Computer based welder training and the development of combined virtual welder training and virtual metallurgy

Ron Scott, FREng., BSc, C Eng., FIMMM

Metaltech Services Ltd is a UKAS accredited mechanical and chemical analysis laboratory in the North East of England. Part of the work carried out involves weld procedure and welder qualification test work. Therefore, during the past 10 years we have seen good welds and also welds with imperfections and defects. This opportunity to view a large number of weld samples has enabled MSL to understand how difficult it can be to consistently produce a high integrity weld and to appreciate the amount of repetitive training that is required for a welder to achieve the required competency.

Our involvement with the evaluation of weld quality has provided good background information to enable us to carry out a development project to produce a computer-based welder training system using Virtual Reality and Augmented Reality techniques. VR/AR methods of welder training have been evaluated in several published research documents[1,2,3] and EU projects[4] and all the results give positive support for the use of these techniques. VR and AR can assist identify people that have the natural skill for welding. They can assist with welder training and also provide training assistance to perform correction actions for experienced welder's technique when poor welds are produced.

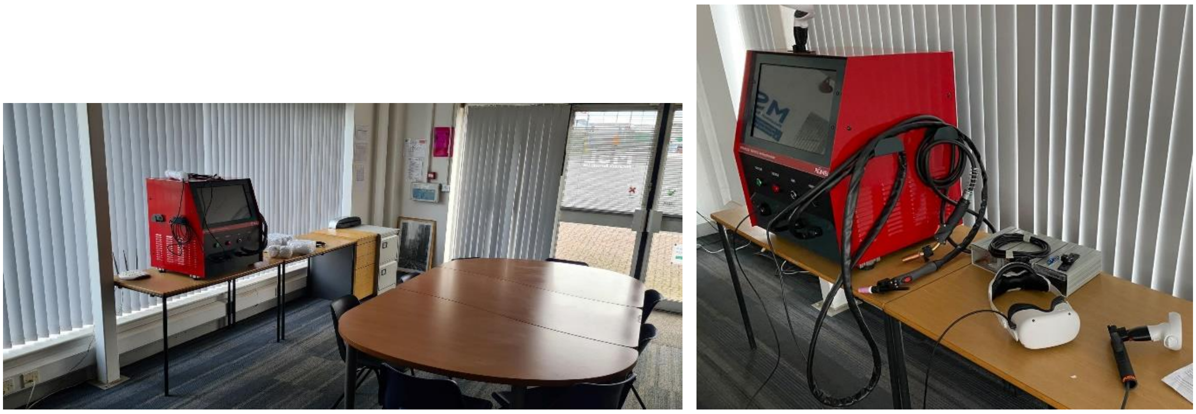

Figure 1. Demonstration VR/AR welder trainer in Metaltech Services Reception area (March 2023)

There is now convincing evidence that VR welder training should be the preferred choice since it avoids the use of material, welding power, welding consumables and welding gases and eliminates any safety concerns. In addition, the software evaluates the weld quality and provides quantitative value of the

[1] Ananya Ipsita et al, Towards Modelling of Virtual Reality Welding Simulators to Promote Accessible and Scalable Training, CHI '22, April 29-May 5, 2022, New Orleans, LA, US, https://dl.acm.org/doi/fullHtml/10.1145/3491102.3517696

[2] Vei Siang Chan et al, VR and AR virtual welding for psychomotor skills: a systematic review, Multimedia Tools and Applications (2022), https://www.ncbi.nlm.nih.gov/pmc/articles/PMC8857740/pdf/11042_2022_Article_12293.pdf

[3] A. P. BYRD et al, The Use of Virtual Welding Simulators to Evaluate Experienced Welders, DECEMBER 2015 / WELDING JOURNAL 389-s, https://www.researchgate.net/publication/301491084_The_Use_of_Virtual_Welding_Simulators_to_Evaluate_Experienced_Welders

[4] Virtweld 2009-2011, InteractivWeld 2013 (created SKS Skill, Knowledge, Stability), eu-Weld 2016, Digiweld 2018, Weldchance 2018.

weld quality imperfection/defects which gives the welder immediate constructive feedback so that progress can be monitored and welding technique improved.

During the past five years MSL has reviewed the many commercially available systems that are available and that are being developed. During this period of time, we have prepared a design for a computer-based welder training virtual environment, including a concept of adding virtual metallurgy.

We are working with a key partner company, **Redlab,** with significant experience in both sensor technology and software design for VR and AR to assist with our development of combining virtual welding and virtual metallurgy. Redlab have manufactured VR welder training systems for over ten years and their proven system forms the basis of the development of "Virtual Weld Tutor".

Virtual Weld Tutor- The provision of welding know-how by integrating virtual reality/augmented arc welding skill training techniques and virtual metallurgy. The virtual metallurgy has been created by the use of computational welding mechanics to allow the prediction and an understanding of weld metallurgy, integrity, durability and potential weld failure modes

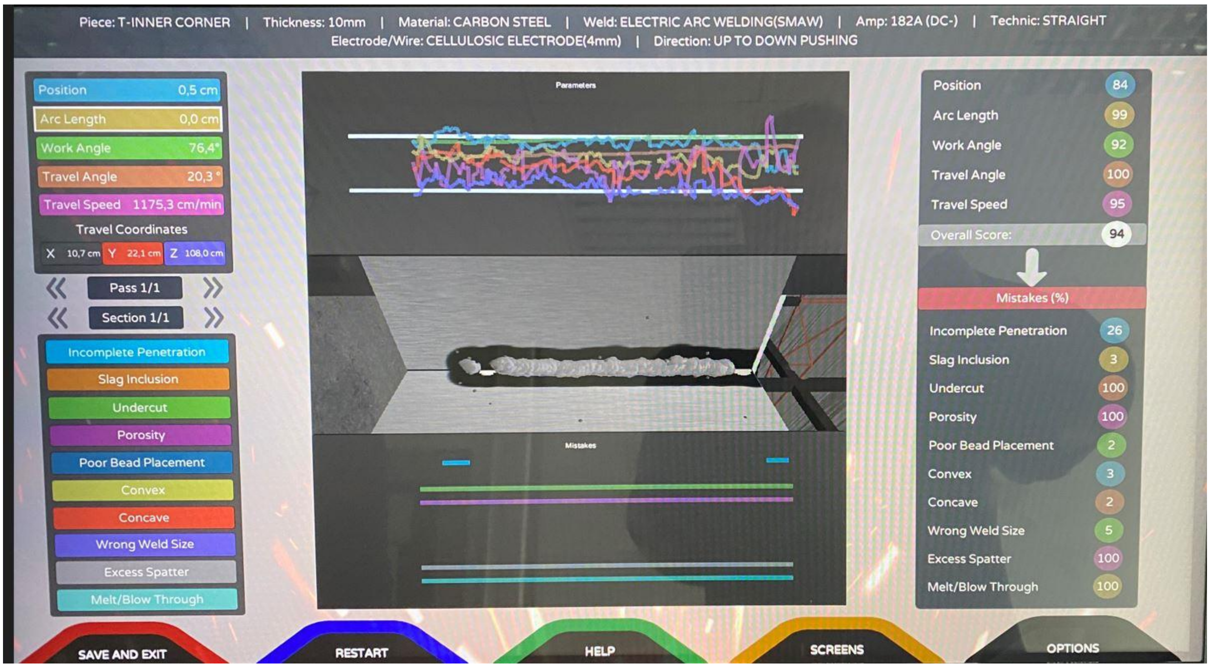

Figure 2 The results of a trial weld (April 2023)

Background to the importance of welding

We can all agree that Industry and Government representatives appreciate the important contribution that welding technology has made to the economic performance of the country. However, at this moment in time, there is a need for better targeted publicity and encouragement for the next generation of welders, to explain the vital importance of welding technology to the UK's industrial performance. It is also important to find an industrial strategy to deal with the current problems faced by all involved in the application of welding that has led to a decrease in the number of the younger generation wanting to take up welding as a career.

There is a need for all concerned with training to develop a more proactive approach and to provide "world class", inspirational leadership in Vocational and Technical training needed to encourage the younger generation to view welding as an important career opportunity.

In the UK we should all be proud of the impressive achievements made by TWI (The Welding Institute) as we celebrate the 100 years anniversary of its formation. (See Figure 3). TWI has provided both training and significant technical contribution to all the technical aspects of welding. This includes the CTOD fracture toughness test and the development of the novel technique of "friction stir welding". In addition, the UK government has made major investments into Nuclear AMRC welding research such as large electron beam welding and laser since 2011. The good news should be supported by a plan to encourage the use AI (Artificial Intelligence) and computer-based welder training to help provide appropriate effective solutions to the problems faced by the welding community.

A major issue facing most industrialised countries is that the number of experienced welders is on a downward trend, which has resulted in a shortage of welders. It is therefore, important for the main industrial stakeholders to find a solution to this problem and to arrest the demise of welding in the UK.

In the UK, during February 2022 it was noted that the number of welders in the UK had fallen by a quarter in five years. Half the welders in the UK are expected to retire by 2027, creating 36,000 vacancies.

According to The American Welding Society older welders are reaching retirement age and younger workers are not replacing them in sufficient numbers. According to one estimate, there will be a shortage of 400,000 welders by 2024.[5][6]

Australia, also has a welding skills shortage and is likely to get worse also due to an aging workforce. Approximately 30% of Australia's existing welding workforce is aged over 45 years.

By 2050, the retirement of welders in Japan, has been predicted to result in a 50 per cent loss in their welding workforce. Japan will need to train around 250,000 welders.

The country that finds the solution to the reluctance of the younger generation to become welders will be rewarded with strong and dedicated welding community which will be essential to maintain a profitable and viable manufacturing industry.

Why is there a shortage of welding personnel?

Within the welding Industry there is agreement that there are several reasons for the shortage of welding personnel with two fairly obvious causes

1. There is a known difficulty with replacing welders as they retire. Typically, the person retiring has significant experience and it is often the easiest solution is to appoint a replacement that has considerably less experience. A recent event that emphasises that this can cause problems occurred in 2018 when there was an announcement of a delay with the missile tubes for the new UK nuclear submarines contracts which gave rise to headlines:
   "UK's new £31 billion nuclear missiles DELAYED by welding defect"[7]
   The subcontractor in the USA (BWX Technologies) had weld quality issue on submarine missile tubes and gave the root cause as "**it had not made the tubes for three years and their skilled welders had retired and were replace by novice welders with insufficient supervision**." The cost for this event was over $30 million in repair costs and substantial delays. A second

[5] https://www.millerwelds.com/resources/article-library/addressing-the-welder-shortage-with-technology
[6] https://worlddidac.org/news/the-importance-of-welding-across-industries-the-shortage-of-welders-and-the-future-of-welding-training/
[7] https://www.express.co.uk/news/world/1000896/nuclear-missiles-uk-defence-news-royal-navy-dreadnought-submarines

subcontractor was also found to have manufactured missile tubes that had cracked welds.

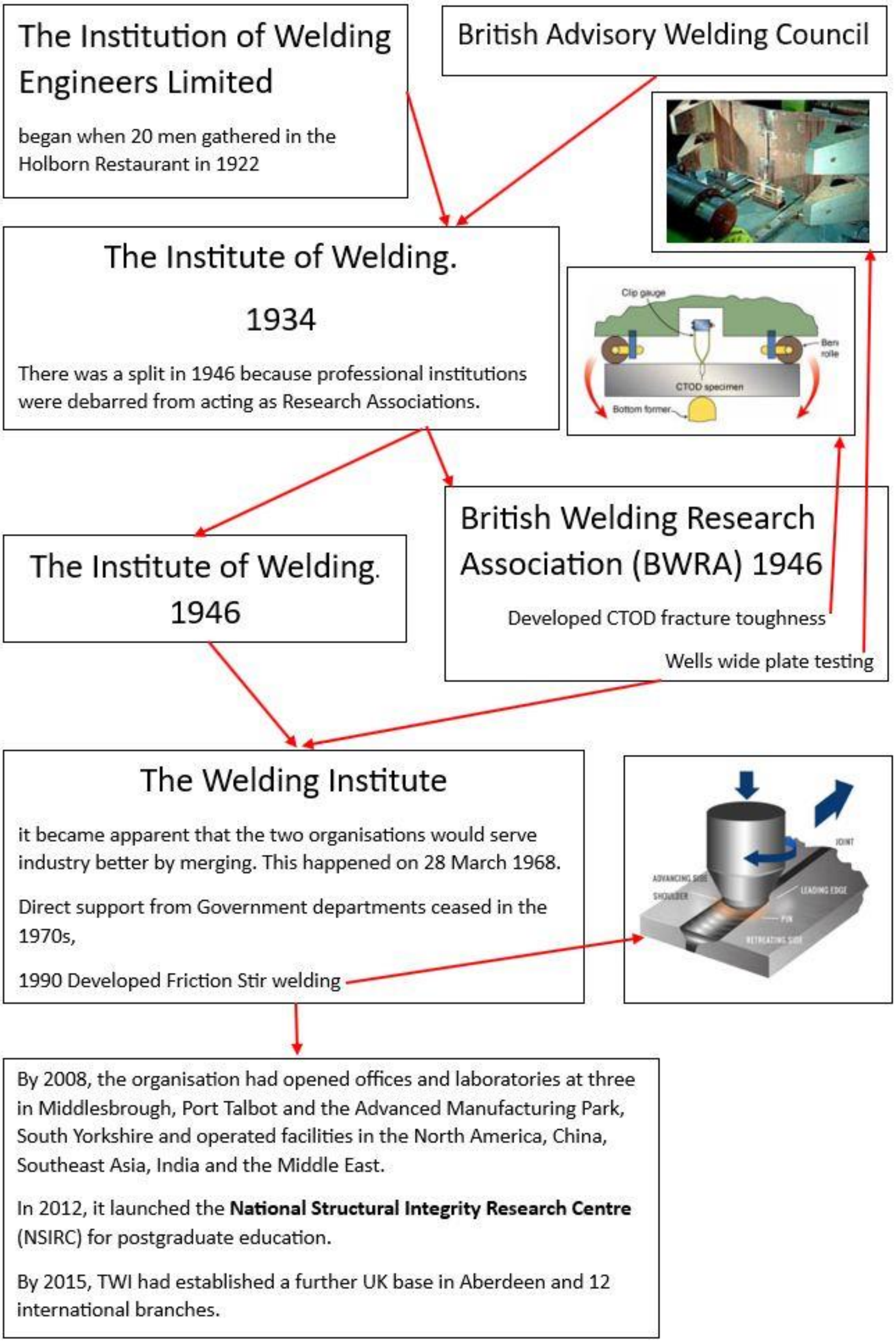

Figure 3. The 100-year history of The Welding Institute[8]

[8]https://en.wikipedia.org/wiki/The_Welding_Institute#:~:text=Originally%20registered%20as%20the%20Institution,welding%2C%20joining%20and%20allied%20technologies.

Due to potential delays and extra costs and important defence issues a report of the events had to be prepared for Congress.[9]

Hopefully, these weld failures do not represent an ominous foreboding at a time when the world is considering return to large stainless-steel fabrication to allow the building of new nuclear power stations. Could similar problems occur since these parts have not been made for over forty years and the welders involved have retired? Could there be a similar lack of skill and knowledge?

2. In recent years the younger generation has developed a negative perception regarding finding a rewarding career in welding.

   Welding Engineers that visit schools to encourage interest in welding, report that the pupils are not interested in welding and do not see welding as a career path. Some of the problems highlighted are:

   i) The belief that the work is repetitive and monotonous.
   ii) That the industry has a history of low pay.
   iii) That the working conditions are dangerous with several health and safety concerns
   iv) That there is a lack of career development

All concerned with these problems, consider that it is a major task to change these misconceptions. However, the situation cannot be ignored and one of the first tasks is to find a way to encourage the younger generation to become involved with welding.

Therefore, it is important to outline and publicise what welding has done for the society in which we live, and the current and future developments that are taking place many of which could represent a utopia for budding entrepreneurs.

Many welding institutes across the world are asking why the lack of trained welders and how to find a solution.

MSL's approach has been to read the words of the UK's most famous welder.[10]

In his recent book Billy Connolly devoted a chapter to becoming a welder in the shipyards. "I became a welder. I was actually becoming an Engineer and I joined the wrong queue. And so, I became a welder, without knowing what a welder was."

He says that he "loved calling myself a welder being part of something bigger than me."

He observed that the shipyards and welding gave him many sources for his stories, "In the local pups at night he was told if anyone nods just ignore it. It is a welder putting his helmet down!"

There was obviously a great sense of comradeship. He commented that "when it rained, they all got electric shocks from their welding sets which the all found hilarious and the fell about laughing"

He worked for five years as an apprentice and then a further two years as a welder.

Billy does comment about the Health and Safety concerns. Some of the welding electrodes were wrapped with asbestos. I was very lucky that after I did my five-year apprenticeship, I stayed on as a welder for only two or three more years and left in my early twenties. "But many men were there much longer and got asbestosis in their forties or fifties."

[9] https://www.gao.gov/products/gao-21-257

[10] Billy Connolly, Tall Tales and Wee Stories,(2019). Billy Connolly, Windswept and Interesting. (2021)

These brief comments show that there can be strong comradeship and an important sense of achievement for being responsible for creating ships and infrastructure. However, the health and safety concerns need to be fully disclosed, discussed and suitable protection provided.

Achievements and Status of Welding Technology

Welding has been a major driving force in worldwide economic development. Welding has allowed major infrastructure development, the extraction and use of energy and chemical resources, and played a major role in defence technology and space exploration.

Welding has emerged as a sector of the economy with a substantial financial turnover and provides a major contribution to the worldwide economic performance, both in terms of jobs created and products manufactured.

Welding has become an established and essential technology in all industrial sectors and has a secure future. Recent predictions of the estimated future turnover in welding technology are:

- Global welding machinery to reach $17.1 billion by 2026
- Global welding consumables to reach $14.2 billion by 2023
- Global welding robotics to reach $9.7 billion by 2028

Welding involves both manual and automatic/ robotic techniques. The performance of the actual welding process is a multi-disciplinary task involving both an individual's psychomotor skills particularly with manual welding and substantial metallurgical and mechanical and electrical knowledge to ensure weld integrity.

For a welder to consistently produce high integrity arc weld represents a challenge.

Welding involves: -

1. Movement-oriented psychomotor "skills" to actually deposit and manipulate weld metal to form a bond between two pieces of material whilst avoiding UV radiation and weld fume.
2. Technical knowledge of the theory and practice of welding to determine the welding process and the welding procedure.

Typically, these roles are split between a person with the skill that we refer to as the welder and the person with the technical knowledge we refer to as the welding engineer. However, during my involvement with training in the technical aspects of welding it is surprising how many graduate level technical students had enrolled because they thought they would learn how to weld!

"Virtual Weld Tutor" aims to provide both the skill and the theory and practice so that anyone that studies welding can acquire both the skill and appropriate technical knowledge. The training method aims to avoid the "old" demarcation between the skill side of welding and the theory and metallurgical aspects of welding.

MSL's aim was to develop a VR/AR welding skill training equipment coupled with "virtual metallurgy" to allow an evaluation of the weld integrity that results in a better appreciation of the effects of variables on weld quality.

A secondary objective was to be able to carry out a virtual weld procedure test using a metallurgical knowledge base. This would allow the evaluation imaginary weld approvals and the optimisation of the processing windows to allow consistent high integrity welds prior to the real weld procedure.

An additional, aim would be to provide the skill side of welding, access to more knowledge so that the welder can be the weld provider and the judge and jury regarding the weld integrity and future performance. This will result in greater responsibility, improved job satisfaction and a better trained work force.

The four principles of material science

This topic has been introduced to show the need for a holistic approach to materials manufacture which should include consideration of manufacture, microstructural development and the mechanical properties achieved which all contribute to allow satisfactory service performance.

It is quite a surprise to review the principles of material development and to find that it was not until around 1990[11] that there was clarity on the four primary elements that are critical to the production of acceptable materials for engineering applications. These were identified as processing, structure, properties, and performance. They were initially viewed as a quadrilateral triangle and also a chain[12] to emphasis each topic was equally important.

This general approach to the production of acceptable materials came from initial metallurgical approach to metals manufacture. The structure/property relationship approach was first used at the turn of the early 1900's and continued to develop as the relationship between microstructure structure, mechanical properties, and performance of metals was clearly established.

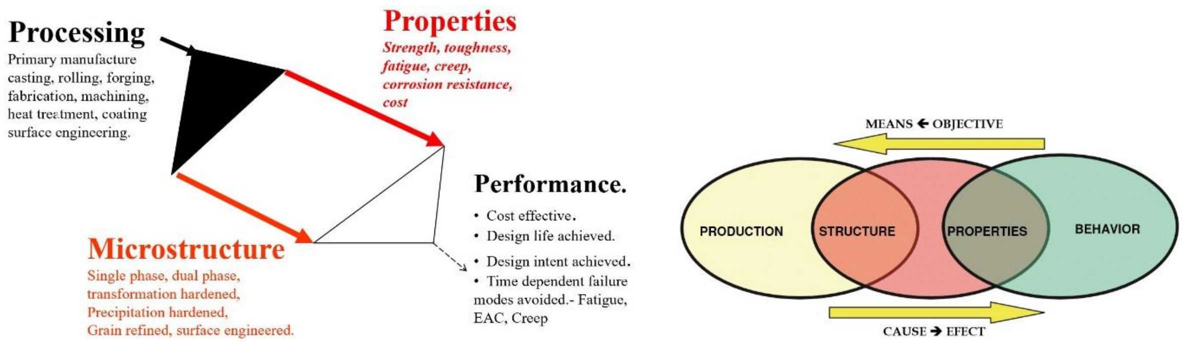

Figure 4 The early tetrahedron and the three-link chain model of the four principles of materials science and engineering

During the 1970's when I worked in the steel industry the relationships between mechanical properties and the microstructure were well established and a key method used for steel development, and control of manufacture. This also extended in the aspects of weldability an important final manufacturing process where there was a range of microstructures developed and the possibility of several imperfections and defects such as cracks, slag and lack of fusion.

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[11] Materials Science and Engineering for the 1990s: Maintaining Competitiveness in the Age of Materials National Academies of Sciences, Engineering, and Medicine. 1989. Materials Science and Engineering for the 1990s: Chapter 1. Washington, DC: The National Academies Press. https://doi.org/10.17226/758.

[12] G. Olson, Computational Design of Hierarchically Structured Materials Science, 1997, 277 (5330), pp.1237-1242. https://www.researchgate.net/publication/235232813_Computational_Design_of_Hierarchically_Structured_Materials

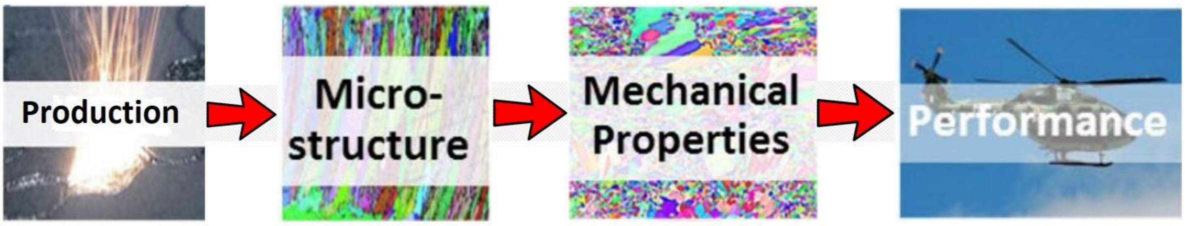


Figure 5 A simple view of the 4 principles of material science

There are many products that demonstrate these principles, for example the development of high strength weldable steels. The main source of understanding of steel quantitative relationships was the work of Hall and Petch on the importance of grain size and from 1963 onwards by Brian Pickering and Terry Gladman who carried out detailed work at Swinden Laboratories and published many of their findings. An excellent major review of Micro Alloyed steel was published in 2016 by TN Baker of Strathclyde University, which included reference to the many aspects of the important history and the recent innovations such as direct rolled thin slab.

Technical Aspects

Microstructure control is crucial to weld quality and the prevention of weld failures both in terms of failure by fatigue and fracture and failure caused by corrosion. The development of techniques to provide more effectively control microstructure created during welding will have a significant positive impact on product cost and quality.

Many fabricated components and structures are welded. Welding has now become an established method of near net shape additive manufacturing for several metals. Invariably, the weld joint is the most critical region from a performance perspective. Fatigue cracking is by far the most common failure mechanism in welded joints, and unstable fracture is perhaps the most dramatic, occurring without warning and often leading to catastrophic consequences.

The heat-affected zone (HAZ) is the region of base metal which has its microstructure and properties altered by welding. The HAZ has complex metallurgical reactions that can degrade the HAZ mechanical properties. Despite their small size, brittle regions within the HAZ can have a strong influence on failure by brittle fracture. The HAZ is the most common region of weld failures directly related to the microstructure.
The main objective of this product development is to provide a metallurgical based capability to predict the final weld microstructure and properties of the HAZ produced during welding to assist the knowledge of the welder and provided an assistance to develop WPS.

Applied VR and AR

The training of new recruits and the retraining of qualified welders has now been transformed into a safe, low cost, closely monitored with automatic evaluation and assessment of the task due to the progress in the field of AR and VR-technology. A helpful diagram that shows the difference between Real Reality, Augmented Reality and Virtual Reality is shown in Figure 4

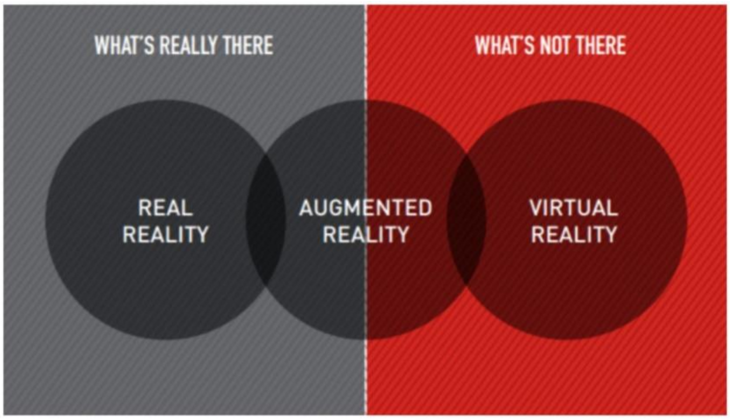


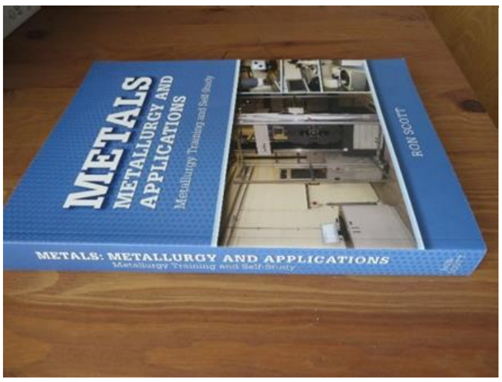
Figure 6 Helpful diagram showing RR, AR and VR

Training simulators are widely used and makes it possible to increase the efficiency of vocation training by several orders of magnitude in compare with the traditional form of welders training. According to the estimates of flagships this market segment, in particular Fronius, Seabery and others, this allows to prepare certified welders more, then 34%, to reduce the training period by 56%, decrease the cost of laboratory work by 68%, to diminish CO_2 emissions to the environment, to save considerable resources and materials, to avoid physical risks for students in 84% of cases

Welding metals

At an early age we are all taught that steel is an alloy of iron and carbon with some manganese, silicon, chromium and nickel and possibly other elements. A documented proof that steel was carbon plus iron was provided by Sir Humphrey Davy in his book "Elements of Chemical Philosophy" published in 1840. Davy stated that Sir George Mackenzie had made steel by adding diamonds to molten iron. It was also reported that Sir George used his mother's jewellery!

To understand the response of steel to welding there is a need to be aware that there are many grades of steel and also that there is a need to understand some aspects of metallurgy. During the time that I was involved with the teaching of weld metallurgy I prepared a power-point that listed the specific topics relevant for the understanding of welding. This is shown in Figure 8. At this point in this presentation ideally there should be an adjournment to allow a study of the new terms shown in Figure 8. To assist with this task we recommend MSL's metallurgy training manual that also has a chapter on welding.[13]



Chapter 1	Background to key events and developments
Chapter 2	The Structure of Metal
Chapter 3	Steel Selection and Steel quality
Chapter 4	Heat treatment and Surface Engineering
Chapter 5	Mechanical Testing
Chapter 6	Fracture
Chapter 7	Corrosion
Chapter 8	Welding
Chapter 9	Metal Casting
Chapter 10	Engineering Materials
Chapter 11	Prediction of Micro-Structural Evolution in Steel

Figure 7 MSL's book Metals metallurgy and applications, metallurgy

[13] Ron Scott, Metals metallurgy and applications, metallurgy training and self-study, 2020,

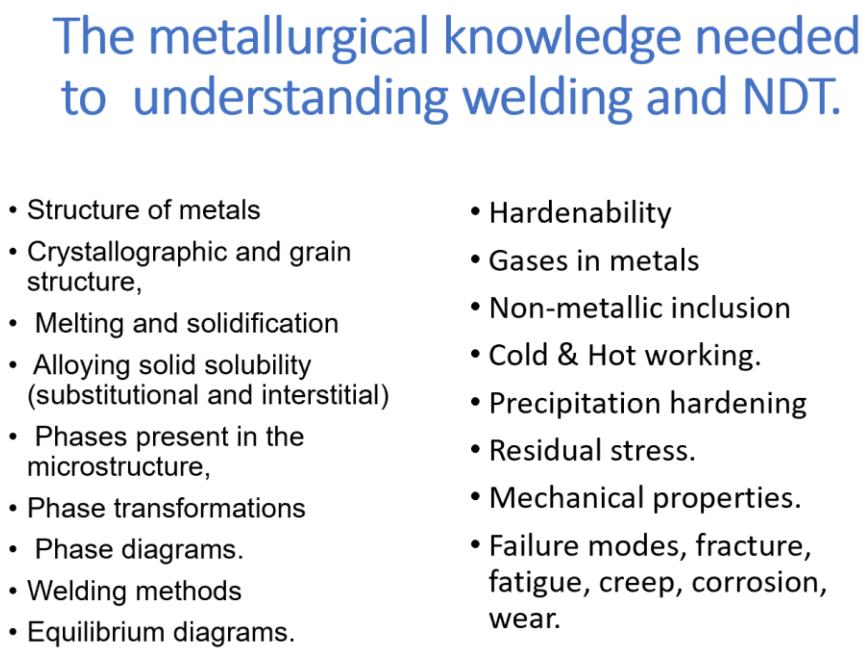


Figure 8

Steels are sometimes referenced by their microstructure and sometimes by a commercial name or application. Some of the important groups are

low carbon automotive steel strip,
low-carbon weldable structural steels,
engineering steels
stainless steels,
wear resistant steels,
tool steels,
carburizing steels
nitriding steels,
bearing steels,
rail steel.

Multi-alloyed steels and guidance to weldability

When alloy steels contain a number of elements with different percentages, their microstructure cannot be simply represented on the simple phase diagram and it is necessary to look for other ways to assess and present the effect produced by the alloying elements on the structural transformations occurring during heat treatment.

The method that has been used for the past 70 years was developed by Anton Schaeffler (1948).[14] The method uses the fact that some alloying elements can be classified as ferrite stabilizers, which tend to promote the formation of the bcc α-phase, or as austenite stabilizers, which tend to promote the face centred cubic (fcc) γ-phase. In predicting the room temperature microstructure of stainless

[14] Pierre Guiraldenq et al, The genesis of the Schaeffler diagram in the history of stainless steel, Metall. Res. Technol. 114, 613 (2017). https://www.metallurgical-research.org/articles/metal/pdf/2017/06/metal170104.pdf

steels, therefore, the balance between the ferrite and austenite formers can be considered. Based on an empirical approach the Schaeffler diagram was developed. (See Figure 9)

The Schaeffler type diagram indicates the structures produced after rapid cooling from 1050°C.

The chromium equivalent represents the proportion of elements (expressed as weight percentage) that behave like chromium in promoting ferrite according to: Cr equivalent = Cr + 2Si + 1.5Mo + 5V + 5.5Al + 1.75Nb + 1.5Ti + 0.75W

The austenite formers give: Ni equivalent = Ni + Co + 0.5Mn + 0.3Cu + 25N + 30C

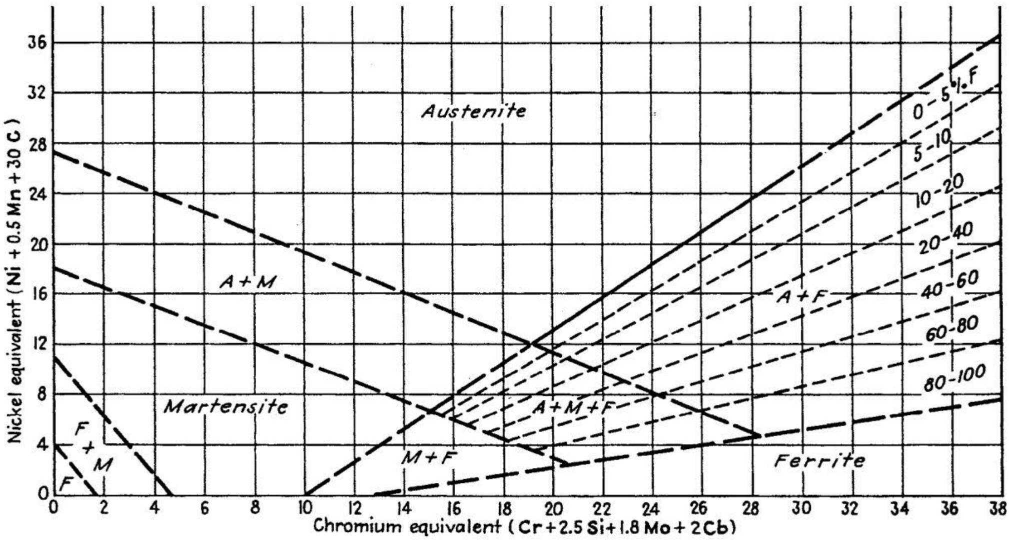
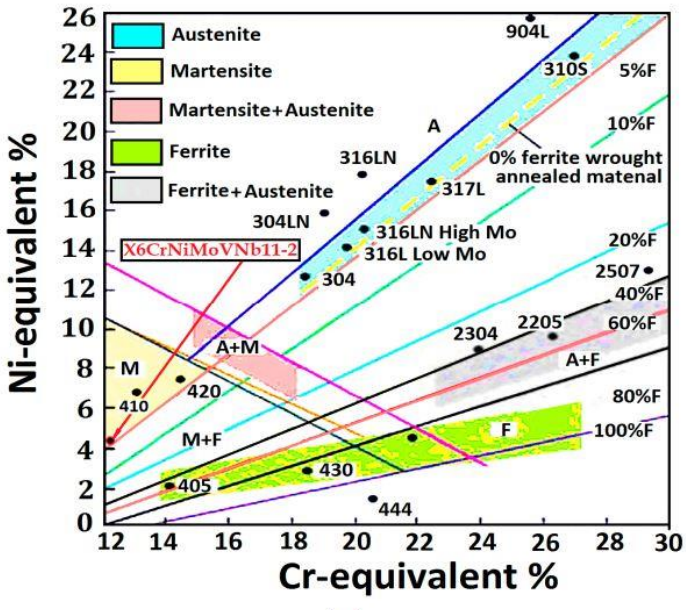


Fig. 5. First Schaeffler Diagram published in 1948 [18].

Figure 9 The first Schaeffler diagram published in 1948



(a)

Figure 10 A Schaeffler diagram from 12% chromium equivalent showing several stainless steel

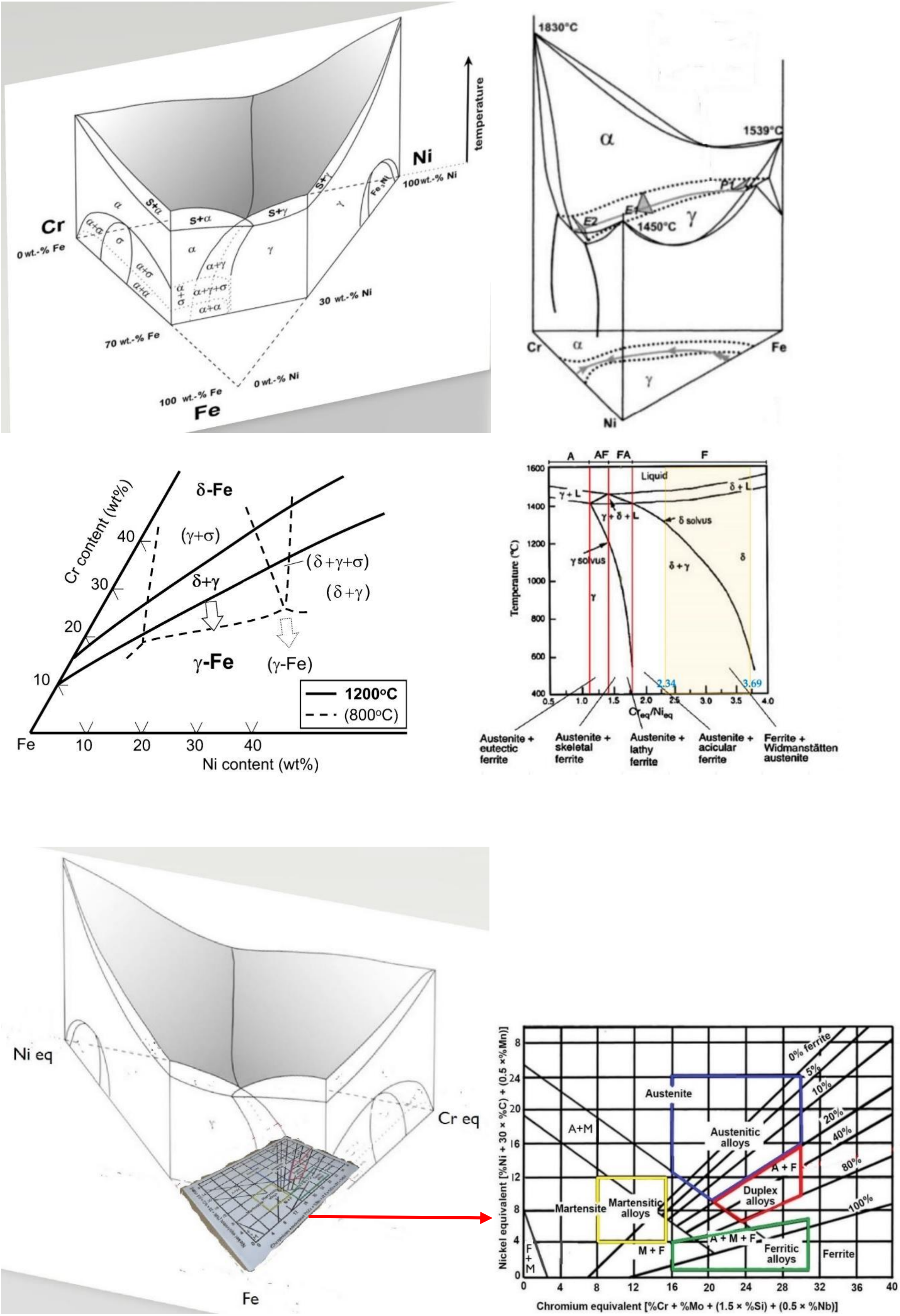


Figure 11 Diagrams showing details of the ternary Fe-Ni-Cr equilibrium diagram and the relationship with the Schaeffler diagram

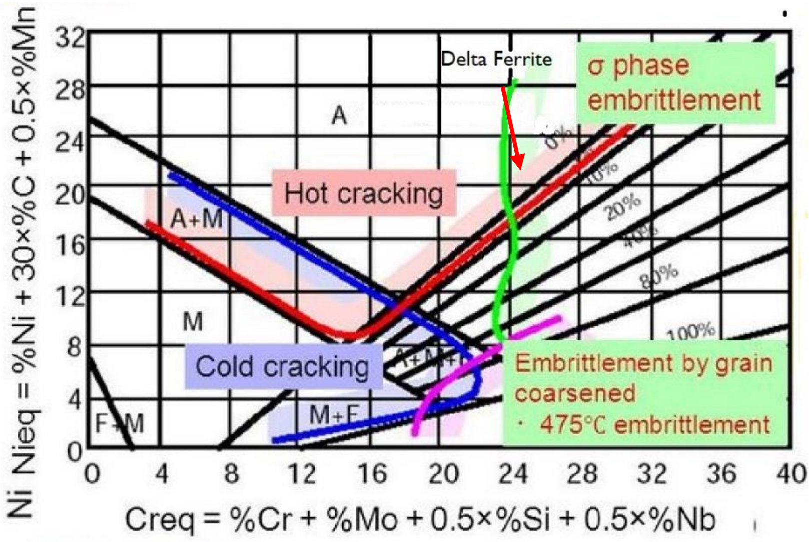
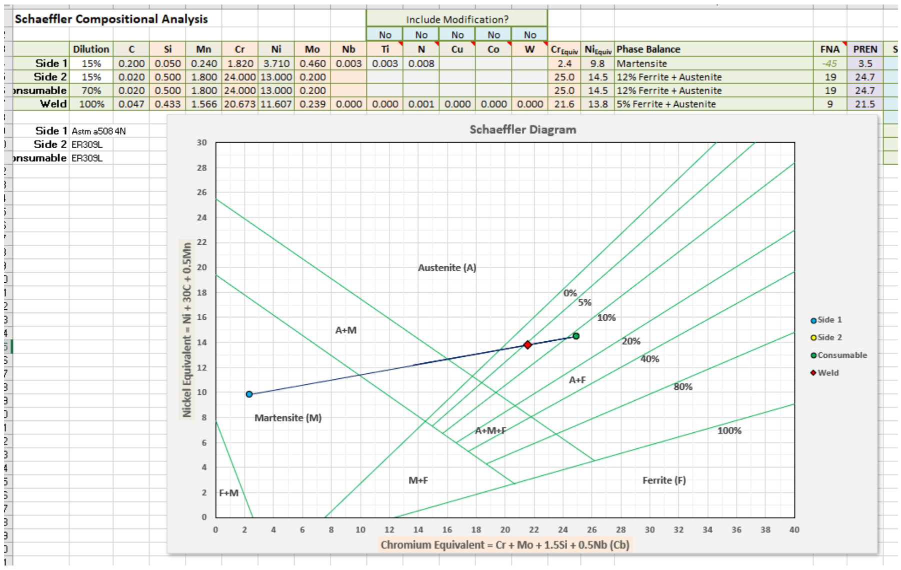


Figure 12 This diagram outlines some of the known welding problems that need to be avoided 1. Hydrogen induced cold cracking associated with martensitic grades, 2. Hot cracking associated with austenitic stainless, 3. Formation of sigma phase and low toughness and corrosion resistance associated with high chromium levels and duplex stainless. 4. Grain coarsening causing embrittlement associated with ferritic grade.

Using Schaeffler diagram to predict the weld microstructure

The Schaeffler diagram is an important tool for predicting the microstructure of stainless-steel weld deposits and the various phases (structures) present in the weld. The position in the Schaeffler diagram defined by the Cr- and Ni-equivalents gives the proportions of martensite, austenite, and ferrite in the resulting microstructure. The diagram is applicable to austenitic stainless steels having carbon contents up to 0.12% and cooling rates equivalent to welds.

There are several excel spread sheets available to allow a prediction of the microstructure based on the composition and the dilution that occurs during welding



Schaeffler Compositional Analysis

									Include Modification?									
									No	No	No	No	No					
	Dilution	C	Si	Mn	Cr	Ni	Mo	Nb	Ti	N	Cu	Co	W	Cr_{Equiv}	Ni_{Equiv}	Phase Balance	FNA	PREN
Side 1	15%	0.200	0.050	0.240	1.820	3.710	0.460	0.003	0.003	0.008				2.4	9.8	Martensite	-45	3.5
Side 2	15%	0.020	0.500	1.800	24.000	13.000	0.200							25.0	14.5	12% Ferrite + Austenite	19	24.7
onsumable	70%	0.020	0.500	1.800	24.000	13.000	0.200							25.0	14.5	12% Ferrite + Austenite	19	24.7
Weld	100%	0.047	0.433	1.566	20.673	11.607	0.239	0.000	0.000	0.001	0.000	0.000	0.000	21.6	13.8	5% Ferrite + Austenite	9	21.5

Side 1	Astm a508 4N
Side 2	ER309L
onsumable	ER309L

Figure 13 Excel spreadsheet used to predict the weld microstructure based on chemical composition and dilution

A brief introduction to the theory and practice of transformation hardening steel

To provide a simple understanding of the hardening of steel the following factors are important because this is the cause of hardening in the high hardness region of the heat affected zone (HAZ) during welding

- Steel exists as BCC (body centred cubic) atomic structure at room temperature. The BCC can only accommodate a very small amount of carbon
- At about 910ºC the atomic structure of pure iron changes to FCC (face centred cubic) which can accommodate up to 2% carbon
- The change from BCC to FCC is known as the allotropic change
- This change in atomic structure forms the basis of "transformation hardening"
- For example, the steel is heated to form the FCC atomic structure known as austenite. The carbon is taken into solution in austenite
- If the structure is cooled rapidly the carbon is trapped and the transformation occurs by a shear mechanism (no diffusion) and forms martensite which is hard
- The hardness of the martensite depends mainly on the carbon content. The graph used the most by worldwide organizations for predicting the martensite content based on the carbon content and hardness is shown in Figure 14.
- If cooling occurs at a slower rate some carbon diffusion occurs to form a separate compound of iron carbide (Fe_3C) and the transformation creates bainite and at even slower cooling rate produces ferrite/pearlite.

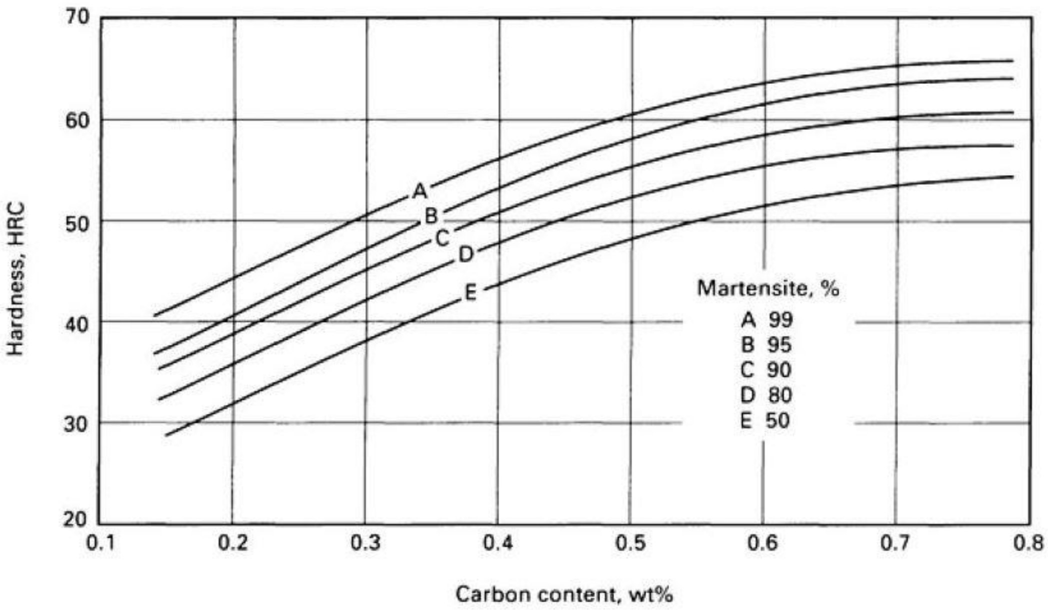


Figure 14 The hardness of quenched steel based on carbon and percentage martensite

The concept of "weldability"

The American Welding Society (AWS) defines "weldability" as "the capacity of a metal to be welded under the fabrication conditions imposed into a specific, suitably designed structure and to perform satisfactorily in the intended services". Although this definition may not be universally acceptable it is worthy of note, because it refers to factors other than merely "the capacity of a metal to be welded". The terms "fabrication conditions imposed", "suitably designed structure", and “to perform satisfactorily in the intended service" are all relevant.

Obviously, for instance, it is not economical to apply preheat to every joint in the welding of a ship or bridge. It is therefore important for the steelmaker to be aware that simply “improving the capacity of a metal to be welded" will not solve all fabrication problems and that due regard should be given to other factors which may well be of greater importance (strength, toughness corrosion resistance). From a practical point of view a weldable material is one where the costs and difficulties involved in welding it is acceptable from an economic and delivery standpoint. Choosing materials of construction, therefore, becomes a matter of judgement between basic material costs, alternative welding processes available, and the quality requirements and strategic nature of the final fabrication. The industry prefers a holistic approach where all aspects are considered. For steels Graville developed a simple graphical approach which give a clear summary of the weldability of steel; this graph is shown in Figure 15

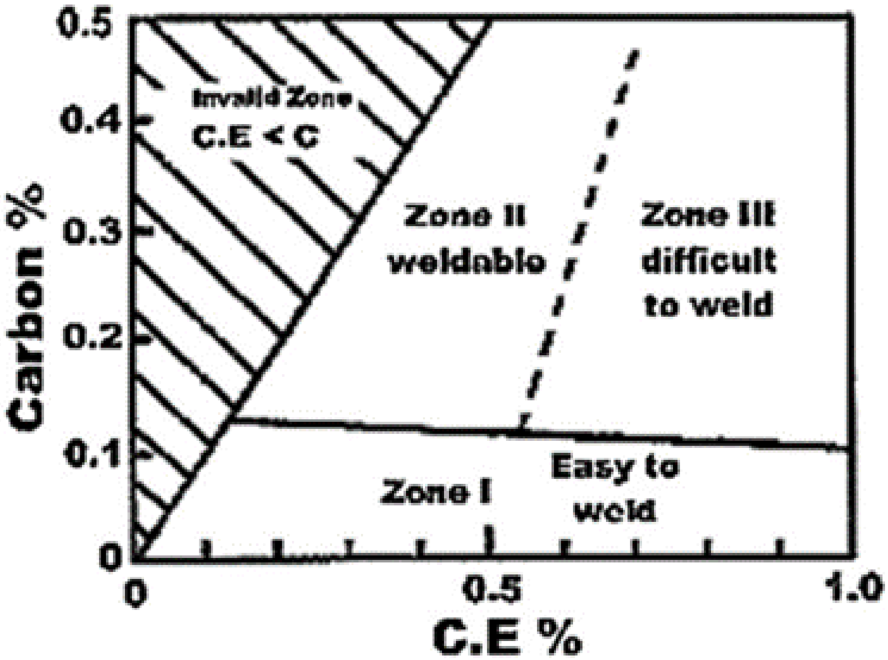


Figure 15 Graville diagram showing weldability of steels with various carbon and alloy content

Zone I steels have high hardenability, but carbon content is so low that even the hardest microstructure is not susceptible to cracking.

Zone II are shallow hardening but can develop sensitive microstructures because of their increased carbon content. Preheating the higher carbon/high CEV level is an effective means of reducing the cracking tendency.

Steels in Zone III combine high hardenability with high carbon content, compounding the problem considerably. In this instance extremely careful procedures, which include control of hydrogen, controlled cooling and post-weld heat treatment, may be required. This work further endorsed the use of the Pcm* (index of crack susceptibility), initially developed by Ito-Bessyo, for steels in Zone I and Zone III.

The understanding of the effect of the carbon level and steel alloy content on weldability led to the development of low carbon equivalent steels which could be successfully welded under the most adverse conditions without the need for pre-heat.

Table 1 Carbon equivalent formulas and their applicability

Carbon equivalent formula	Application range according to Talas et al. [11]	Application range according to Yurioka et al. [3]	Reference
Group A			
$CE_{IIW} = C + \frac{Mn}{6} + \frac{Ni+Cu}{15} + \frac{Mo+V}{5}$	C-Mn steels with high CE content	$C \leq 0.08$ %	13
$CE_{WES} = C + \frac{Si}{24} + \frac{Mn}{6} + \frac{Ni}{40} + \frac{Cr}{5} + \frac{Mo}{4} + \frac{V}{14}$			14
Group B			
$CE_{DNV} = C + \frac{Si}{24} + \frac{Mn}{10} + \frac{Ni+Cu}{40} + \frac{Cr}{5} + \frac{Mo}{4} + \frac{V}{10}$	Steels with lower CE contents	0.08 % $\leq C \leq 0.12$ %	15
$CE_{T} = C + \frac{Mn}{10} + \frac{Cu}{20} + \frac{Ni}{40} + \frac{Cr}{20} + \frac{Mo}{10}$			16
Group C			
$Pcm = C + \frac{Si}{30} + \frac{Mn}{20} + \frac{Cu}{20} + \frac{Ni}{60} + \frac{Cr}{20} + \frac{Mo}{15} + \frac{V}{10} + 5B$	Pipeline steels	C ≤ 0.12 %	17
$CE_{PLS} = C + \frac{Si}{25} + \frac{Mn}{16} + \frac{Cu}{16} + \frac{Ni}{60} + \frac{Cr}{20} + \frac{Mo}{40} + \frac{V}{15}$			18
$CE_{HSLA} = C + \frac{Mn}{16} - \frac{Ni}{50} + \frac{Cr}{23} + \frac{Mo}{7} + \frac{Nb}{5} + \frac{V}{9}$			19
Group D			
$CE_{N} = C + f(C) * \left(\frac{Si}{20} + \frac{Mn}{6} + \frac{Cu}{15} + \frac{Ni}{20} + \frac{Cr+Mo+Nb+V}{5}\right)$ $f(C) = 0.75 + 0.25 \tanh[20(C - 0.12)]$	All steels	$C \leq 0.3$ %	20

Table 1 Carbon equivalent formula