Trans. JWRI, Vol. 25(1996), No.2

Computer Based Assessment of Weldability

by Horst Cerjak and Bruno Buchmayr

Department of Materials Science and Welding Technology
Technical University Graz
Graz, Austria

Abstract

The various aspects to assess the weldability of structural steels and the dominant influencing factors are considered. Several computer based approaches are compared regarding their capability for this task. It was found that for the requirements of engineering practice, semi-empirical relationships, which are based on well-balanced experimental data bases and expert systems, provide sufficient quantitative information for welding engineers. They are now more and more used in practice. In contrast to parametric approaches and expert systems, mathematical models for the determination of weldability are much more sophisticated. Based on modeling of the fundamental mechanisms involved and their influence on the weldment performance, an improved understanding of the interacting processes can be obtained which is quite valuable for materials experts in order to optimize materials and welding processes on the highest level available. They are mainly based on fundamental thermodynamical and kinetic concepts. Impressive progress has been gained in the last decade in this modern and explorative field of welding engineering and science [1, 2, 3]. Mathematical models are shown concerning the HAZ-behaviour of HSLA steels and fusion line metallurgy of dissimilar 1% Cr to 12% Cr weldments. Applications of modern software packages like Thermo Calc, DICTRA and Mathcad for the modeling of different aspects of weldability and the use of the FEM program SYSWELD for residual stresses calculations are discussed.

1. Introduction

It is a challenging task for welding engineers to ensure reliable weldments under economical conditions. The influencing factors and characteristic parameters which need to be considered for the assessment of the weldability of low alloyed steels are outlined in **Figure 1**. It requires a broad knowledge of the various metallurgical phenomena involved, which are affected by influencing parameters encountered during a complex fabrication process and during service. Thus, it is obvious that the interacting processes can only be understood qualitatively and lot of experiences and information are necessary to fulfill more stringent requirements. Most of the related information provided in handbooks, standards or internal specifications, which support the engineer with appropriate parameters. But not a single weldability test or a data set is able to cover all aspects or conditions. It needs to consider many related and/or independent phenomena to achieve a global assessment. In addition, test results have to be converted to real welding conditions, which may cause considerable deviations. To reduce the experimental effort and with the goal to predict the weldability of structural steels, several empirical equations have been derived based on the evaluation of large data sheets.

Transactions of JWRI is published by Joining and Welding Research Institute of Osaka University, Ibaraki, Osaka567, Japan.

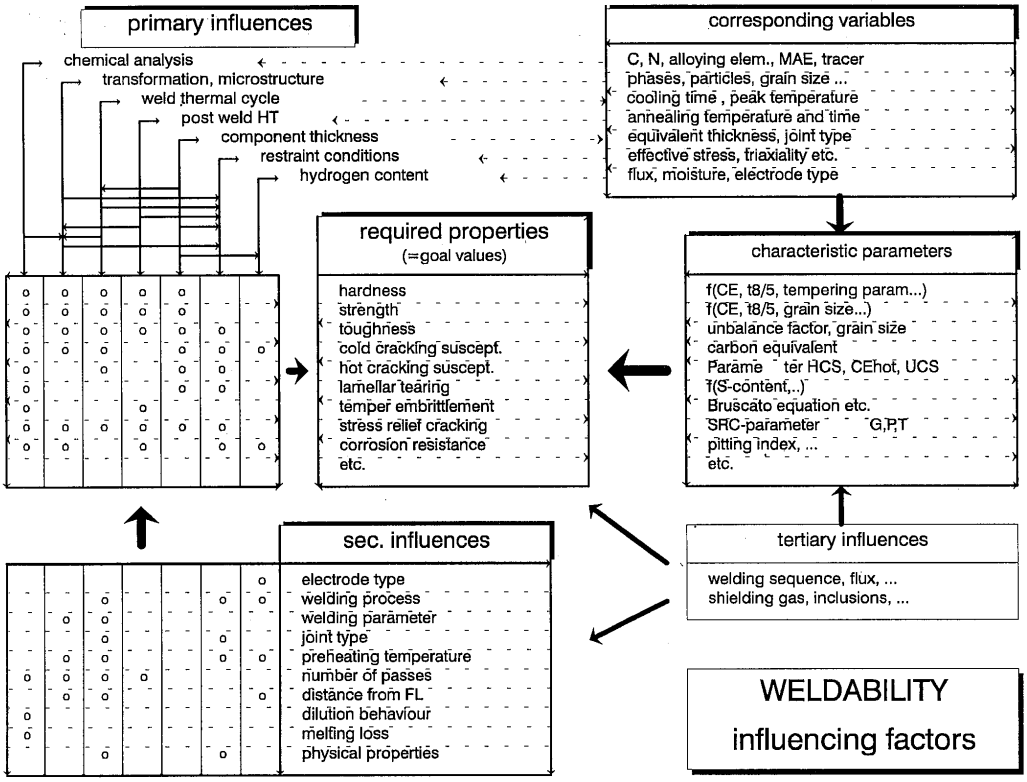


Figure 1 Influencing factors and characteristic parameters regarding the weldability of steels.

With the increased availability of personal computers and progress in their capabilities, more and improved approaches can now be used by welding engineers. Correctly applied, it may lead to an increased efficiency and access to welding related information, which may give an improved product quality including less scatter of the mechanical properties and in addition an increased productivity.

In this paper, the various aspects of the assessment of weldability using computer based methods will be discussed regarding their applicability and capability to solve welding-problems. The aspect of modeling of weldability will be discussed in more detail using examples of successful applications.

2. Assessment of Weldability

2.1 Methods of Assessment

Welding technology is complex and the quality of a weldment is a function of the interaction of a large number of variables and microstructural changes during the welding process. These interactions need to be controlled to ensure defect free welds and to meet the requirements of structural integrity. To assess the manifold facets, various considerations and tests are needed to be sure of any unpleasant surprise.

In principle, several methods are applicable to assess the weldability of structural steels, viz.

- investigation of real, full scale weldments
- welding simulation, e.g. using a Globule machine
- welding CCT diagrams
- hardness measurements across the HAZ
- special weldability tests, like Implant, Tekken or CTS test etc.
- computer based methods.

A comprehensive assessment needs a sound knowledge and various approaches to support the engineer with relevant information and significant parameters, which form the

basis for his decisions. In recent years, these tasks (data collection, data evaluation and prediction) are mainly performed by numerical programs.

2.2 Computer based methods

In addition to the aforementioned mechanical testing methods, empirical correlations are used to describe weldability, e.g. , the well-known IIW carbon equivalent.

There are numerous equations or sensitivity parameters in use which represent a first order approximation of a particular property and its main influencing factors. Essentially, the user has to be aware that the empirical models are only applicable in a defined range or for a particular steel type, otherwise inaccurate results can be obtained and misleading interpretation of results can be made.

Looking for suitable computer methods to assess the weldability of metallic materials, there are several alternatives, like

- data bases with results of special weldability tests
- empirical or parametric equations
- knowledge based systems (expert systems) and
- modeling based on fundamental physical metallurgy.

In the following the computer based methods will be considered in more detail.

2.2.1 Data bases (DB)

Using the DB-approach, results of cold cracking, hot cracking and other tests have to be stored with all relevant influencing parameters. Although it is easy to create a data base one needs further evaluations (e.g. multiple regression analysis or other statistical procedures) to provide an improved understanding of the influencing parameters and to make predictions feasible. Although DBs are easy to handle , there are several problems involved, like

- insufficient support for the problem analysis itself
- problems to combine relevant material data for assessment purposes
- some properties are difficult to quantify e.g. weldability aspects
- DBs do not really support the decision making process
- no further information or assessment can be obtained
- completeness and user friendly access are sometimes weak points.

Out of these reasons, data bank systems have to be coupled with other approaches, like knowledge based systems, evaluation routines, etc. In that case, we speak about integrated software structures.

2.2.2 Empirical relationships

Most of the assessment procedures are however based on parametric equations, which take into account most important parameters in an analytical form, which should be based on physical principles. Using those systems, the influence of chemical composition and welding parameters on weldability of steels can be predicted quite satisfactorily in many cases.

Although the approaches used are simplified tools to describe the complex processes during welding, they provide quite helpful information about the effect of the influencing parameters, provided that they are used reasonable and within the valid ranges. On the applicability and accuracy of the parametric equations has been reported in detail elsewhere, see the reference[4]. A main advantage of parametric equations is however, that they can be used for online process control, because in contrast to more sophisticated methods the calculation time is negligible short.

One successful example to assist welding engineers regarding weldability problems, is the comprehensive computer program "HAZ-CALCULATOR" which has been developed by our group[5]. It provides about 50 metallurgical based algorithms. They can be applied to unalloyed, normalised and microalloyed structural

steels, quenched and tempered steels, low alloy steels, heat resistant and austenitic stainless steels. With respect to the ferritic steels, aspects of transformation behaviour, hardenability, strength, toughness, embrittlement, cracking susceptibility etc. can be dealt with. With respect to austenitic stainless steels, microstructure, hot cracking tendency, dilution, sensitisation, pitting corrosion and mechanical properties can be considered. The interactive program also provides additional information on relevant problem areas, on the applicability ranges of the implemented algorithms and provides some useful auxiliary facilities. The software was designed to enable the user to make the correct decision regarding weldability aspects. Several case studies show the versatile applicability of this software. Finally, other available welding software is briefly reviewed, which may be helpful for welding engineers.

2.2.3 Expert systems

Another computer based possibility to assess the weldability is to use knowledge based or expert systems. Those systems use rules and other forms of knowledge representation to find logical correct measures.

Expert systems may also be powerful to assess various aspects of welding technology. The reason for that is, that in the past, many decisions and assessments were purely made based on experiences. Even in welding standards and handbooks, there are still a lot of recommendations and decision tables, which can be directly transferred into knowledge based systems. Primarily, the diagnostic capabilities of XPS is used in manifold ways.

In the field of welding technology, expert system applications are mainly concerned with the following objectives (see also the reference [6-12]):

- Selection of suitable welding processes
- assessment and avoidance of welding defects
- selection of suitable consumables
- design optimisation of welded components
- diagnosis of failures of welding machines,

etc.

A recent example of an expert system for the selection of suitable consumables is the software package „WELCOME“[12] which enables an easy and powerful access to optimal welding consumables based on user-definable specifications. In addition, estimation of welding costs, further welding related information is included.

In [13] an overview of commercial expert systems and prototype versions for welding engineering has been given.

2.2.4 Mathematical Models

In contrast to parametric approaches, mathematical models for the determination of weldability are much more sophisticated and are therefore mainly used for research and development of base materials and consumables. Only a few physically based models are commercial available. Based on modeling of the fundamental mechanisms involved and their influence on the weldment performance, an improved understanding of the interacting processes can be obtained, which is quite valuable for materials and welding experts in order to optimize materials and welding procedures on the highest level available. They are based on fundamental physical equations (partial differential equation for heat flow or diffusion) either by use of finite differences or finite element methods. The methods applied are based on thermodynamical and kinetic concepts. Despite the fact, that the effort for modeling is rather high, the model has still to be validated using experimental investigations. In spite of this restriction, great efforts are under way worldwide to develop applicable software for the modeling of welding phenomena. Many of these new developments are presented at the II W-International Seminar "Numerical Analysis of Weldability" which is organized biannually by the authors in Graz-Seggau, Austria. The impressive results of these seminars are published in the book ,,Mathematical Modeling of Weld Phenomena" [1, 2, 3]. A short review of these activities is given in the reference[14]. In the following some numerical models, developed at TU-Graz, are reviewed, which deal

Table 1 Chemical composition of tested materials.

	C	Si	Mn	P	S	Al	Cr	Mo	Ni	Cu	V	Ti	Nb	N_{ges}	Ti/N
X70/20	0.105	0.36	1.68	0.012	0.002	0.024	0.055	0.016	0.044	0.072	0.066	0.005	0.045	0.009	0.56
X80/21	0.072	0.29	1.84	0.012	0.005	0.036	0.032	0.011	0.023	0.027	0.005	0.018	0.047	0.0049	3.7

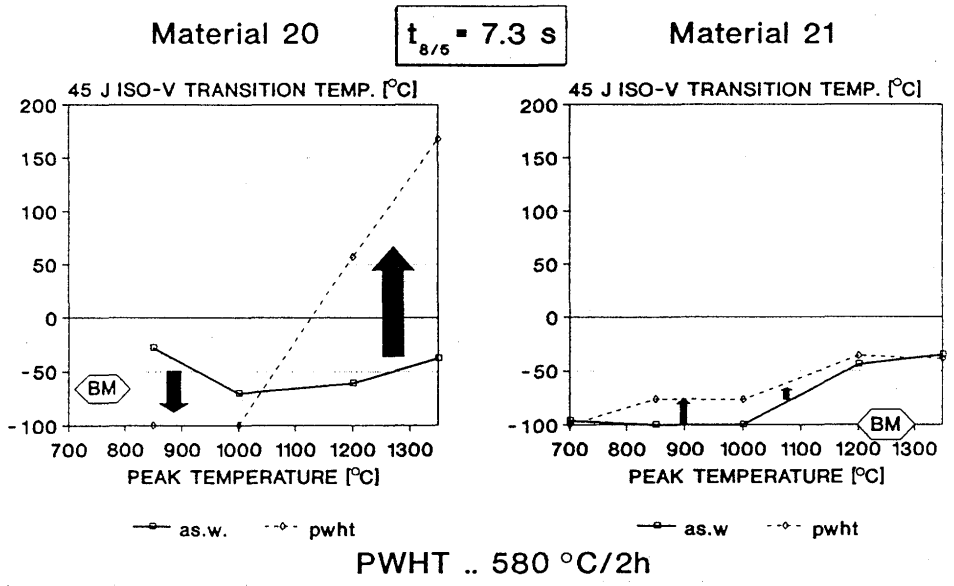


Figure 2 Influence of PWHT on toughness. HAZ Simulation using $t_{8/5}$=7.3s

with various aspects of weldability. In addition, some tools available now for performing weldability modeling tasks are mentioned. Further details are given in the reference[4, 15, 16].

3. Models and tools for weldability assessment

3.1 Modeling of the PWHT embrittlement in the HAZ of HSLA steels[17 18]

Due to their chemical design, TMCP-steels are prone to have significant toughness variations in the HAZ subregions when they are exposed to post weld heat treatment procedures (PWHT) after welding. The HAZ toughness behavior of two similar steels: Type X70 (referred as material 20) and X8O (referred as material 21) with different amounts of V, Nb, Ti and N, are discussed below. The chemical compositions are given in table 1.

For both steels, the 45 J ISO V-transition temperature in the HAZ as a function of the peak temperature of Globule simulated samples (cooling time $t_{8/5}$ = 7,3 sec.) in the as welded (as. w.) and in the PWHT (58O℃/2h) condition is shown in Fig. 2. For comparison the transition temperature of the base material (B.M.) is also plotted. The effect. of PWHT on the toughness of both materials is significantly different, e.g. material 20 shows a significant loss of toughness when peak temperatures higher than 1000℃ are applied. At high peak temperatures of about 1350℃, the PWHT causes a 45 J TT shift from -60℃ to +160℃, whereas material 21 shows only a small effect.

Theoretical investigations based on the ternary solubility product, developed by Easterling and Strid[19], were performed. This model uses the assumption of regular solutions, Henry's law, infinite diffusion rates of interstitials and uniform precipitation distribution. The precipitate phase is treated as a mutual solution of one compound in the other and of the type $(A_yB_{1-y})C_n$. A and B are substitutionally dissolved elements and C is an interstitial. For the present application the stability of MX precipitates was investigated.

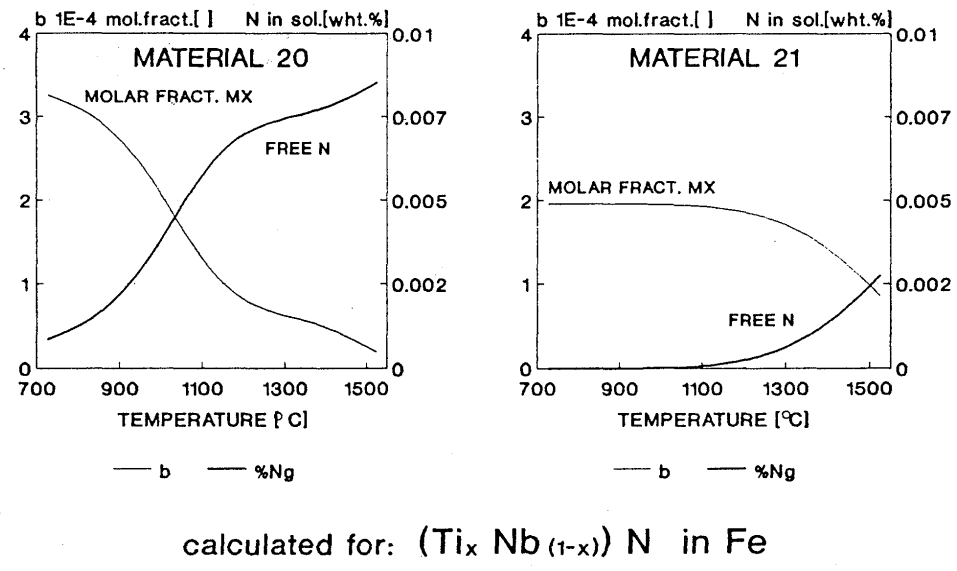


Figure 3 Evolution of free nitrogen as a consequence of the solution of MX precipitates.

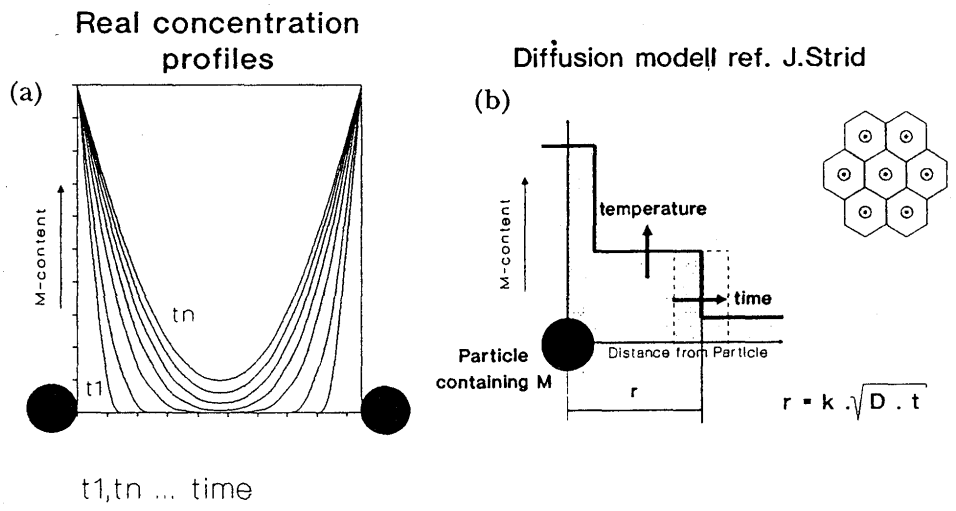


Figure 4 Solution of MX–particles during weld–thermal cycles, derived by the Strid–Easterling model [19].

Therefore m and n had to be 1.

The calculated mole fraction of MX particles and the concentration of free nitrogen in the matrix, which is a result of the solution of $(Ti_xNb_{1-x})N$, is plotted as function of the peak- temperature in **Fig. 3**. At a peak temperature of 1350°C (left diagram in Fig. 3) about 80 % of the total nitrogen content of material 20 is solved in the γ-matrix under equilibrium conditions. In material 21 only about 10 % of the total N content are in solution because of the more stable Ti-rich particles. These calculated theoretical results were fully confirmed by TEM investigations. The content of free nitrogen as a function of peak temperature shows the same tendency as the PWHT embrittlement, however at lower temperatures, because of the equilibrium assumptions (compare Figs. 2 and 3).

The non equilibrium situation during the weld thermal cycle was described by the kinetic model by Strid and Easterling[19]. Any change of the solubility level is combined with a diffusion-controlled homogenisation process.

Figure 4 (a) shows the time-dependent concentration profiles between two particles in the matrix. For the precipitation kinetics a simplified diffusion model was used, which

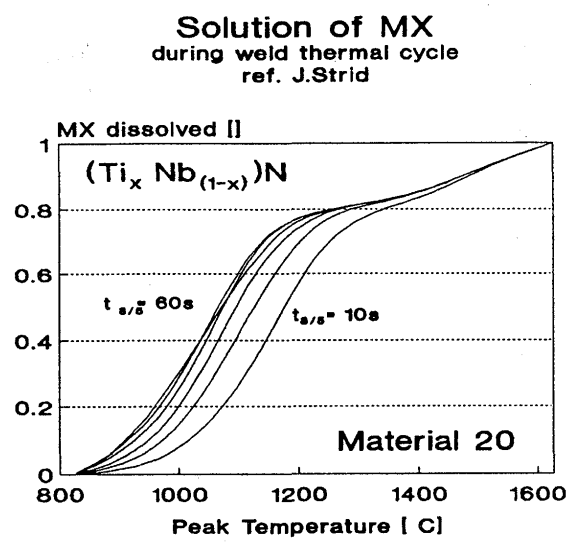


Figure 5 Solution of MX–particles during weld–thermal–cycles. Derived by the Strid–Easterling model [19].

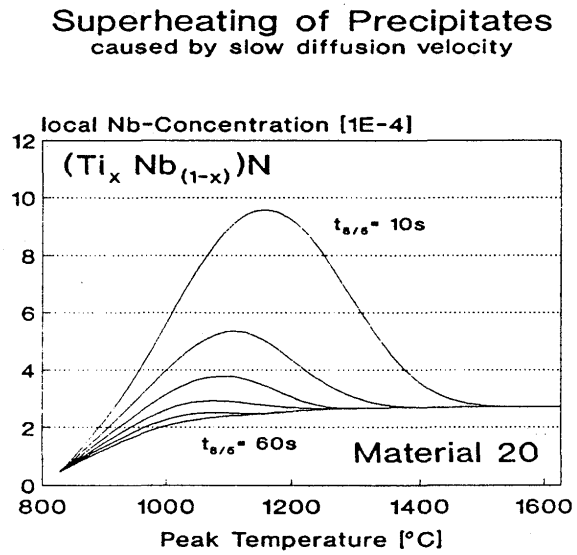


Figure 6 Nb–concentrations.

assumes a zone with radius r that has a homogeneous concentration of the soluted elements. The concentration level is calculated by the ternary solubility product. The dimension of r is a "diffusion length", which is calculated by integration over the weld thermal cycle. If all particles are of the same size and the distance between neighbouring particles is constant, the model is able to represent a global structure, because in this case the structure can be devided into congruent sphere cells with the particles in the centre. If r becomes the cell radius, the kinetic model is consistent with the equilibrium ones.

Applied to material 20, the kinetic models provides results as shown in **Fig. 5**. The number of soluted MX particles is calculated as a function of the peak temperature of the weld thermal cycles for different heat inputs indicated by the cooling time t8/5. Because of the time-dependent diffusion we can see a shift of the solution lines to higher temperatures at low heat inputs. This superheating effect can be seen very clearly in **Fig. 6**, wherein the local Nb-concentration within the diffusion zone (marked by r in Fig. 4) is plotted as a function of the peak temperatures of the weld thermal cycles for different heat inputs. In situations with low heat input, the diffusion process is too slow to allow any chemical compensation. This is why the concentration of Nb around the (Ti, Nb)N particles is much higher than the equilibrium model would predict. Based on the thermodynamical calculations, a correlation between the effect of PWHT on toughness and the amount of free nitrogen was assumed. Thus, it was only possible to relate the tendencies of toughness behaviour and free nitrogen, not the absolute temperature values. If the amount of free nitrogen is evaluated by the kinetic model, both, tendency of embrittlement and absolute temperature levels show a very good correlation, as shown in **Fig. 7**

As a consequence of this model, it can be stated from the precipition kinetics during PWHT that it is necessary to restrict the content of free nitrogen in order to avoid HAZ embrittlement.

A direct transfer of this conclusion to other cases may be not useful because other metallurgical mechanisms like tempering of martensite or solid solution strengthening have to be taken into account.

3.2. Modeling of the microstructural changes in the fusion line area of dissimilar welds between 1 % Cr to 12 % Cr steels during PWHT[20]

In many technical applications, i.e. in steam power generating plants and petrochemical processing plants, weldments between

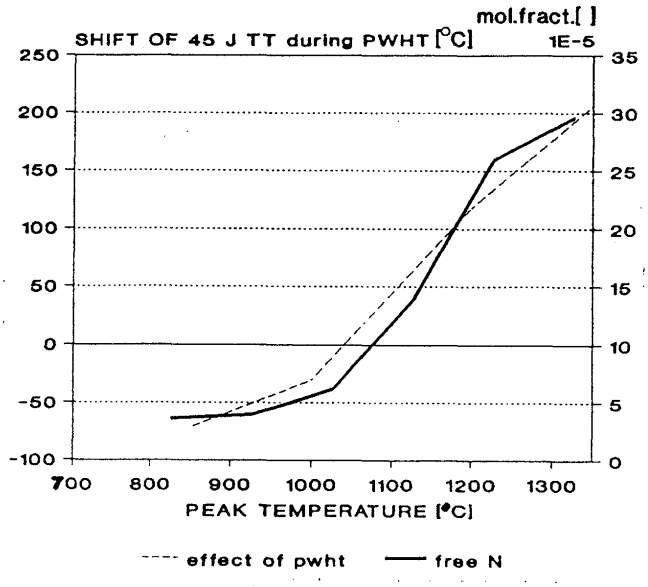


Figure 7 Shift of 45JTT caused by PWHT (580℃/2h) compared to the amount of free nitrogen evaluated from the kinetic Strid-Easterling model [19].

different kinds of heat resistant steels are commonly used. It is known that due to the chemical difference (especially of the Cr-content), microstructural changes occur during post-weld heat treatment and service, in the fusion line region of the dissimilar, weld viz a carbon depletion in the low alloy steel HAZ and the formation of a carbide seam in the higher alloyed filler metal. These changes determine the mechanical properties and the fracture appearance and have governing influences on the life time of those weldments.

A model which describes the microstructural changes in the fusion line area of a 1% CrMoV to a 12% CrMoV steel weldment was proposed by Buchmayr and Kirkaldy[21]. It is based on the fundamental work by Kirkaldy' s for simultaneous precipitation and diffusion[22, 23].

A ternary diffusion model was proposed in the reference[21] to allow simultaneous ternary diffusion and precipitation on one side and carbon migration and carbide precipitation and Ostwald ripening on the other side.

Relations of the volume fraction of precipitates, equal molar volume of precipitate and matrix and ternary diffusion interactions were taken into account during the formulation of the set of equations and relations. A numerical procedure was developed to predict the carbon profile and the amount of precipitates on both sides of the fusion line, when a PWHT temperature of 700℃ is applied and a carbide equilibrium is reached which determines the $M_{23}C_6$ carbide content on the higher Cr side and the amount of M_3C type carbide on the low Cr side. To solve the modified Ficks-equation, an explicit finite difference method was used.

The calculation procedure comprises the following steps:

- setting of initial conditions
- determination of Cr and C in solution
- calculation of effective diffusion coefficient and check of stability criteria with respect to each time increment
- solving the modified second Fick law for both sides
- using the solubility product to determine the chromium content in solution
- calculation of dissolution rate on the left hand side
- determination of total C and total Cr content
- calculation of amount of precipitates
- taking into account the boundary conditions
- setting the input values for the next time step equal to the previous results.

As a result, **Figure 8** shows the total amount of carbon and **Fig. 9** the corresponding amount of precipitates at the fusion line as the function of annealing time at 700℃.

At the beginning the carbon migration is driven by the difference in thermodynamic activity caused by the difference in chromium content. On the left hand side, carbon depletion takes place combined with the dissolution of M_3C particles. The dissolution rate is given by the difference between the equilibrium con-. of α/M_3C phase boundary and the level of carbon in solution in the matrix. On the high chromium side, the carbon peak increases up to a saturation level.

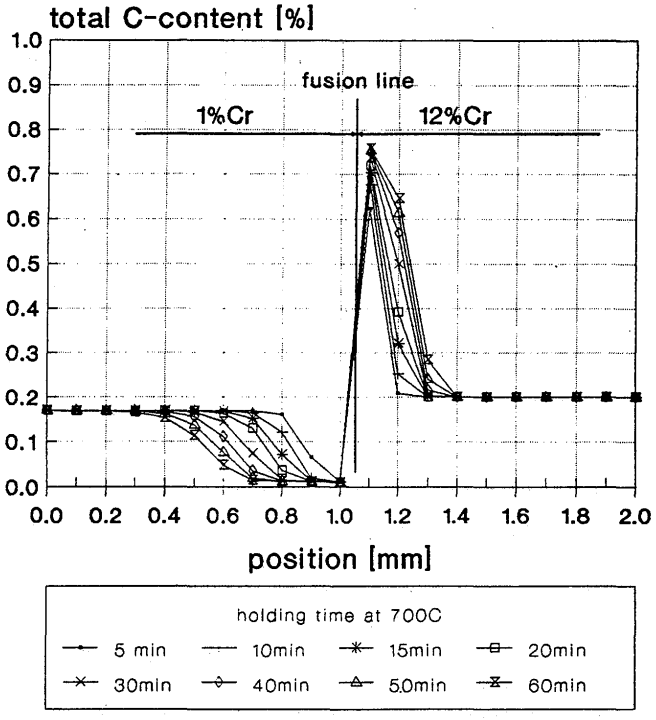


Figure 8 Profile of total carbon concentration.

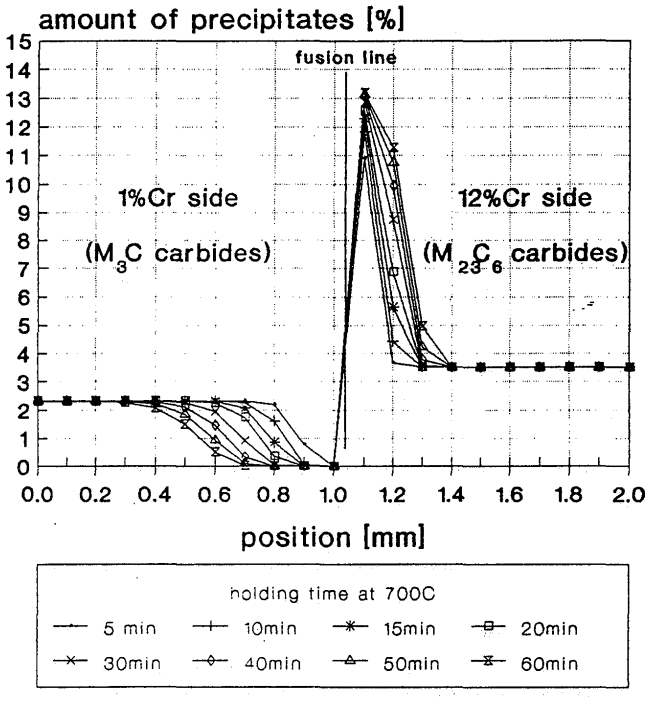


Figure 9 Calculated amount of precipitates for the1%Cr /12%Cr couple.

In the particular case, the C peak reaches a level of about 0.75 % after one hour annealing. The time dependence of the development of the carbon peak is shown in **Figure 10**, which can be described by a typical $\sqrt{Dt}$ expression.

As soon as the activity difference directly at the fusion line becomes almost zero, the carbon enrichment progresses into the high chromium region, whereby the migration speed is reduced by the decreasing driving force related to the decreasing ternary diffusion effect. Therefore the C-profile becomes more trapezoidal than triangular, so that after long annealing times an almost equally dense carbide seam is formed. The inability of chromium to diffuse is responsible for this phenomena occurring, otherwise a common error function profile may be expected. The distribution of chromium in solution is given simply by considering the solubility product. The distribution of C and Cr in solution determines directly the amount of precipitates, as shown in Fig. 9.

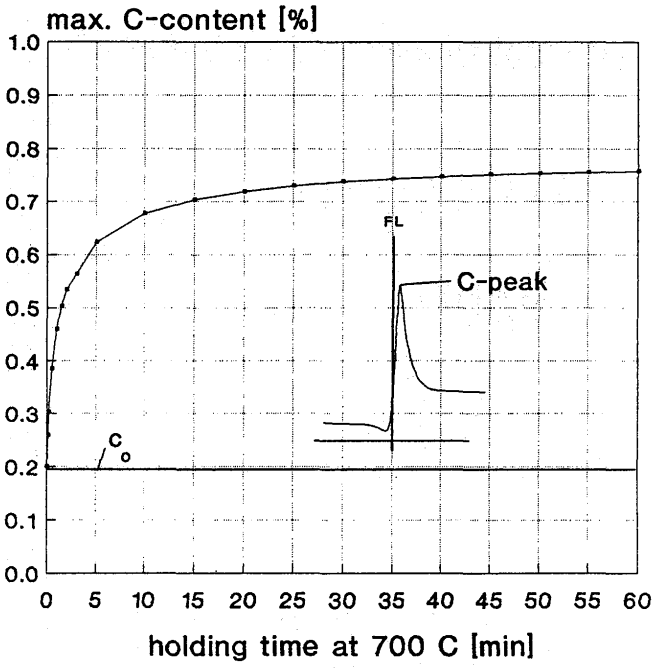


Figure 10 Development of maximum C-peak at the fusion line in the 12%Cr filler metal (calculated)

By comparing these numerical calculations with measured C-profiles and investigation of the carbide morphology a good agreement for the shape of the carbon profile as well as for the maximum carbon content in the carbide seam could be found. The thickness of the calculated carbide precipitation seam in the

Cr-rich part and the thickness of the C-depleted zone in the low Cr-material corresponds closely to the measured one[24]. This model was in addition successfully applied for the design of a "graded joint" produced by HIP-process to solve the problem of dissimilar welding25)"

Recently this approach proposed by Buchmayr and Kirkaldy[21] was recognized by, Engström Höglund and Ågren[26]. Using the computer program DICTRA[27] developed by this group, a general model for the treatment of diffusion in multiphase dispersions is used. The model is based on multicomponent diffusion data and basic thermodynamic data. These new model is implemented into the DICTRA code, which is linked to THERMO-CALC regarding the calculation of the chemical forces and local equilibria. The example is described in chapter 3.3.2.

3.3 Thermodynamical Equilibrium and Diffusion Calculations using Thermo Calc and DICTRA

3.3.1 *Thermodynamical Equilibrium Calculations using the Computer Program Thermo Calc*

The equilibrium in multicomponent and multiphase systems can be calculated by minimising the Gibbs free energy of the system. This task can be performed using a commercial available program package (e. g. Thermo Calc, developed at KTH Stockholm[28]). It uses thermodynamical databases, preferably the SGTE (Scientific Group Thermodata Europe[29]), which contain experimental data from sub-systems. The CALPHAD approach[30] enables the extrapolation for multicomponent systems. At low temperatures the equilibrium state will be reached only after long times. Due to the high heating and cooling rates during welding, any equilibrium consideration for the modeling of weldability seems not to be meaningful. However, it was demonstrated that in some cases this tool can be very helpful for the assessment of microstructural changes, which occur during welding[31]. Examples, where equilibrium calculation may be useful, are (described in detail in the refrence[31])

- Recalculation of parts of the Schaeffler-diagram and determination of Cr- and Ni-equivalents for different steel types
- Calculation of transformation temperatures A_{e1} and A_{e3}
- Solution temperatures of precipitates (important for the post weld heat treatment)
- Influence of various alloying elements on the precipitation behaviour
- Optimisation of the alloy composition for a good weldability
- Simulation of solidification sequence using Scheil's approach.

Figure 11 shows the influence of the chromium content on the phase diagram of the new Japanese 10% Cr heat resistant steel NF616 (the chemical composition is given in **table 2**). The calculated solidus temperature of this alloy is 1426°C. Small changes in the composition, e.g. higher chromium and carbon content, can lead to a decrease of the solidus temperature, as illustrated in Figures 11 and **12**. It is known that the solution of carbides (in the mentioned alloy mainly $Cr_{23}C_6$, solution temperature about 900°C) can cause a local higher content of the elements Cr and C. Welding with a peak temperature of 1350°C in the HAZ leads to unexpected liquid phases in this area. After a Gleeble welding simulation with the mentioned peak temperature, phases with lower hardness could be found. The existence of these phases can be explained using the calculated phase diagrams (Figs. 11 and 12).

In spite of the fact, that the software package Thermo Calc was originally designed for the description of the equilibrium conditions of different phases in complex alloys, it also helps to understand weldability phenomena and to model the phases which can be expected after welding. Furthermore, it is a prerequisite for any consequent kinetic calculation, viz. by the calculation of the driving force.

3.3.2 Computer Aided Calculation of Diffusion using the Program Package DICTRA

An example for the applicability of this code is given in **Figs. 13** and **14**. A diffusion

Table 2 Chemical composition of NF616 steel.

	C	Si	Mn	Cr	Mo	W	V	Nb	Al	Ni
Nf616(YAT)	0.124	0.02	0.47	9.07	0.46	1.78	0.19	0.063	0.002	0.06

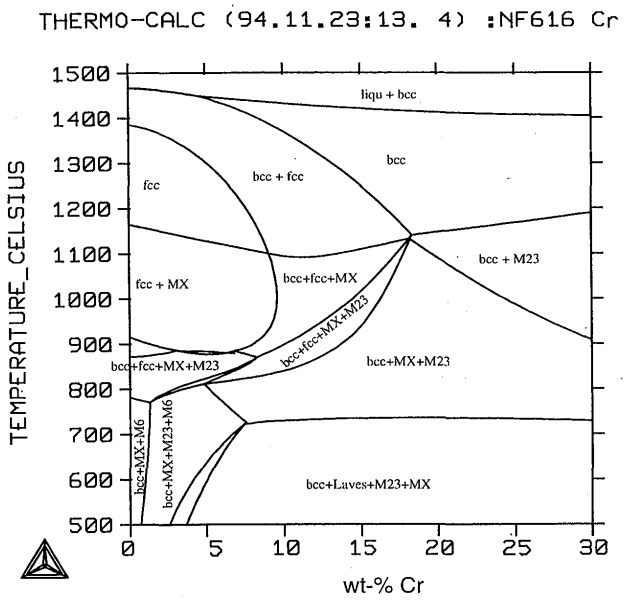


Figure 11 Influence of chromium content on the phase diagram of NF616 steel.

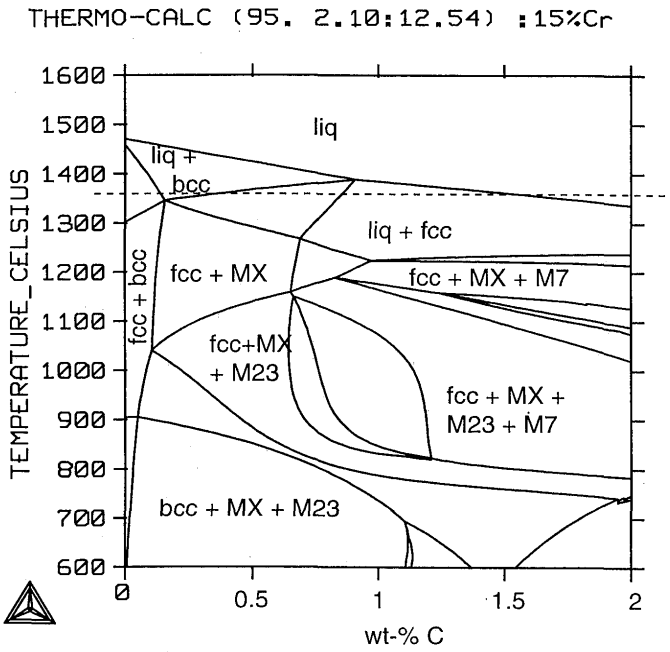
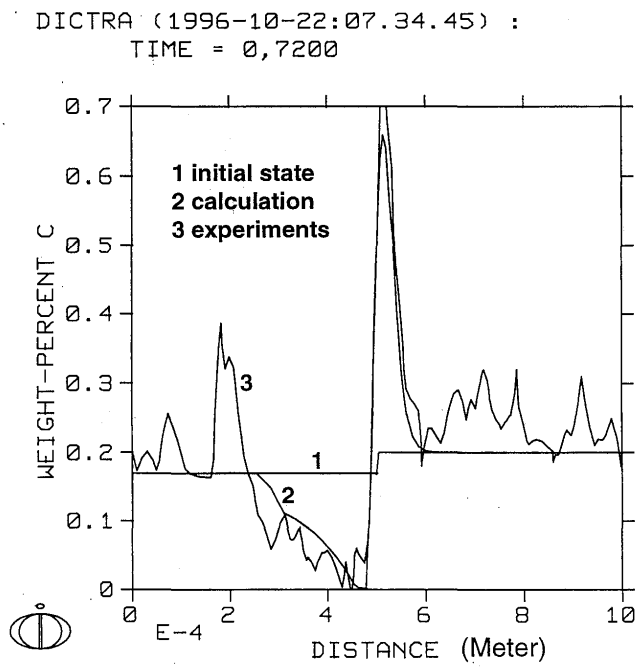


Figure 12 Phase diagram of NF616 steel with the assumption of a local increase of chromium content(15wt−%)



Figurer13 Calculated and experimental determined carbon profile in a dissimilar weld after annealing at 680℃ for 2hours.

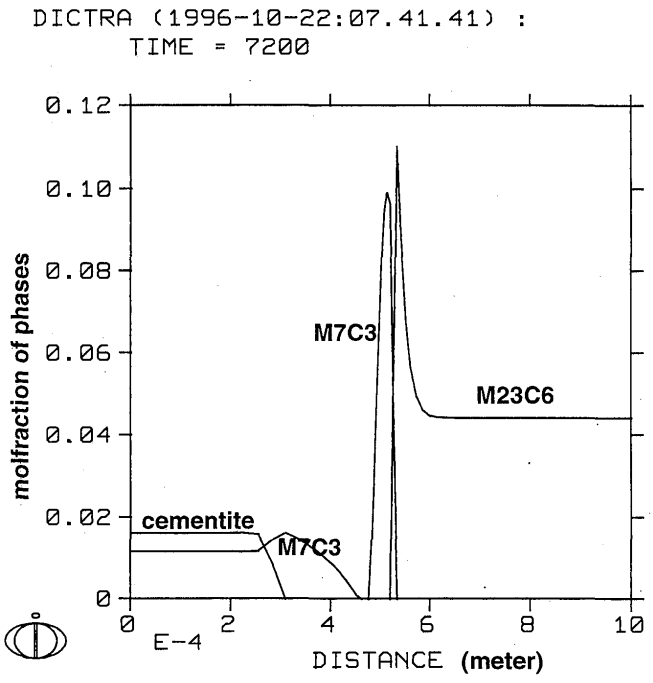


Figure14 Calculated precipitation profile in a dissimilar weld after annealing at 680℃ for 2 hours.

simulation was performed for a dissimilar weld between a 1%CrMoV and a 12%CrMoV steel, which is mentioned in chapter 3.2. Figure 13 shows the calculated carbon profiles in the initial state (1) and after annealing at 680℃ for 2 hours (2). Line (3) in this diagram shows the data obtained from experiments performed by Witwer[24], used by Buchmayr and Kirkaldy[21]. The calculated precipitation profile is given in Fig. 14.

These results show the applicability of this software and the good agreement to the original results presented above.

3.4 Modeling of the residual stress distribution in the weld region of an austenitic stainless steel tube using LPHSW[33]

Last pass heat sink welding (LPHSW) is a welding procedure to be applied on girth welds of tubes in order to transform tensile residual stresses in the inner surface region of the tube into compression residual stresses. The aim for the application of this procedure is to prevent the danger of a possible stress corrosion attack on the inner surface of the tube which can be caused by the combined action of liquid solution, a sensitised HAZ microstructure and residual stresses in tension. The commercially available software package Sysweld[32] was used to model the residual stresses in the cross section of a girth weld of an austenitic stainless steel tube, diameter 114 mm, wall thickness 5.3 mm before and after the application of an additional weld bead applied on the outer side of the weld, while the inner surface was cooled by cold water (LPHSW-procedure)"

For this problem the geometry was simplified using the symmetry of the tube[33]. For the reason that in reality the tubes which have to be connected are very long, only a short part was modeled and fixed with constraint conditions at both ends. The thermal boundary condition is the convection in air outside and water inside the tube, respectively. This FEM-code enables to prescribe temperature dependent boundary conditions.

All material properties can be considered as temperature dependent as well as a function of the actual microstructure. The case of

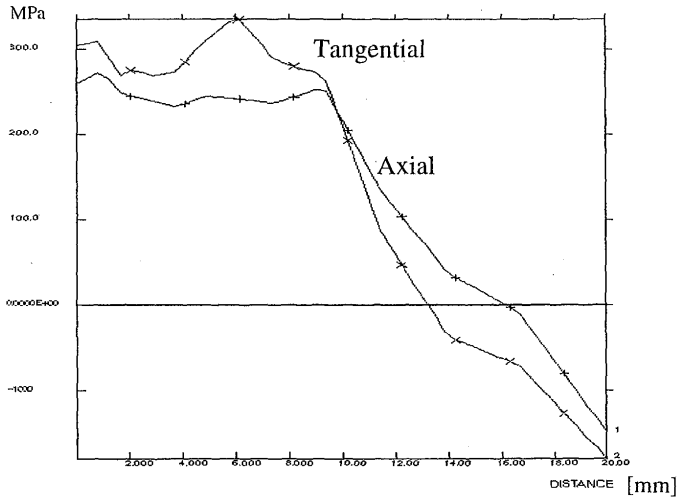


Figure 15 Axial (a) and Tangential (b) residual stress distribution in a weld region of an austenitic stainless steel pipe (114mm inner diameter, 5.3mm wall thickness) befoe LPHSW.

austenitic stainless is much simpler because there is no phase transformation. The stress-strain curve used for this calculation was temperature dependent as well.

At first, a 4-layer V-groove joint was assumed and the residual stresses before LPHSW were calculated. The axial and tangential stresses after 4-layer welding are shown in **Fig. 15**.

To simulate the oscillation of the heat source, it has to be taken into account that the transverse speed is much higher than the welding speed. Therefore a simplified heat-source was considered which had a width equal to the amplitude of the oscillation. The higher heat input on the outer border was neglected.

The temperature time curves obtained by calculating certain points of the mesh were used for the adjustment of the heat input, respectively the efficiency of the welding process (**Fig. 16**).

In **Fig. 17** the calculated distribution of residual stresses after application of a LPHSW-pass is shown. Comparing Fig. 15 and Fig. 17, it can be observed that the expected effect by redistribution of the residual stresses from tensile to compressive stresses in the welding zone took place. These numerical results on the residual stress distribution before and after application of the LPHSW pass, could

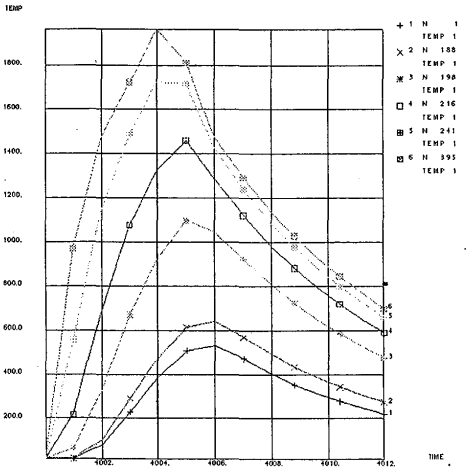


Figure 16 Temperature–time function calculated for some nodes in the cross section of the weld during welding of the LPHSW–pass.

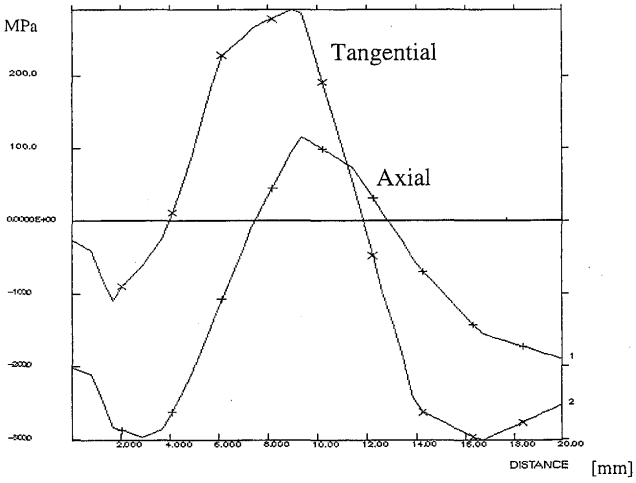


Figure 17 Axial and tangential residual stress after LPHSW.

be verified quite accurately by experimental investigations of weldments, using X-ray and hole drilling residual stress measurement.

After model verification, the effect of the welding parameters on the distribution of residual stresses can be studied and the procedure can be optimized according to the needs of the user.

Comparing to plain welding tests, the application of modeling provides great advantages in the optimisation of welding processes and in the prediction of the service behavior of those weldments.

3.5 Computer Algebra as a Tool for the Mathematical Modelling[34)]

Metallurgical phenomena, which affect the mechanical behaviour of weldments can be described by fundamental thermo-physical-chemical equations. Various aspects of weldability can be considered and process parameters can be optimised. UP to now rather conventional programming languages (like Basic, Fortran, Pascal or C) and appropriate numerical algorithms are used for model building. Recently, new mathematical software packages are available, which allow a unique way of problem solving. By this support, the major task concentrates on the basic engineering activities, i.e. the formulation of the mathematical equations, while the programming effort and the development phase for simulation models is drastically reduced. Using the software package MathCAD, some case studies will demonstrate the advanced capabilities "

A more detailed description of these and other case studies can be found in the reference[34)]. These tools allow a fast and elegant solution of practical welding problems. However more complex cases still need sophisticated finite element or finite difference calculations, like for the prediction of residual stresses.

3.5.1 The Weld Thermal Cycle

The microstructural changes in the heat affected zone are triggered by the weld thermal cycle, which depends primarily on the heat input, the plate thickness and the preheating temperature. Using the German standard SEW-088, originally proposed by Uwer and Degenkolbe[35)], the temperature time cycle for different positions in the HAZ can be predicted.; **Figure 18** shows the result in form of a MathCad screen for a butt weld using a heat input of 20kJ/cm ($t_{8/5}$=7,7s), plate thickness of 30mm, SMAW welding and no preheating.

3.5.2 Particle dissolution in the HAZ

In micro-alloyed HSLA steels, the kinetics of carbides and nitrides are of interest,

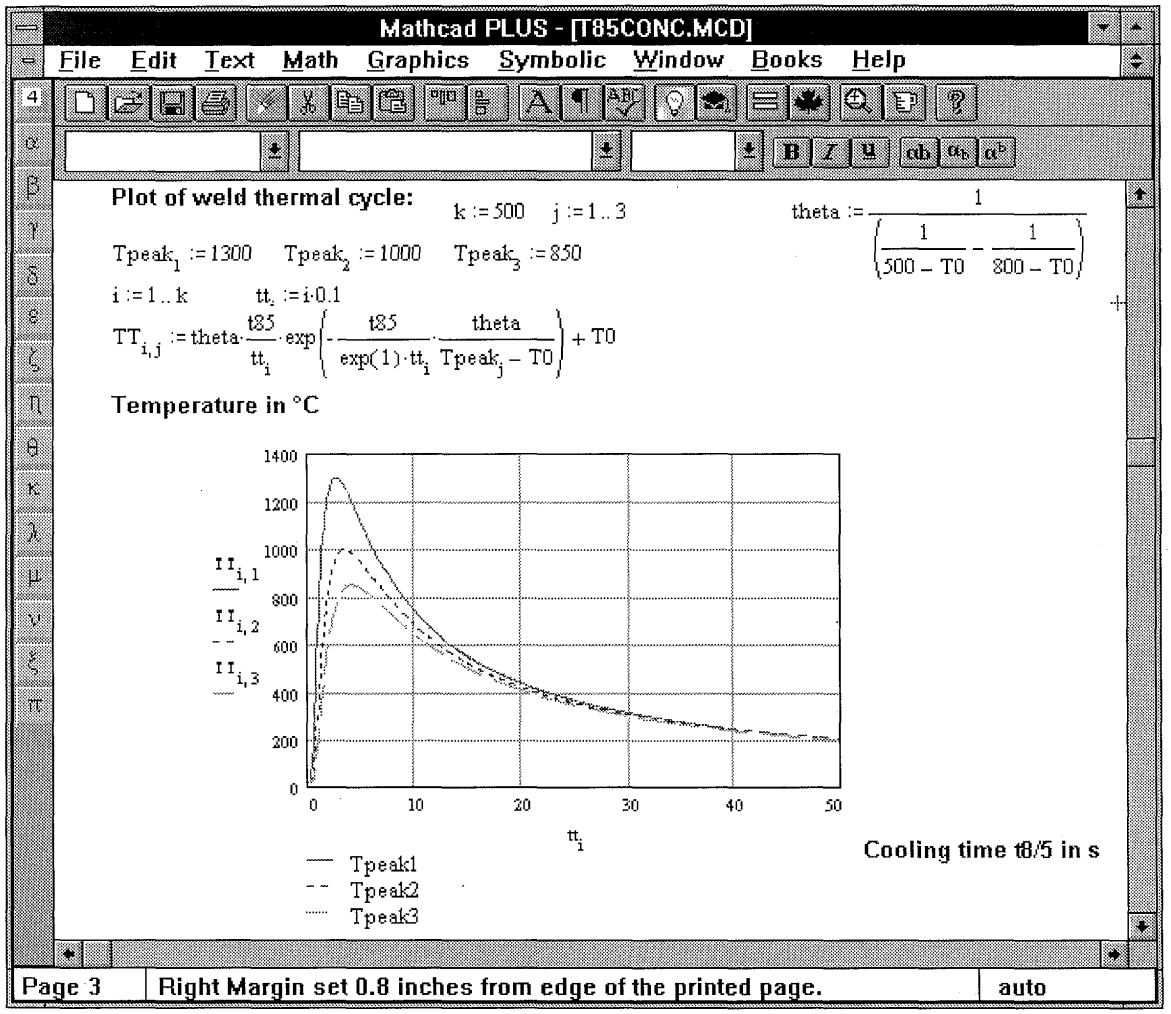


Figure 18 Weld thermal cycle calculated and visualized by a MathCad–program.

because they have a strong influence on the strength and toughness in the HAZ. Again the starting point for any welding consideration is the isothermal treatment of the dissolution kinetics. Afterwards, the dissolution behaviour in the HAZ can be predicted, see **Fig. 19**.

4. Conclusions

Computer based assessment of weldability enjoys increasing acceptability in the community of welding engineering world-wide. UP to now software packages which comprise different aspects of weldability based on well established parametric approaches i.e. the software package "HAZ Calculator" are used widely in welding engineering practice.

Expert systems support the welding engineers in his daily work i.e. during the selection of proper weld consumable or welding parameters for special applications.

Mathematical Models to describe the complex phenomena involved in the term weldability are much more sophisticated because they are based on physical, thermo-dynamical and kinetic equations and need therefore a great effort for the development. They are therefore up to now mainly used for research and development of materials, consumables and welding procedures.

In spite of these difficulties, in the last years great progress was made in development of models describing the manifold aspects weld-ability: Weld pool behaviour, solidification effects, microstructural development during

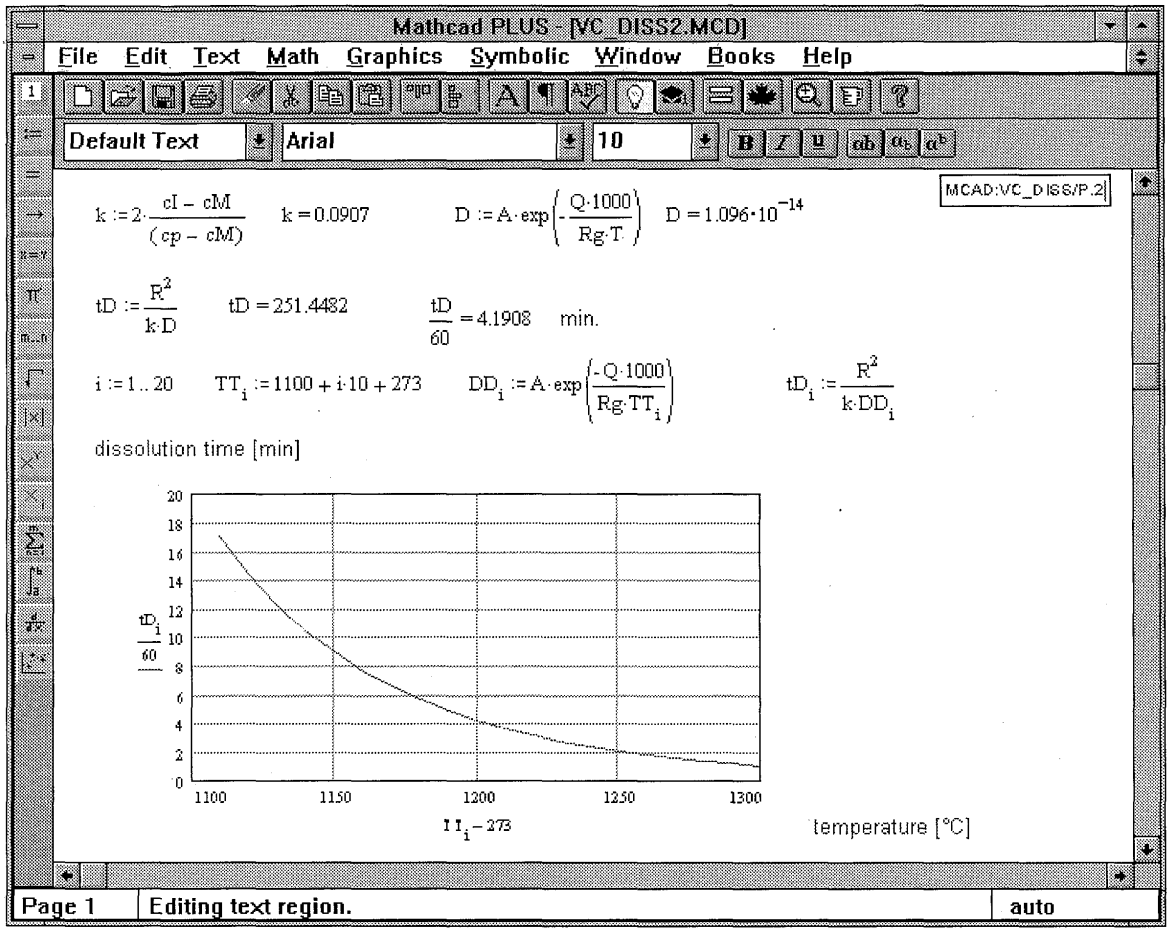


Figure 19 Calculated dissolution time for vanadium carbide under isothermal conditions.

cooling after welding and during PWHT, hot-, cold-stress relief cracking behavio explosive development of the computer science and technology accelerates these developments. In the case of coupled models it became obvious, that a better understanding of the basic principles of welding and weldability could be gained. The co-operation of the international community of welding modellers convinces, that in a near future mathematical modeling, based on the fundamentals will be widely used by welding engineers to support their responsible tasks.

Acknowledgements

The authors acknowledge the support of their co-workers in the Department of Materials Science and Welding Technology, Technical University Graz, especially Bernhard Schaffernak and Norbert Enzinger during preparation of this paper.

References

1) H. Cerjak and K. Easterling (eds.): Mathematical Modelling of Weld Phenomena, institute of Materials,London.(1993)
2) H. Cerjak and H.K.D.H. Bhadeshia (eds.): Mathematical Modelling of Weld Phenomena 2, Institute of Materials, London, Book 594 (1995)
3) H.Cerjak, H.K.D.H Bhadeshia (eds.): Mathematical Modelling of Weld Phenomena 3, Institute of Materials London, Book 650 (1996)
4) B.Buchmayr: Computereinsatz in der Werkstoff- und Schweißtechnik DVS-Verlag, Fachbuchreihe Schweißtechnik Bd. 112 (1991)
5) B.Buchmayr: HAZ-Calculator - A Software System for Welding Engineers, Recent Trends David, J.M.Vitek, ASM International(1990), P.327
6) W. Lucas: Microcomputer Systems, Software and Expert Systems for Welding Engineering, Welding Journal, 66 (1987), (4),P19
7) W. Lucas and A.D. Brightmore: Expert

Systems fo Welding Engineers, Metal Construction (May 1987),.254
8) J.Norrish and J.E.Strutt: Expert Systems and Computer Software Aids for WeldingEngineers, Welding and Fabrication 56 (1988), (10), P.337
9)P.M. Perozek and A.D. Brightmore:Diagnostic Expert Systems for Welding Engineers, Proc. of 2nd Int.Conf. on Computer Technology in Welding, TWI, Cambridge, 8-9 June 1988, p.P49/1
10) A.H. Kuhne, H.B. Cary and F.B. Prinz: An Expert System for Robotic Arc Welding Welding Journal 66 (1987), (11), p.21
11) W.A. Taylor: Expert Systems to generate arc Welding Procedures, Metal Construction 18 (1986), (7), P.426
12) W.Berger, B. Buchmayr, H. Cerjak and H. Schabereiter: WELCOME - Ein hybrides Auswahlsystem für Schweißtechnischen DVS-Berichte 179 (1996), p.36
13) B. Buchmayr and H. Cerjak: Eine Übersichst zum schweißtechnischen Softwareangebot, DVS Berichte 179 (1996), p. I
14) H. Cerjak and B. Buchmayr: Mathematical Modelling-A Tool for Advanced Welding Joining Technology?. ,Proc. 6th Int. Symposium of the Japan Welding Society, Nagoya, Japan, 19-21 Nov. 1996, Paper B-1. 1
15) B . Buchmayr: Modelling of Microstructural Changes During Welding of HSLA Steels, Int. Conf. Computer Technology in Welding, TWI, Brighton, UK, 4-7 June 1990
16) B . Buchmayr and H. Cerjak: Mathematical Description of HAZ behaviour of Low-Alloyed Structural Steels, IIW-Conf. Weld Quality-The Role of Computers, Vienna, July ,Pergamon Press p.43
17) H.Kammerstetter, H. Cerjak and A. Samoilov: Modelling of Precipitation Solution in TM- Steels During Weld Cycles, Mathematical Modelling of Weld Phenomena, eds. H. Cerjak, K.E. Easterling, Institute of Materials, London (1993), P.213
18) H. Kammerstetter: PhD Thesis, Technical University Graz (1989)
19) J.Strid and K.E. Easterling: Acta Metall 35 (1985), (11), P.2057
20) B. Buchmayr: Ternary Diffusion in Dissimilar Steel Welds, Mathe-matical Modelling of Weld Phenomena, H. Cerjak and K. Easterling (eds.), Institute of Materials, London, Book 533 (1993), P.225
21) B.Buchmayr, J.S.Kirkaldy: Fundamentals and Application of Ternary Diffusion, ed. G.R. Purdy, Pergamon Press, New York (1990), p. 164
22) J.S. Kirkaldy: Can. Met. Quart.8 (1969) 35
23) J.S. Kirkaldy: Oxidation of etals and Alloys. ASM Ohio (19 7 1) 210
24)M. Witwer; Untersuchungen an Mischschweissverbindungen warmfester CrMoV-Staehle (GS-17 CrMoV 5 11 an X20 CrMoV 12 1), Doctoral Thesis, Technical University Graz, May 1989
25) R. Prader, B. Buchmayr, H. Cerjak, A. Fleming and J. Peterseim: Thermodynamic Interactions in Hot Isostatic Pressed Grade Structures of Dissimilar Heat Resistant Steels, Zeitschrift für Metallkunde 12 (1995), P.864
26) A.Engström, L. Höglund and J. Ågren: Metallurgical and Materials Transactions A, 25A (1994), P. 1127
27) J. Ågren: ISIJ International 32 (1992), P.291
28) B. Sundman: Anales de fisica 36B (1990), p. 69
29) B. Sundman, B. Jansson and J.-O. Andersson: Calphad 9, 2 (1985), P. 1S3
30) B. Sundman and J. Ågren: J. Phys. Chem. Solids 42, P.297
31)B.Buchmayr,B.Schaffernak: Thermodynamishe Gleichgewichtsberechnungenzur Abschät-zung möglicher Gefügeveränderungen in Schweißver-bindungen, DVS-Berichte 179 (1996), p.79
32) D. Bru, J. Devaux, J.M. Bergheau and D. Pont: Influence of Material Properties at High Temperatures on the Modelling of Welding Residual Stress and Deformation State, Mathematical Modelling of Weld Phenomena 3, H. Cerjak, H.K.D.H Bhadeshia (eds.), Institute of Materials London (1996)
33) N. Enzinger: Vergleich von gemessenen und mit Hilfe der FEM-Methode berechneten Schweißeigenspannungen austenitischen Rohrrundnähten, Diploma Thesis, Technical University Graz (1996)
34) B. Buchmayr: A New Tool for Modelling of Weldability, Mathematical Modelling of Weld Phenomena 3, Institute of Materials London, Book 650 (1996)
35) J. Degenkolbe, D.Uwer and H.G. Wegmann: Thyssen Techn. Berichte H. 1/85, 1985, p.57