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Effects of Thermocapillary Forces during Welding of 316L-Type Wrought, Cast and Powder Metallurgy Austenitic Stainless Steels

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Abstract

The Large Hadron Collider (LHC) is now under construction at the European Organization for Nuclear Research (CERN). This 27 km long accelerator requires 1248 superconducting dipole magnets operating at 1.9 K. The cold mass of the dipole magnets is closed by a shrinking cylinder with two longitudinal welds and two end covers at both extremities of the cylinder. The end covers, for which fabrication by welding, casting or Powder Metallurgy (PM) was considered, are dished-heads equipped with a number of protruding nozzles for the passage of the different cryogenic lines. Structural materials and welds must retain high strength and toughness at cryogenic temperature. AISI 316L-type austenitic stainless steel grades have been selected because of their mechanical properties, ductility, weldability and stability of the austenitic phase against low-temperature spontaneous martensitic transformation. 316LN is chosen for the fabrication of the end covers, while the interconnection components to be welded on the protruding nozzles will be fabricated from forged 316L or 316LN, and welded 316L tubes. Autogenous welds between the nozzles and the interconnection components will be performed by the automatic orbital TIG technique. Several thousands of welds are foreseen. When welding together grades of slightly different composition, or grades issued from different fabrication methods (cast, PM, cold or hot rolled, forged…), phenomena such as variable weld penetration, "off-centre welding" and "arc wander" may possibly appear, resulting in uncontrolled formation of non axisymmetric welds. Such deflections of the weld pool are difficult to correct for an automatic process and may affect the soundness of the weld. A large and systematic campaign of welding tests associated with video recording of the melt pool has been carried out. Hot metal deflections have been precisely quantified. The results are interpreted in terms of the different content of soluble surface-active elements of the various steel batches and the directions of the thermocapillary flow arising from these different contents. This interpretation gives a quantitative prevision of the hot metal deflections. Possible corrections applicable to automatic welding processes are discussed.

Keywords: TIG welding, austenitic stainless steels, variable weld penetration, "off-centre" welding, "arc wander".

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1. INTRODUCTION

During welding of steels, temperature gradients of surface tension result in convective currents acting on the surface of the molten pool. These currents are called Marangoni flows. The presence of soluble surface-active elements in the weld puddle controls the shape of the weld. There have been several attempts [1-13] to establish a correlation between these elements and the penetration of the weld or its geometry. It has been shown that surface-active elements such as: S, O [1-5], Se [2,4], Te [2] affect the penetration. It was found [6] that nitrogen, by enhancing sulphur activity in iron, has an indirect influence on penetration. Reactive elements such as Ca, Ce, La, Mn would combine with sulphur to give their respective sulphides and reduce the concentrations of soluble sulphur [5]. Phosphorus decreases sulphur activity by forming phosphorus-sulphur and iron-phosphorus-sulphur compounds [1]. Studies carried out on stainless steels [7,8,9] have shown that additions of sufficient amounts of Al, reacting with oxygen to form aluminium oxides, reduce weld penetration. The presence of Si acts on the viscosity of the molten metal and may increase or decrease the weld penetration as a function of the S content of the steel [10]. The influence on penetration of several other elements as well as their mutual influence was also assessed [11].

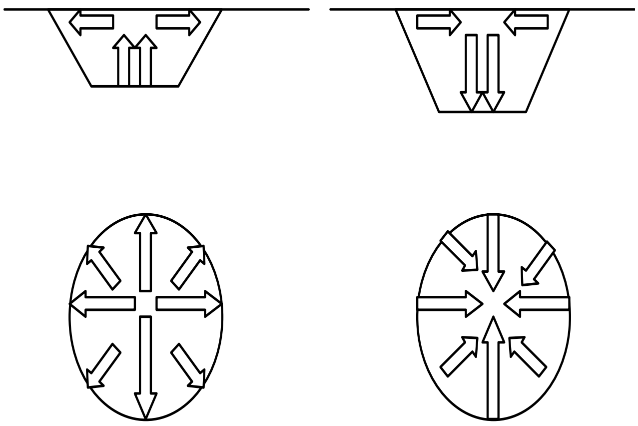
In ferrous alloys, the temperature gradient $d\gamma/dT$ of the surface tension γ induces a Marangoni force F_γ equal to:

$$\mathrm{F}_\gamma = -\frac{d\gamma}{dT} \cdot \nabla T \qquad (1)$$

where ∇T is the temperature gradient along the surface of the weld pool. Although three other forces (Lorentz, buoyancy, aerodynamic drag) operate in the weld pool, Marangoni forces are predominant under normal welding conditions and have the main effect on the weld profile [12,13].

The direction of the flow in the weld pool due to the temperature gradient of the surface tension depends on the sign of $d\gamma/dT$. As shown in Figure 1, for a negative gradient, flow is radially outward (decreasing penetration), while for a positive one the flow is inward (penetration increases). The coefficient $d\gamma/dT$ is positive for a material with a high rate of surface-active elements, such as sulphur and oxygen that cause an inward flow and a deeper-penetrating weld. This coefficient is negative in pure metals or very low impurity steels. The S content limit between outward and inward flow is between 30 ppm and 60 ppm according to Scheller et al. [2] or 80 ppm according to Marya and Olson [14].

On this basis, steels can be classified as High Sulphur (HS) or Low Sulphur (LS).



a) LS : b) HS :

Figure 1: *Opposite patterns of fluid flow due to two different signs of the temperature gradient of the surface tension [3]: a) steel with low content of surface-active elements, negative gradient, outward flow, reduced penetration. b) sufficient amount of surface active elements, positive gradient, inward flow, enhanced penetration.*

Several studies have shown that surface-active impurities influence the surface tension to a different extent. In particular Marya and Olson [14] could quantify this influence on the surface tension of pure Fe containing S, O, Se. In our case, since measured Se content is always < 1 ppm, sulphur and oxygen should play the major role.

From the data of [14] a Sulphur Equivalent (S_{eq}) can be defined as :

$$S_{eq}\% = \mathrm{S}\% + 1.33 \cdot \mathrm{O}\% \tag{2}$$

2. EXPERIMENTAL

The phenomenon of off-centre welding is studied by performing automatic orbital butt welds of pipes and pipes on nozzles of end covers. A drawing of the end cover is shown in Figure 2. The extremities of the nozzle to be welded on the pipe and the pipe itself have an external diameter of 84 ± 0.1 mm and an internal diameter of 80 ± 0.1 mm.

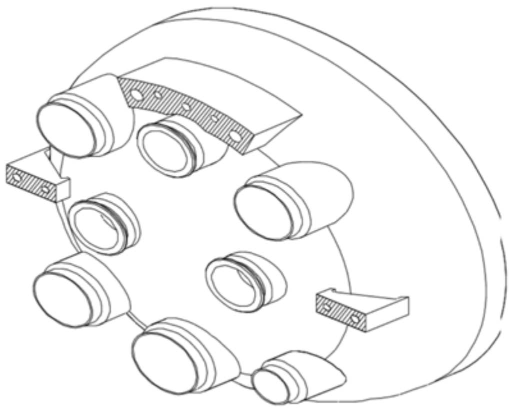


Figure 2: *Schematic drawing of the end cover. Six nozzles have to be welded on each end cover. The diameter of the cover is approx. 570 mm.*

Autogeneous full-penetration TIG welds are performed, fully representative of the fabrication process. Welding parameters are rigorously identical for each test in order to guarantee, from test to test, reproducible energy transfers and temperature gradients ∇T. In this way, the deviation measured for each test mainly accounts for different $d\gamma/dT$ coefficient.

Grade	*Product*	Supplier	Cr	Mo	Ni	C	H /ppm	*N*	*Si*	*Mn*	*P /ppm*	**S /ppm**	**O /ppm**	S_{eq} /ppm
316LN	*Forged pipe*	Grimm	17.5	2.8	13.8	0.016	5.6	*0.16*	*0.36*	*1.62*	*180*	**20**	**20**	66.6
316L	*Welded tube*	Notz	17.3	2.7	12.6	0.021	2.2	*0.04*	*0.41*	*1.65*	*270*	**10**	**29**	68.6
316L	*Forged pipe*	Sandvik	17.3	2.5	12.6	0.01	3.6	*0.02*	*0.37*	*1.62*	*310*	**270**	**48**	334
316LN	*Cast cover*	A&D	17.4	2.9	13.0	0.019	2.0	*0.24*	*1.08*	*1.63*	*<300*	**50**	**62**	133
316LN	*PM cover*	RT	17	2.5	13.1	0.016	-	*0.15*	*0.58*	-	*150*	**30**	**120**	190
316LN	*Cast cover*	WC	17.3	2.1	12.7	0.021	2	*0.17*	*0.75*	*0.92*	*120*	**10**	**215**	396

Table 1: *Compositions (weight %, unless otherwise stated) of the austenitic stainless steel pipes and tubes (first group) and end covers (second group). The chemical analysis of the different products is based on material certificates and dedicated measurements performed by EMPA /CH (N), A2M Industrie /F (O, H) and Mecasem /F (Se, Te). When measured, Se and Te content are always < 1 ppm. Bold characters identify surface-active elements, italic characters reactive elements. A* S_{eq} *is calculated for every product on the basis of Eq. (2).*

Austenitic stainless steels of 316L-type are considered. A series of welds is made between three pipes of different heats, grades and/or fabrication, and between these pipes and the nozzles of two cast end covers, produced by Aubert et Duval /F (A&D) and William Cook /GB (WC), respectively and of a Powder Metallurgy (PM) end cover from Rauma Technologies /FI (RT). The composition of the six materials is shown in Table 1. Welding parameters are shown in Table 2. The campaign is aimed to weld together the maximum possible number of couples. For each grade of steel, full-penetration welds are also performed with the usual parameters of Table 2.

Welding details :	
Travel speed:	1.5E-02 m/s
Peak current:	68 A
Base current:	32 A
Peak time:	0.2 s
Base time:	0.2 s
Arc length:	1.5E-03 m
Tip angle	45°
Gas flux and flow rate:	
Shielding:	Ar, 1/6 l/s
Backing:	Ar, 1/12 l/s

Table 2: *Parameters of the TIG orbital welding. The welding procedure has been specified and approved according to the standard EN 288-3.*

In order to quantify the influence of welding parameters on the weld pool shift, a complementary campaign of test has been carried out on some couples by varying the tip angle (increased up to 70°), and/or adding 2 % of hydrogen in the shielding gas. All the other parameters are kept unchanged (see Table 2).

For each test, the possible welding off-centre is measured by drawing a reference line on the whole circumference, 20 mm away from the edge of one of the tubes to be welded and measuring the shift between the edge plan and the median plan of the weld bead with a binocular magnifying-glass and a graduated rule.

Moreover, for each weld metallographic investigations are performed on three cross-sections of polished specimens cut across the weld. The specimens are observed using a LEITZ DMR microscope equipped with a QUANTIMET Q600 image analyser. In this way, the geometry of the weld pool and the possible off-centre weld phenomenon is quantified on the whole thickness. In particular, for the full penetration welds individually performed on the different steel grades, the (back-to-front) ratio of the widths (W_b/W_f) [2] of the welds could be measured.

Finally, a video of the melt pool is recorded in order to visualise the phenomenon of off-centre welding and to assess whether arc wander phenomena occur.

3. EXPERIMENTAL RESULTS

Full penetration welds performed on each steel grade allow the weld penetration expressed by the ratio W_b/W_f to be quantified. This parameter is preferred to the depth/width (D/W) parameter of penetration accessible through partial penetration tests since the results are directly comparable with the ones of fully penetrated welds of dissimilar grades. Values of W_b/W_f are reported in Table 3 together with the S_{eq} (see § 4.1) and Si content of the different steels.

Penetration is generally higher for the grades containing the highest S_{eq}. In grades such as 316LN cast cover by A&D, Si could reduce penetration by affecting the viscosity of the pool. As well, the penetration is relatively low for the 316LN PM cover, since only a fraction of the total oxygen is available in solid solution (high rate of oxides).

Grade	Product	S_{eq} /ppm	Si /%	*Wb/Wf*
316LN	*Forged pipe*	*66.6*	*0.36*	*0.68*
316L	*Welded tube*	*68.6*	*0.41*	*0.70*
316LN	**Cast cover A&D**	**132.5**	**1.08**	**0.46**
316LN	**PM cover**	**189.6**	**0.58**	**0.69**
316L	**Forged pipe**	**334**	**0.37**	**1.06**
316LN	**Cast cover WC**	**396**	**0.75**	**0.84**

Table 3: *Penetration measured by the parameter Wb/Wf is the highest for the grades with the highest oxygen and sulphur content. The heats are arranged in order of increasing* S_{eq} *(LS: italic,* **HS: bold***).*

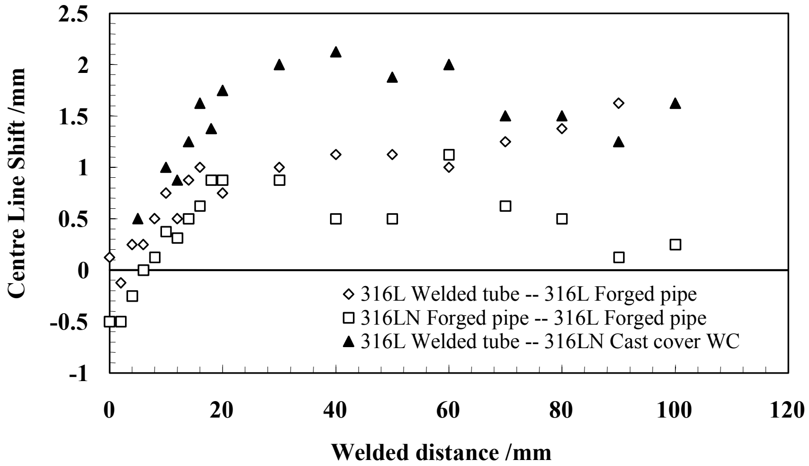


Figure 3: *Shift between the edge plan and the median plan of the weld bead as a function of the distance travelled.*

In order to study the phenomenon of off-centre welding, a series of twelve welds on couples of different products is performed with the following results:

- Off-centre welding only occurs when combining together some of the heats listed in Table 1. The phenomenon is reproducible and measurable. Quantitative results of the displacement of the pool for the different couples are shown in Table 4.
- The shift between the edge plan and the median plan of the weld bead (called Centre Line Shift), CLS, gradually increases, from the weld departure up to the first 20 mm of weld. Figure 3 shows the dependence of the shift on the distance travelled for three different couples of products. Video-tape recording of the welding operation gives also clear evidence of a gradually increasing shift.

Table 4 shows that the shift is low or negligible for products having similar S_{eq} (both LS and HS) and is relevant for products having opposite content (LS with HS) or very different HS contents. In this case, the shift is always towards the product with the lowest S_{eq}.

For some of the couples, the shift of the weld pool can locally attain 2 mm (see Figure 3 and Table 4) and may cause incomplete penetration of the weld. The presence of this type of imperfection does not allow the welding procedure to be approved according to EN288-3 (this standard requires full penetration to fulfil the stringent quality level for imperfections classified by the standard EN25817).

Test n°	Product welded	Together with	CLS /mm	max. CLS /mm	ΔS_{eq} /ppm
1	**316L Forged pipe -**	**316LN Cast cover WC**	0.01	0.63	62
2	*316LN Forged pipe*	*316L Welded tube*	0.03	0.5	2
3	*316LN Forged pipe*	**316LN Cast cover A&D**	0.08	0.25	83
4	*316L Welded tube*	**316LN Cast coverA&D**	0.27	1	64
5	**316 LN PM cover**	**316 L Forged pipe**	0.55	0.75	144
6	*316L Welded tube*	**316 LN PM cover**	0.6	0.88	121
7	*316 LN Forged pipe*	**316 LN PM cover**	0.6	0.75	123
8	**316LN Cast cover A&D**	**316L Forged pipe**	0.73	1.63	202
9	*316LN Forged pipe*	**316L Forged pipe**	0.87	2	267
10	*316L Welded tube*	**316LN Cast cover WC**	1.2	2.13	327
11	*316LN Forged pipe*	**316LN Cast cover WC**	1.28	1.38	329
12	*316L Welded tube*	**316L Forged pipe**	1.6	2.38	265

Table 4: *Measure of the average and maximum Centre Line Shift (CLS) of each couple of materials ordered by increasing CLS. The weld is displaced towards the material cited in the first column. As in Table 3, LS: italic,* **HS: bold**.

A complementary series of welds has been performed in order to ascertain whether a mass effect, such the one present when welding a massive end cover on a pipe, might exert any influence on the off-centre welding phenomenon. Two pipes (316L welded tube and 316L forged pipe, LS and HS behaviour, respectively) have been cut into two parts. The two parts have been welded together on half circumference and the obtained assembly has been welded to the nozzle of one end cover. The remaining second half of the circumference has been welded. CLS was null or negligible in the two welded half-circumferences, independent on the presence of the mass of the end cover. The test shows that the mass of the end cover has no measurable influence on CLS.

The butt welding of pipes might be affected by linear misalignment, due to slightly different thickness or diameter of the pipes or errors of pipe positioning. In order to ascertain whether misalignment might play a role on off-centre welding phenomena, two half pipes (from the LS product "316LN forged pipes") are welded by introducing a linear misalignment of 0.3 mm to 0.4 mm. No measurable CLS is observed.

The addition of hydrogen in the shielding gas decreases the weld pool shift. Welding with a larger tip angle has no clear effect on the weld pool shift, while welding with a larger tip angle and with 2 % addition of hydrogen decreases the weld pool shift.

4. DISCUSSION

4.1 Quantitative interpretation of results

Off-centre welds towards the LS side are experimentally observed when a LS and a HS behaviour products are welded together. Several studies qualitatively interpreted this phenomenon [15-18]. LS and HS heats have different fluid flows that are asymmetrical on the two sides of the line joint. Heiple and Roper [15] first gave a comprehensive interpretation of off-centre welds in terms of asymmetric surface tension force, confirmed by Tinkler et al. [16].

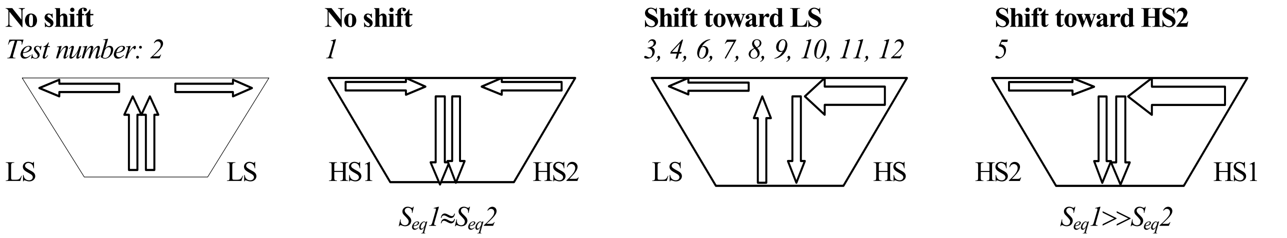


Figure 4: *Four different cases of convective movements when welding mixed products. Reference to the twelve tests of Table 4 is made for each behaviour.*

The schematic drawing in Figure 4 shows four fluid flow behaviours associated with different heat couples: two LS products, two HS products with similar S_{eq} contents, a LS with a HS product and two HS products with very different S_{eq} contents. As Figure 4 clarifies, only the last two cases result in an off-centre welding.

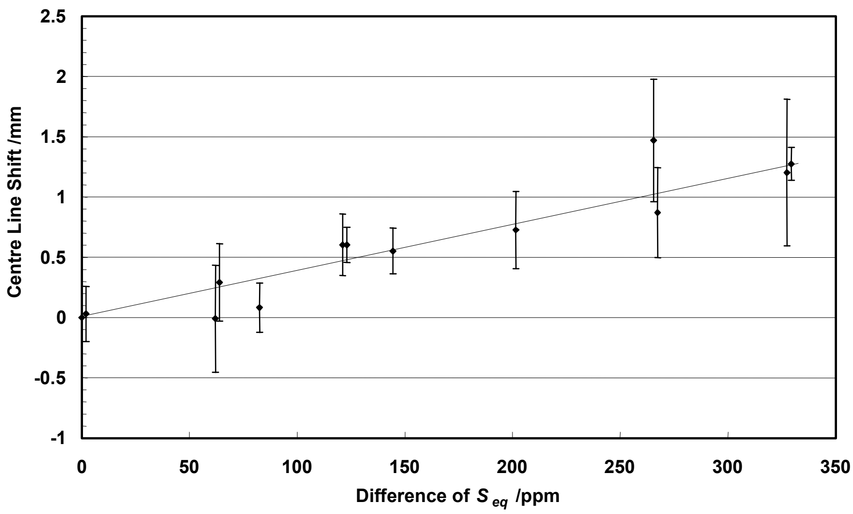


Figure 5: *Centre line shift as a function of the difference in equivalent sulphur content of the welded materials. The centre line shift is positive when the weld pool is displaced towards the material having the lower S_{eq}. The difference in S_{eq} is always positive.*

Figure 5 shows the dependence of the centre line shift measured at different points of the welds performed in the present campaign, on the difference of S_{eq} between the two products assembled together. As expected from the results in Table 4, the dependence has a roughly linear behaviour. According to Figure 5, the critical difference of S_{eq} above which an off-centre weld is significant can be roughly situated between 80 ppm and 200 ppm.

Nevertheless, the interpretation of the shift on the basis of the difference between one surface active element (S) or a linear combination of two of them (S_{eq}) can only be a first guess and might not be totally exhaustive [16]. Only the fraction of surface-active elements which are available in solid solution contributes to the penetration. When alloyed with other elements (e.g. to form inclusions), they have no effect on surface tension. Weight factors for the calculation of S_{eq} are different according to authors. According to Burgardt and Campbell [11], the factor would be 1 for S and 0.5 for O. Finally, the measurement of the average CLS is based on measurements that are accurate only within ± 0.25 mm. On this basis, the dependence shown in Figure 5, although based on a relatively large number of accurate experimental data, on several steel products and in full agreement with the linear dependence assessed by Tinkler [16], should be considered only as semi quantitative.

4.2 Corrective actions

A corrective shift of the weld line could be envisaged on products of known surface-active element content. This solution is unsafe since it has been demonstrated that the shift gradually increases, is sometimes unstable and not easy to predict on the basis of material certificates which do not normally contain quantification of several surface active elements. The following three alternative solutions could be envisaged:

1) Specify strictly controlled limits for S.
2) Add copper heat sinks around the tubes to be welded [16].
3) Use a shielding gas mixture Ar + 1 % O_2 [16].
4) Use a shielding gas mixture Ar + 2 % H_2 and/or an electrode with a larger tip angle.

Solution 1 would be restrictive, if intended in the sense of reducing to very low levels the amount of acceptable S content, since international standards allow for relatively high maximum S (150 ppm to 300 ppm). Moreover, these standards do not require quantification of O. It would be expensive to specify severe restrictions. On the other hand, specifying a minimum and maximum limit for S is admitted by the standard (e.g. EN 10088-3 recommends to specify 150 ppm ≤ S ≤ 300 ppm for products that have to be machined). In this case, care must be taken in order to avoid that such high S contents can induce hot cracking in fully austenitic autogeneous welds (316LN grade). From the result of this study we suggest, when a selection is possible between different material sources, to select product couples to be welded together of low S content and for which the difference of S_{eq} does not exceed 80 ppm.

Solution 2 might be useful when there is limited or no freedom in product selection. If $d\gamma/dT$ is imposed, the idea is to act on the temperature gradient ∇T. Asymmetrical convective flows induce asymmetrical temperature gradients and preferential melting of one of the two products. By positioning heat sinks on both sides of the weld seam, the heat transfer would be better balanced and the shift of the weld pool reduced to negligible values. This solution has been effectively applied to control weld pool shifts and irregular penetration in 304L tube welding [16]. The limits of this solution are the sensitivity to surface contact conditions and space requirements, which make it inapplicable to the welding between the tubes and the nozzles of the end cover.

Solution 3 has been reported as significantly reducing the weld pool shift [16]. Oxygen additions in the shielding gas is known to reduce surface tension. The oxidised aspect of the weld and the possible presence of oxide inclusions reducing toughness at low temperatures make this solution inapplicable for our purposes.

The use of an electrode with a larger tip angle, associated with hydrogen in the shielding gas (solution 4) reduces the weld shift by concentrating the heat flow and reducing heat dispersion.

5. CONCLUSIONS

The shift of the weld pool observed experimentally when welding dissimilar products of 316L-type stainless steel can be entirely interpreted in terms of different content of surface-active elements. This result confirms previous findings of several authors and demonstrate that the interpretation also applies to products obtained from very different fabrication methods (cast, powder metallurgy, forged, rolled and welded).

Sulphur and oxygen are the surface-active elements playing a major role for the products considered. When merely considering penetration, other elements (e.g. Si) are suspected to contribute to this phenomenon, since one of the studied grades, although nominally containing high S_{eq}, behaves mainly as a LS product. As well, the oxygen available in solid solution might be only a fraction of the nominal O content in the PM product, which shows for these reasons a weld penetration typical of a LS grade.

A S_{eq} could be defined as a linear combination of S and O contents. The shift of the weld pool is linearly dependent on the difference between the S_{eq} content of the two products. Specifying or selecting, whenever possible, product couples showing a small difference in S_{eq} and containing overall reduced surface-active elements would be the safest way to guarantee uniform weldability. If this cannot be achieved, possible alternative solutions are critically discussed.

6. ACKNOWLEDGMENTS

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