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# The influence of metallurgical data on residual stresses in Computational Welding

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## Abstract

Fusion welding processes are the primary joining techniques used in the fabrication of civil structures and mechanical engineering assemblies. The fusion of the parent and filler materials and the subsequent rapid cooling induce thermal and residual stresses within the component, leading to its distortion. Numerical codes used to simulate the welding process are continuously gaining interest for their potential to determine the optimum process parameters.

However, the reliability of the results obtained by means of finite element analysis (FEA) is conditioned to the quality of metallurgical parameters. In particular, continuous cooling transformation phase diagrams are not always available in literature and, even when some empirical relations are used to estimate the phase transformation temperatures, the results obtained contain some inaccuracies.

This work is aimed to study the influence of two main metallurgical parameters, i.e. the bainite start and martensite start transformation temperatures and the time constant for each cooling speed, on thermal residual stresses. In addition, the phase distribution has also been assessed due to its importance concerning the embrittlement of the weld.

Phase distribution has been found to be very sensitive to metallurgical parameters. Errors in phase proportion evaluation go up to 100% and 20% for input errors ( $M_{start}$ ,  $B_{start}$ ) in the range of 50 °C and 20 °C, respectively; such uncertainties in transformation temperatures are plausible if empirical correlation to estimate metallurgical data are used. On the other hand, residual stresses are lesser influenced by errors in metallurgical data, being the discrepancy for the mean stress less than 2% with an absolute error of 20 °C for  $M_{start}$ .

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## 1. Introduction

Fusion welding represents one of the main joining methods used in steel construction industry. In fact, it is less cost and time expensive than other joining techniques. However, residual stresses and distortions are introduced in the workpiece in addition to those coming from cutting or cold forming. To keep deformations under control, experience plays an important role in this field. Nowadays, computational welding mechanics is proving itself as a viable method to simulate the chosen welding process. Designers are particularly interested in residual stresses and deformations assessment; in this way they can study the best welding process and assembly procedure. In order to obtain correct dimensional tolerances in mechanical engineering assemblies, it's

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possible to calculate the machining allowance or to account for deformations in order to compensate the effects. In carbon steels residual stresses are affected by phase transformations. Hence, the joint microstructure is an important factor that determines the mechanical properties of the joint itself.

Nomen	clature
ТР	transformation plasticity
M <sub>s</sub> M <sub>f</sub>	martensite start temperature martensite finish temperature
$\mathbf{B}_{s}$	bainite start temperature
$\mathbf{B}_{\mathrm{f}}$	bainite finish temperature
HAZ	heat affected zone
tf	time factor
$P_i$	phase proportion of i-phase
$P_{eq}$	phase proportion at equilibrium
$\tau_i$	characteristic time of transformation for phase i
Т	temperature
Ť	temperature cooling rate °C/s

Lindegren (2001) stated that "the major obstacle for using the simulations in industrial practice is the need for material parameters and the lack of expertise in modelling and simulation". This study is focused on the first issue.

To the best of the authors knowledge, an extensive material database is absent for this type of analysis. High temperature stress and strain curves are difficult to find in literature as well as CCT diagrams.

A practical workaround to avoid material testing is the use of empirical correlations. Saunders et al. (2004) provide a review of empirical models and propose a new extension. They chose Kirkaldy's model, because of clearly identifiable set of input parameters and good accuracy for low alloy steel, and extended it to highly alloyed steels. This correlation is implemented in JMatPro®. The chemical composition, for every steel type and grade, is defined within a relatively small range in steel standards. These easy obtainable values represent the input needed for the extended Kirkaldy model. Results contain a level of uncertainties depending on the correctness of chemical composition and on the quality of the model fitting, which is higher for low alloys steels.

Aim of this work is the assessment of the sensitivity to errors in metallurgical parameters and exploring which phase transformation effect could be neglected in carbon structural steels without compromising results in terms of stresses and distortions.

It's worth noting that also others parameters contain uncertainties. They can derive from different welding operators and be quantified in a statistical variance of parameters such as welding speed, heat input and so on. In the same manner, environmental variables like ambient temperature and convection coefficients contain uncertainties. In a workshop production, compared to an assembly line where processes are automatized, the control of all variables is difficult if not impossible and the welding operators plays a crucial role. FE simulation risks to become unreliable because boundary conditions and welding parameters are not consistent with the actual weld. It is difficult to deal with all these issues in one time, but all the influencing variables can be thought as an equivalent CCT diagram. Different parameters cause different cooling rates and temperature gradients in the workpiece which are the basis for the computation of metallurgical phases, stresses and strains.

## 2. Numerical experiment set-up

For the shake of simplicity, only two main metallurgical variables are investigated. The first one is the couple of values  $B_s$  and  $M_s$ . Both of them are modified at the same time, which corresponds to moving down the bainite curve as it is shown in Figure 1. It has to note that 'bainite start' must coincide with 'pearlite end' temperature because a temperature range in which no isothermal transformation happens can't exist in the numerical model. Similarly,  $B_f$  is equal to  $M_s$ . This represents an approximation for the final stage of the transformation. Nevertheless, since the transformation happens mostly in the upper region, the error is negligible compared to the influence of others sources.

The second metallurgical variable is the time constants of the transformations defined in the Leblond-Devaux kinetic model (Leblond and Devaux, 1984):

$$\frac{dP_i}{dt} = \frac{P_{eq,i}(T) - P_i}{\tau_i(T,T)} \tag{1}$$

where  $P_{eq,i}(T)$  is the equilibrium fraction of phase i at the temperature T,  $P_i$  is the i phase proportions,  $\tau_i(T,T)$  is the characteristic time of transformation.

The original set of values has been multiplied by a time factor tf (dimensionless) to shift the diagram horizontally. The relation is

in fact exponential and a simple addition would not be sufficient to obtain measurable differences in results. The CCT diagram is a semi-log plot and, to obtain a measurable effect, the time constants have to be scaled by a multiplicative factor. More precisely, the characteristic time of transformation has been modified according to Eq. (2):

$$\tau_i(tf \cdot \dot{T}, T) \tag{2}$$

In Sysweld numerical code,  $\tau_i$  dependence on the cooling rate is introduced by means of a more suitable form for numerical implementation. A comprehensive explanation could be found in Ferro et al (2006).

In this analysis, the heating transformation to form austenite has always been kept constant. Martensitic transformation is modelled by Koistinen-Marburger law (Eq. 3).  $M_s$  is changed according to Table 1, while the coefficient *b* has been kept constant in order to adjust  $M_f$  automatically.

$$m(T) = 1 - e^{-b(M_s - T)}$$
(3)

Table 1 is the matrix showing the parameters used for each simulation; all the labelled X cases are tested with the metallurgical model and transformation plasticity activated except otherwise specified. For the shake of simplicity the filler metal has been assumed to be the same as the parent material.

Table 1. Matrix for the designed experiments, various combination of time factor tf and starting temperatures offset have been considered. For TP the phase effect has been considered but transformation plasticity neglected, for NP no metallurgical model has been included.

	$\mathrm{M}_{\mathrm{s}},\mathrm{B}_{\mathrm{s}}\left(^{\circ}\mathrm{C}\right)\!\!\rightarrow$	а	b	с	d	e
	tf	-50	-20	0	20	50
	$\downarrow$					
А	· 1/5			Х		
В	· 1/2			Х		
С	· 1	X, TP	Х	X, TP, NP	Х	X, TP
D	· 2			Х		
Е	· 5			Х		

Raberger et al. (2005) discovered that TP has to be taken into account for materials with low transformation temperature. In the present model only the accommodation effect (Greenwood-Johnson mechanism) has been included. The Magee mechanism (orientation effect) is considered negligible during welding according to Leblond and Devaux (1989). Ferro et al. (2006) suggest that both transformation plasticity and volume change cannot be neglected in the calculation of residual stresses. However, the influence of transformation plasticity with respect of volume change effects is not clear yet. This will be addressed later in the present work (cases in Table 1 labelled with "TP"). Only for the extremes "aC" and "eC" and original case "cC" the influence of TP has been compared to the volume change effects. The metallurgical model was always active except for the case "cC NP" (table 1).

It is thought that used procedure provides high flexibility and has a general validity because the isolated effect of variables can be investigated.

## 2.1. Continuous Cooling Transformations diagrams

The estimation of plausible errors in metallurgical data was obtained by comparing low carbon S355 steel CCT diagrams taken from different sources. The experimental diagram from Seyffarth et al. (1992) is taken as reference. The first CCT diagram used for comparison is the one included in the Sysweld database. Other two diagrams are calculated by using empirical correlations from nominal chemical composition and from the same composition reported in the reference diagram. It can be noted that M<sub>s</sub> of both Sysweld CCT diagram and the experimental one is equal to 420 °C. On the other hand, by using the experimental chemical composition in the extended Kirkaldy model, M<sub>s</sub> is 411 °C. Furthermore, if the standard chemical composition is used, M<sub>s</sub> is 399 °C. The error is about 20 °C, thus it was chosen as representative for the first temperature offset (letter "b" and "d" in Table 1). Perlite starting point is 704 °C for both experimental and Sysweld diagrams, and 730 °C and 711 °C for the standard chemical composition and the experimental composition derived diagrams, respectively. At those high temperatures, errors are less influencing and for this reason the 'perlite start' temperature is not inserted as a variable. B<sub>s</sub> values are 630 °C, 576 °C and 591 °C for the three models respectively, with an error higher than 40 °C. 50 °C was thus chosen as the second offset (letters "a" and "e" in Table 1) for the first variable formed by the couple M<sub>s</sub> and B<sub>s</sub>.



Fig. 1. CCT diagram used for FE analysis. The influence of the parameters is shown by the arrows.



Fig. 2. CCT diagrams derived by using empirical correlations

A time factor greater than 1 means that the same transformation occurs for a faster cooling rate (CCT diagram moved to the left) (Fig. 3). On the contrary, a time factor lower than 1 implies that martensite is formed even for slow cooling rates ("cA" case).



Fig. 3. Comparison between "cA" and "cE" cases (time factor of 1/5 and 5 respectively). For the blue diagram, martensite is formed only for very fast cooling rate

## 2.2. FE model

A butt-welded joint has been considered for the analyses (Fig. 4). The plate is  $60 \times 40$  mm with a thickness of 3 mm. By taking advantage of the symmetry, only one half of the joint was modelled. The ends are left unclamped while the heat source is modelled using the Goldak's function (Goldak et al., 1984), which parameters have been chosen in order to simulate a one-pass welding (see Table 2).

Table 2.	Goldak	heat	source	function	paramet	ers
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a <sub>r</sub> [mm]	a <sub>f</sub> [mm]	c [mm]	b [mm]	$\mathbf{f}_{\mathrm{r}}$	$\mathbf{f}_{\mathrm{f}}$	v [mm/s]
3.5	2.2	6	2.2	1.4	0.6	10

The power input is 2.85 kW and a process efficiency of 64% has been assumed. The welding speed is supposed to be constant at 10 mm/s.



Fig. 4. (a) 3D numerical model. (b) Middle section: it is shown the point where the temperature profiles are analysed and the line (arrow) where the stress field is compared

The number of 8-node linear elements is about 20000. Low-order elements are chosen because of their better performance in non-linear solutions (Lindgren et al. 1993) and a reduced integration scheme has been adopted to avoid volumetric locking (Mcdill and Oddy 1995, Belytschko et al. 2000). A refined mesh is used where high thermal gradients are present. No adaptive meshing has been implemented because of the relatively small model analysed. Finally, for the shake of simplicity, weld bead deposit effect by element activation/deactivation was not taken into account.

## 2.3. Material model

The material was the S355 carbon steel, which chemical composition is summarized in Table 2. This steel grade is known to have a good weldability and for this reason it is widely used in civil engineering.

Table 2. Chemical composition of S355 structural carbon steel	

С	Mn	Si	Cr	Ni	Cu	S
0.18 %	1.6 %	0.55 %	0 %	0 %	0 %	0.035 %

Stress and stain curve as a function of phases and temperature is taken from Ferro et al. (2006). Ferrite-pearlite, bainite, martensite and austenite microstructures are included in the analysis. The austenitic grain size effect was neglected.

The cut-off temperature is set equal to the fusion temperature (1500°C). For elements reaching this temperature, stresses, total and plastic strains are cleared. The strain hardening of the material is thus reset in the weld bead zone similarly to a recrystallization effect.

Since the plate undergo only one welding cycle, the Bauschinger effect can be also neglected and the isotropic hardening model is though to be representative of the constitutive behaviour of the material.

## 3. Thermo-metallurgical Results

Thermal results are comparable for all cases. It has to be noted that even when no metallurgical model has been included, such as in the "*NP*" case, temperature profiles are still similar.



Fig. 5. Temperature profile in the central node (Fig. 4b)

The fusion zone is shown in Fig. 6. Since the geometry is always the same a relative comparison among the obtained stress

results can be representative of the effects of the CCT curve parameters.



Fig. 6. Fusion zone in the middle cross-section for all the cases.

About residual stresses, we have to note that peak stress is extracted from the middle section of the model. On the other hand, the stress field is taken along a vertical line (Fig. 4b) that was found do not contain the peak stress.

### 3.1. Metallurgical Phases

By lowering both  $M_s$  and  $B_s$ , the maximum martensite proportion decreases while the maximum bainite proportion increases (Fig. 7a). As a matter of fact, as  $M_s$  decreases, bainite has more time to form. However, when the time factor *tf* increases (Fig. 3), bainite forms also with high cooling rates. This is the reason why in Fig. 7b it is shown that bainite keeps growing at the expense of martensite.

Bainite has generally less impact on residual stresses. The transformation occurs at high temperatures when the yield stress is low. The same cannot be said about martensite transformation which occurs at lower temperatures when the material has a higher yield stress and its behaviour is elasto-plastic.

For very low time factors *tf* it is found (Fig. 7b), as expected, that the maximum percentage of martensite is much higher if compared to the maximum bainite proportion.



Fig. 7. Maximum bainite and martensite percentage after cooling down in the plate. (a) with varying transformation temperatures (b) with varying time factor

By varying both  $M_s$  and  $B_s$  input temperatures, variations of -31.6% to 15.8% and 31.6% to 29% are obtained for martensite and bainite proportion, respectively, if compared to the reference case "*cC*".

The effect of the time factor tf is more evident compared to  $M_s$  and  $B_s$ . In fact, martensite percentage varies from 1.8% to 42.1% and bainite percentage variations are even higher, namely from -74.9% to 107.1%. Small variations in the CCT diagram result in high variation of the final microstructure of the joint.

## 4. Stress results

Compared to phase proportions, the influence of metallurgical input parameters on residual stresses is lower. Stresses along the thickness are analysed since they are responsible for angular distortion. Maximum values, occurring ahead of the weld bead on the topside of the plate, are thought to induce more angular deformation than stresses on the middle plane.

#### 4.1. Transversal Stresses

Transversal stress distribution has peak in proximity of the top weld bead as shown in Fig. 8. Both the maximum and the averaged values are taken into account, being the maximum value much more important for angular deformations and fatigue life. The averaged stress value is representative of the whole stress field.



Fig. 8. Transversal stress distribution after cooling down for "cC" case

The higher the time factor, the higher the averaged transversal stresses (Fig. 9a). Thus, as *tf* increases, the averaged martensite percentage in HAZ decreases, even if the peak value of martensite percentage doesn't reflect this trend for values of *tf* grater than 1 (as it can be seen in Fig. 7b). For *tf*=2 percentual errors could go up to 10.6% and for *tf*=  $\frac{1}{2}$  the error on the mean stress is - 5.6%, but for an extreme case it goes up to 23.5%.

By moving up the CCT diagram by changing  $M_s$  and  $B_s$ , a lower peak stress is obtained because of the increased martensite content (Fig. 10). The volume change inducted by the displacive trasformation induces compressive residual stresses with a reduction of the stress field and the peak stress, as well. Bainite has a less pronunciated effect. The averaged stresses as a function of *tf* (fig. 11b) follow the same trend as the maximum martensite phase (fig. 7b) meaning that the maximum phase percentage is strictly correlated to the averaged value on the weld bead.



Fig. 9. (a) Residual transversal stresses on plate thickness for different (f values. (b) Residual transversal stresses on plate thickness as a function of M<sub>s</sub>, B<sub>s</sub>

Differences in the averaged stress are enough significant and in the 10% range. It is remarkable that an error in metallurgical data that double or halves the corresponding cooling rate, induces such limited error in residual stress results.



Fig. 10. Maximum peak stress on the plate middle section for different transformation temperatures (a) and time factors tf (b)



Fig. 11. Averaged stress along the line indicated in Fig. 4b versus transformation temperature (a) and tf (b)

## 4.2. Longitudinal stresses

Comparing the two modalities of variation of metallurgical parameters (i.e.: transformation temperatures and t/), peak stresses differences are very limited because yielding has occurred. The maximum percentage difference, with respect to the "cC" reference simulation, is only 1.8 %. However, for both cases, absolute differences are low and it can be concluded that longitudinal stresses are constant with respect of metallurgical parameters as it can be seen in Fig. 12. Longitudinal stresses are much higher than the in-plane stresses because of the high level of constraint and the presence of martensite that has a yield stress of about 800 MPa.



Fig. 12. Maximum longitudinal stress, following the welding direction, on the whole model.

## 5. The influence of phase transformation effects on the residual stress field

In order to assess the possibility of using general purpose FEM software, the "cC" case has been replicated with the metallurgical model deactivated. Phase transformation effects on residual stress filed are the specific volume change and TP. Figure 13 shows the transverse stress results obtained with the metallurgical model activated, deactivated and only TP deactivated. A simplified simulation with no metallurgical model ("NP" case) produces peak stresses with values five times higher than those obtained with the complete model because the compressive effect induced by the displacive transformations is lost. It is thus not acceptable to neglect the phase transformation effects for calculating residual stresses.

Results suggest that transformation plasticity (TP) can significantly relax the residual stress field. Different thermal strains between phases causes transformation plasticity. Moreover, TP is a function of the actual yield stress in addition to the stress applied, according to Greenwood-Johnson's theory [12]. For this reason, the constitutive material law is a fundamental parameter influencing the TP effect.



Fig. 13. Effect of phase transformations on residual stresses along the thickness of the model (Fig. 4b)

#### 6. Conclusions

The effect of metallurgical parameters on phase proportions is found to be very high. By assuming a common temperature transformation uncertainty of about 20°C a relative variation of 20% is obtained for phase proportions results. Accurate CCT diagrams are thus recommended if a reliable microstructure has to be predicted by the welding simulation.

If the main objective of the simulation is instead to calculate residual stresses, an uncertainty of 12% in the  $M_s/B_s$  (50 °C absolute error) produces a maximum variation of 6.8% on stress results. Moreover, a more reasonable absolute error of 20 °C induces an error of only 1.8% for the averaged stress.

Errors on cooling curves, represented by the time factor uncertainties, are more relevant especially when the CCT diagram moved to the left (higher time factor) because of the exponential nature of the diagram. A multiplicative factor *tf* of 2 for every cooling rate, means that the diagram moves of about 5 s on the left where the cooling rate reaches 100°C/s. This is a quite relevant error that influences up to 11% the averaged stress results. On the other hand, if the CCT diagram moves on the right of the same quantity (i.e.  $tf = \frac{1}{2}$ ), the error is reduced to 6%.

It is concluded that, for carbon steels, metallurgy data may contain some degree of errors without affecting significantly stress results. A phase transformation model is confirmed to be necessary to obtain reliable stress fields. It is remarkable that errors in the metallurgical parameters are reduced in the mechanical simulation.-Empirical parameters estimation has proven to be a viable method for residual stresses evaluation where direct CCT testing is expensive and most of all time consuming.

#### References

- L.-E. Lindgren, Finite Element Modeling and Simulation of Welding. Part 3: Improved Material Modeling, J. Therm. Stress. 24 (2001) 195-231. doi:10.1080/014957301300006380.
- N. Saunders, Z. Guo, a P. Miodownik, J.-P. Schillé, The Calculation of TTT and CCT diagrams for General Steels, (2004) 1–12.
- J.B. Leblond, J. Devaux, A new kinetic model for anisothermal metallurgical transformations in steels including effect of austenite grain size, Acta Metall. (1984). doi:10.1016/0001-6160(84)90211-6.
- P. Ferro, H. Porzner, A. Tiziani, F. Bonollo, The influence of phase transformations on residual stresses induced by the welding process-3D and 2D numerical models, Model. Simul. Mater. Sci. Eng. 14 (2006) 117–136. doi:10.1088/0965-0393/14/2/001.
- R. Raberger, M. Brandner, B. Buchmayr, Influence of TRIP on the residual stress development during heat treatment of high alloyed cast irons Conf, Proc. IDE 2005 (Bremen, Ger. (2005) 365–371.
- J.B. Leblond, J. Devaux, J.C. Devaux, Mathematical modelling of transformation plasticity in steels I: Case of ideal-plastic phases, Int. J. Plast. (1989). doi:10.1016/0749-6419(89)90001-6.
- P. Seyffarth, B. Meyer, A. Scharff, Grosser Atlas Schweiss-ZTU-Schaubilder. Duesseldorf, DVS, (1992).
- J. Goldak, A. Chakravarti, M. Bibby, A new finite element model for welding heat sources, Metall. Trans. B. 15 (1984) 299-305.
- L.E. Lindgren, A. Carlestam, M. Jonsson, Computational Model of Flame-Cutting, J. Eng. Mater. Technol. 115 (1993) 440. doi:10.1115/1.2904243.
- J.M.J. Mcdill, A.S. Oddy, a Nonconforming Eight To 26-Node Hexahedron, 54 (1995).
- T. Belytschko, W.K. Liu, B. Moran, Nonlinear Finite Elements For Continua And Structures, 2000. doi:10.1016/S0065-230X(09)04001-9.
- D. Deng, H. Murakawa, Influence of transformation induced plasticity on simulated results of welding residual stress in low temperature transformation steel, Comput. Mater. Sci. (2013). doi:10.1016/j.commatsci.2013.05.023.