proceedings had been completed, further, it would maintain and reinforce the discipline of keeping to the sequence and ritual of sword construction by forge welding, [3-5].

Welding principle: Application of welding processes should always be in accordance with a qualified ritual, i.e. a weld procedure.

2.4. How Is the Principle of Qualifying Weld Procedure Respected in Todays' Welding Fabrication Industry World – Wide

It is important to comment here on this latter welding principle from asking a question.

Figure 5. *Japanese Samurai sword maker forge welding the blade.*

Question: Does the modern and present day welding fabrication industry give the appropriate respect and acceptance to this principle of working to qualified rituals i.e. welding procedures?

Answer: A resounding --- NO!!! Has this "attitude" led to catastrophic failure events, well that is an emphatic YES!!! Evidence to prove this fact are the two most researched catastrophic failures of welded structure, the John Thompson pressure vessel failure in 1965, [6] and Alexander L. Kielland Oil Platform Collapse in 1980, [7]. The fundamental and true cause of these two failures of welded structure was a non-compliance and lack of strict adherence to a qualified welding procedure, [6] and [7], and see Figures 6 and 7.

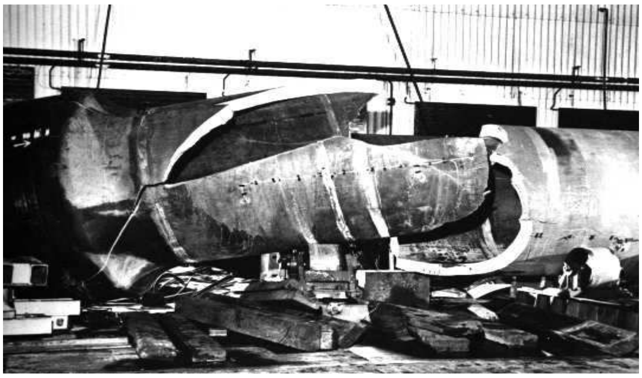

Figure 6. *The John Thompson pressure vessel failure upon hydraulic testing, this catastrophic failure did happen because the weld procedure was abandoned during fabrication.*

Figure 7. *The collapsed Alexander L. Kielland Oil Platform showing the failed brace D6 and the true source of the propagated crack which was the hydrophone insert welded joint. No qualified, weld procedure, welder and inspection techniques were used to manufacture this welded joint, a catastrophic failure was incurred as a result of this behavior.*

Welding principle: To obtain a welded joint between metals for example, one has to supply energy into the atoms residing in the joint, based upon the data contained in a qualified weld procedure.

Question: Where does this energy input come from for atom bonding?

Answer: The energy certainly does not come from human beings, which is to quash a currently held view that is where this energy originates from. The readers might try this experiment for themselves and see if anything happens: Take two short lengths of austenitic stainless steel pipe say 25mm O. D. and 2.77mm wall thickness and try to join them end to end, just by touching and at ambient / room temperature --- Nothing happens, but if you heat to 1600°C with a TIG torch and its process (GTAW), you will observe bonding taking place i.e. welding action.

Welding principle: Here with this latter experiment you have just proved a principle that human beings, including those we term a welder, do not weld anything, it is the *welding process applied that does the welding action i.e. providing the energy in the form of heat for the atoms to bond in the joint area.*

2.5. The Development and Historical Progress of Welding Processes

For thousands of years after the initial development of forge welding no new welding processes were discovered, this was because nothing better than a furnace for heating metal pieces came along, this situation persisted up and until the advent of the early twentieth century approximately. Because of this latter fact, forge welding, see Figures 8 and 9, therefore formed the backbone of welding engineering and its technology, despite this being the case mechanical engineers were able to design and build very substantial structures such as battleships, bridges, tunnels, pressure vessels and massive chains for example, [8]. Development of welding processes and techniques therefore plateaued right up to the "change point" which was the second world war, (WWII).

Figure 8. *Hot rivet forge welding.*

Figure 9. *Blacksmith forge welding.*

Progress in welding techniques needed a new source of heat energy and this only happened in earnest when the physics of electricity began to be exploited, this led to the introduction of electric arc welding processes, [8]. Early versions of arc welding processes happened in the later years of the nineteenth century and the earliest arc welding process was derived from experimenting with lead acid batteries as an energy source and arcing between graphite electrodes, the arc generated would provide a heat source into which wrought iron or steel rods could be placed and melted, [8] and [9]. In addition, the parent metal could be also melted in the vicinity of this arc and mixed with the melting iron rods, once this physical mixing was complete the entire liquid metal pool was allowed to solidify and thereby produce what we now term the "weld or welded joint". This latter arc process, [9], was further developed by attaching a coating to the filler rods e.g. by wrapping the rods in newspaper (cellulose) or by extruding pastes of oxide and silicate based fluxes on to the rod surface. Later into the early twentieth century the heat source for this Manual Metal Arc (SMAW) welding process was changed to using step down AC transformers and by WWII this process "came of age" characterized by a significant improvement in weld performance, [8] and see Figure 10.

Figure 10. *The Manual Metal Arc welding process with flux coated electrode, brought into production of the Liberty Ships during WWII.*

Question: What do we mean by improvement in performance of the Manual Metal Arc (SMAW) welding process?

Answer: What we have talked about so far is the application of a heat source to bring about the atom bonding feature of "welding". However, no mention of the other requirement we desire has been highlighted which is the quality of the produced and welded joint. The SMAW and a sub-version of this flux based welding process (Submerged Arc, SAW) were the only electrically powered welding techniques to be capable of producing welds with acceptable mechanical properties up to and including WWII, [8]. Up and until this point in time the predominant and essentially only welding process commonly used in engineering was the forge welding process, usually in the form of hot riveting and blacksmithing, see Figures 8 and 9 again. It should be however noted that other welding processes existed pre WWII, e.g. oxyacetylene and gas metal arc however, the resulting weld quality in terms of the imperfection level achieved from these welding processes was poor and as a consequence the mechanical properties of the welded joint tended to be always inadequate in some way to disappoint mechanical engineers and the manufacturers of the welded structures of the time, [8].

Question: Where does welding i.e. atom bonding, take place in metal pieces forged by a blacksmith and or in the hot rivet forge welding process?

Answer: Welding takes place within the forged metal piece or rivet itself, in the positions of internal imperfection surfaces, see Figure 11, which shows a typical internal ingot defect, a cavity in this case where its internal surfaces are fused derived from the forging action. (A fact not appreciated by some of todays' scientific presenters in the media).

We must therefore observe that up to the twentieth century the evolution in welding techniques and processes was slow and essentially non- existent. It needed further understanding of the physics of electricity and the demands of the WWII effort to provide further and accelerated development of welding processes.

Figure 11. *Typical internal defects of ingots, the internal surfaces of the defect are fused out by bringing about atom bonding derived from the forging action. Therefore, welding will have taken place and that is why forging should be termed forge welding.*

Figure 12. *Brittle fracture of a Liberty ship upon launching.*

A good example of this latter fact was the change in the fabrication technique of producing the Liberty ships during WWII. The traditional method of making the Liberty supply ships and indeed other types of ship, was to hot rivet forge weld the steel plates together. There was essentially nothing really wrong with the hot rivet method of ship construction but it could not meet so readily the demand for ships in the timescale required by WWII. By switching to using the SMAW welding process, see Figure 10, it facilitated faster ship fabrication, however, the ship builders suffered an almost immediate problem which was catastrophic failure upon launching, see Figure 12. At the heart of the problem was the steel first allocated for construction of the Liberty ships did not possess low temperature toughness at around 0°C. The effects of low toughness properties in the steel used were exaggerated by the application of the SMAW welding process. To overcome these major difficulties, the steel was changed in composition by alloying with Manganese and Silicon and the SMAW welding process was applied using parameters derived from qualified weld procedures (rituals), [10]. All this activity involved deliberate "Empirical Science"! Derived from this incident occurring and the way the problem was resolved, it became established that welding processes should only be applied from parameters that come from a qualified weld procedure --- a ritual.

Welding principle: To obtain an acceptable welded joint, the joint must receive a definite and precise quantity of controlled energy to facilitate adequate atom bonding.

Welding principle: Welding engineering is based upon empirical science and the physical application of welding processes.

Question: But haven't we known about the role of the ritual from centuries ago, derived from forge welding activity?

Answer: Yes, but during the WWII would be the point in time of recognition and acceptance of the fact that welding must only be carried out to qualified procedure i.e. ritual.

After WWII, new and existing electric arc welding processes required development and or improvement in their ability to deliver controlled electrical energy to joints. This feature of welding engineering was derived from progress and discovery, in general and material science, engineering science and testing techniques. A result of this latter activity, after WWII, has led to a multitude of welding processes being available to use in the fabrication industry, [11]. Examples of development were: a new ceramic material was needed to construct the shield gas cup on the torch for the Tungsten Inert Gas welding process, see Figure 13, and improvements in the electrical components for rectification of AC to DC current capability brought about the Gas Metal Arc (GMAW) processes to become more effective in delivering the required weld quality, see Figure 14. Other important examples of welding energy delivery systems were derived from Electron and Laser beams and Mechanical Friction. We can now observe that the evolution of welding principles and its engineering technology was relatively slow up to WWII but has progressed very rapidly afterwards, [8].

Figure 13. *The Tungsten Inert Gas (GTAW) Process with ceramic, torch components and shield gas cup.*

Figure 14. *The Metal Inert/Metal Active Gas (GMAW) welding process.*

2.6. The Development and Requirement for Welding Fabrication Specifications, Codes and Standards

Despite this evolution of welding processes, people involved in welding engineering and fabrication realized in the 1940's, 1950's and 1960's that it was not sufficient to have just a controlled welding energy delivery system to obtain what could be regarded as a satisfactory outcome for the welded joint. It became accepted that a satisfactory weld must possess an appropriate "material" and "physical" condition, which are the major components of "weld quality". Today we call this weld quality that is desired, as the "Common Objective", [2], see Figures 15, 16 and 17.

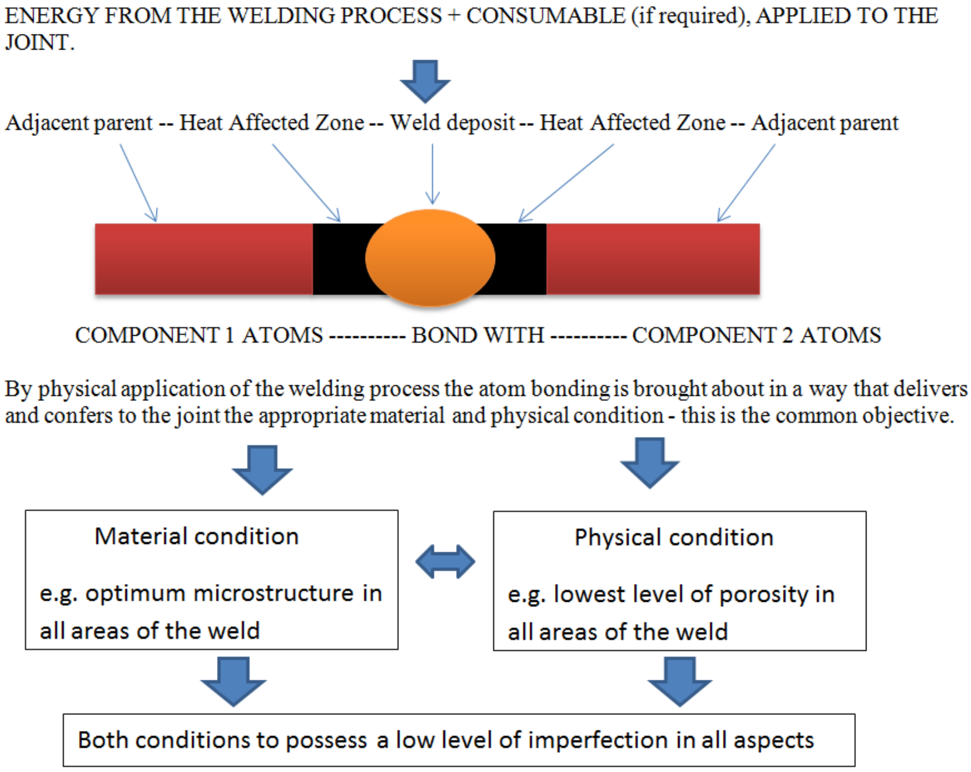

Figure 15. *Areas of a fusion welded joint and the "Common Objective" of welding action.*

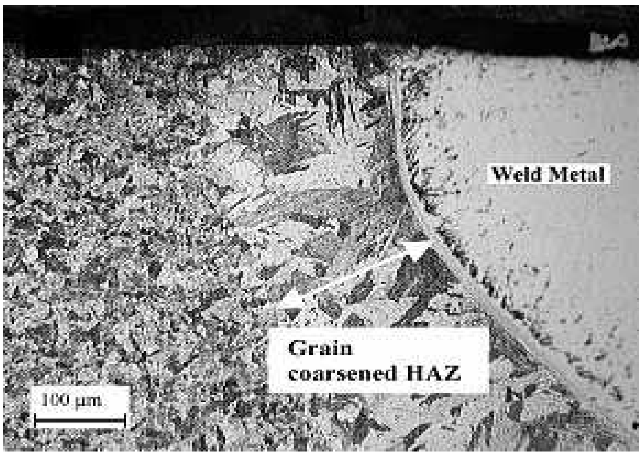

Figure 16. *Microstructure imperfection in a fusion weld, grain growth in the parent metal heat affected zone and adjacent parent metal, in a martensitic stainless steel.*

Figure 17. *Physical imperfections in a fillet weld, lack of:- root fusion, sidewall fusion and penetration.*

Welding principle: For all persons belonging to the fraternity of welding engineering, no matter what their *individual discipline is within the profession, there is a "Common Objective" to which they must strive to satisfy, which is:- All welding action has to derive and develop the appropriate material and physical condition in the welded joint, that possesses the lowest level of imperfection in all aspects of consideration. --- This is one of the most important welding principles.*

Evolution in welding engineering in the 1940's, 1950's and 1960's and the realization of the requirement to attain a defined weld quality to be fit for purpose, led to the design and strong introduction of what are termed codes, specifications and or standards. Examples of these were and are --- ASME Boiler and Pressure Vessel Code, [12] --- The ASME B31 Code for pressure piping, [13] --- ANSI/AWS D1.1 Structural Welding Code, [14], BS/PD5500 Specification for unfired fusion welded pressure vessels, [15] and many more from the strong industrial nations of this time. Contained within these specifications were listed the welding engineering variables that needed to be controlled during the mandatary development of welding procedures, the testing of these preliminary weld procedures and the defined criteria for permitted and not permitted imperfection level for acceptance of the production welds. The fundamental role of these codes, specifications and standards, [12-15], was to define in detail the characteristics of the relevant "Common Objective", see Figures 14, 15 and 16 again, that was suitable for the welds that constructed certain products and provided the best guarantee of weld fitness for purpose. Further, the definition of a skilled welder was established which was one who only works to a qualified weld procedure for welding a joint. Fitness for purpose of the welds in a particular code, specification and or standard can be further expressed and defined as that which is capable of giving uninterrupted satisfactory performance during the designed service life for a component or structure, without premature failure.

Welding principle: What the published codes, specifications and standards for welding engineering are saying is that essentially all welding activity should be carried out to proven methodology and with qualified personnel.

Question: Why in todays' industrial environment does a considerable amount of welding fabrication be carried out with the welders *"guessing"* the welding process parameters and physical manipulation techniques of the process equipment? The correct welding principles are spelled out in no uncertain terms in the welding fabrication codes, specifications and standards, [12-15], that *"guessing"* is never permitted. Why is this requirement not observed and carried out by welders?

Answer: Welders are not educated and or trained to understand adequately the welding principles. This situation is not the welders' fault! however, it must be corrected in the USA, UK and the rest of the world. --- A very disturbing statement of fact here!

This latter behavior by welders and fabrication companies enhances the probability of catastrophic failure, defined as "sudden and unexpected", in welded structures, see again for examples of the result from Figures 6 and 7 that can be incurred. The *"welder guessing"* problem has been recognized by the International Institute of Welding and has instructed the welding institutions of member countries throughout the world to implement ISO EN 3834 quality assurance standard, as one means of dealing with the situation, [16].

Using empirical science principles, weld procedure development has to investigate the effect of a considerable number of welding variables in order to be successful, which is why welders must not *"guess"* welding process parameters. The following is a typical list of welding variables to be investigated:

Material and its product forms --- Material product form dimensions --- Type of joint --- Welding process --- Joint preparation and dimensions --- Joint preparation method --- Welding position --- Run sequence and type --- Weld surface finish --- Preheat application and Interpass temperature control.

Process Shield gas and Flow Rate, if applicable --- Flux coating if applicable --- Shield gas composition --- Process Torch details, if applicable --- Power input, volts and amps for example --- Travel speed --- Polarity of process --- Mode of power input --- valid codes, specifications or standard.

From this list of variables, that have to be correct and appropriate to have a chance of delivering the relevant "Common Objective", one can appreciate that it is nonsensical, irresponsible, unskilled and an extremely dangerous activity in trying to apply a welding process to a joint without consultation to a qualified weld procedure. *It is sheer folly!* We must now reflect and again ask why it is that modern day welders think it is acceptable to *"guess"* welding parameters for a particular welding process to apply to a joint from bearing the next comment in mind. For centuries early welders never did this irresponsible act of *"guessing"* as they had to strictly adhere to the "ritual" to obtain a successful outcome for the joint or object they were concerned with. It is disappointing to report the evolution of this *"guessing"* activity that shows no respect of the welding principles. Over the years, welding engineering has veered off track and lost direction, described by the author as an infection of an engineering virus, [2], that expresses itself in poor quality of education and training of welding people and apprentices not being as good as it should be.

3. Conclusions

We can now determine some fundamental facts regarding welding and welding engineering.

1. Welding fact: We can now argue that people of all the disciplines within the welding fraternity should be regarded as a "welder" because they have the same "Common Objective". --- It is now possible to define what a "welder" is and does: "A welder is a person who

has the ability to implement those techniques using welding processes which are proven to control and suppress the imperfection levels incurred in welded joints when the qualified welding procedure or instruction is referenced".

2. The terms "welding" and "welding engineering" are different:
   a) "Welding" is simply defined as the bonding of the atoms residing in the component parts of a joint.
   b) "Welding engineering" is an "Empirical science only" [17], and manifests itself as the act of fabrication of structures using the established welding principles.
3. To improve understanding, education in the subject of welding engineering needs to be significantly improved in order to maintain the momentum of its evolution.
4. If the established welding principles are adopted and carried out in full, what can be achieved? see Figure 18.

Figure 18. *Road going liquid gas containing pressure vessel equipment demands high weld quality fabrication, i.e. welds with a controlled low level of imperfection in all aspects. This fabrication quality can and is achieved by implementing the established welding principles. Photograph courtesy of M1 Eng. Ltd, Bradford, UK.*

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