CRACKING FACTORS EVALUATION ON FLASH-BUTT WELDING OF 600 GRADE DUAL PHASE STEEL

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Abstract: *A general evaluation of involved factors on Flash-Butt welding (FB Welding) of 600 Grade Dual Phase Steel (DP600 Steel) is intended, contrasting cracking issues on affected and non-affected welded zones. The first part focuses on the DP600´s mechanical behavior dependent of micro-constituents Ferrite and Martensite, this part also mentions DP600´s chemical composition and thermo-mechanical fabrication process highlights. In a second part, effects of heat input on welded region are presented, showing the relationship between material toughness and thermic affected regions. Finally, the brittlening effect of impurities and inclusions like contaminants on welded regions are sited. In addition, heat treatment is presented like a potential solution to avoid brittle welded regions.*

Key words: *Flash-Butt Welding, Dual Phase Steel, Cracks on Welded regions*

1. INTRODUCTION

For automobilist industries, increasing energy efficiency and reducing emissions levels maintaining quality parameters and safety criteria have been turned a priority necessity; new generation cars are built using Advanced High Strength Steels (AHSS), which are stronger and lighter than older ones. Chenyao et al. (2016) state that Biphasic AHSS reach an equilibrium between fabrication costs and favorable mechanical properties (very good absorption of deformation energy); however, brittle properties when welding.

It is intended to study the brittlening factors into the FB welded region and process, using DP600 steel.

2. BIBLIOGRAPHIC REVIEW

2.1. Dual Phase Steel: DP600

2.1.1. State of the art

Avramovic et al. (2009) indicate that Dual Phase steel mechanical properties are commonly high-grade tensile stress coupled with very good capability of deformation because of a complex interaction between flow (deformation) and hardening into the principal microstructural components: Ferrite and Martensite (and tiny portions of Bainite and retained). Martensite islands into a Ferritic matrix corresponds to the harder (and brittle) phase; Ferrite is the ductile and tough phase. Revilson et al (2011) state when mechanical solicitations, brittle cleavage cracks are present on the Martensitic regions but ductile and high deformation fracture on the Ferritic regions.

Uthaisangsuk (2011) shows that morphology of Martensite also affect the mechanical behavior: Fine fibers of Martensite into the Ferrite grain boundaries allow better stretching material. There exists a huge quantity of mobile discordances produced on the Martensite-Ferrite interface, because of a volumetric expansion (shear deformation) during the Austenite-Martensite transformation when super-cooling (fabrication process). In this case, a better aging property allows better deformations distribution, delaying the failure appearing.

Recently, Caetano (2015) expresses that DP manufacturing process consists on: Hot rolling (higher temperature than intercritical range, approximately 870°C), with rigorous control of chemical composition; Intercritic normalizing (phase transformation); and finally quenching to 599°C, using water as cooling fluid (here the required microstructure is formed).

Avramovic et al. (2009) indicate on Figure 1 an image of DP600 steel microstructure etched portion (Nital treatment) using a Scanning Electron Microscope (SEM), where morphological characteristics of Martensite are revealed.

Figure 1: DP600 characteristic microstructure

Güngor et al. (2010) indicate some technical disadvantages on DP600 applications: Low dimensional precision accuracy; angular distortion before pressing; stronger press machines are required; shorter matrix and dies expected life; and higher frequency of cracking on welded regions. This final disadvantage is the focus on the present paper.

2.1.2. Chemical composition

Güngor et al. (2010) indicate that an important parameter that determines DP Steel´s mechanical behavior is the chemical composition. These steels are characterized by low concentration of Carbon and additions of Manganese, Chrome and Molybdenum. Addition of alloying elements is important to improve the homogenous grain growth, speed of nucleation and improve cooling rates, avoiding undesirable micro constituent formations. Table 1 shows different DP600´s chemical composition from eight different researchers:

Table 1: Weight percentage DP600´s Chemical compositions.

ELEMENT	1	2		3	4	5	6	7*		8
Carbon, C	0.120	0.070	0.106	0.093	0.062	0.051	0.072	0.070	0.050	0.072
Manganese, Mn	2.000	1.840	1.530	1.930	1.150	1.025	1.180	1.660	1.600	1.537
Molybdenum, Mo	0.200	0.150	0.220	0.880	-	0.059	0.010	0.160	-	0.003
Silicon, Si	0.500	0.900	0.201	-	0.020	0.287	-	0.010	0.490	0.491
Phosphorus, P	0.090	-	-	0.014	0.045	0.009	0.017	0.019	-	0.018
Sulfur, S	0.015	-	-	-	0.004	0.002	0.060	0.005	-	0.001
Aluminum, Al	0.020	-	-	0.034	0.028	0.035	0.057	0.043	0.033	0.041
Nickel, Ni	0.012	-	0.030	-	-	0.139	-	0.020	-	0.005
Nitrogen, N	-	0.010		-	-	-	0.005	0.006	-	-
Chrome, Cr	1.000	0.030	0.190	0.022	0.550	0.406	-	0.030	-	0.277
Cooper, Cu	1.500	-		-	-	0.160	-	-	-	0.007
Titanium, Ti	-	0.010	0.018	-	-	0.003	0.001	<0.005	-	0.002
Niobium, Nb	-	-	-	-	-	-	0.002	0.015	0.025	0.022
Vanadium, V	-	-	-	-	-	0.001	0.003	<0.005	-	0.002
Stain, Sn	-	-	-	-	-	0.014	-	-	-	-
Cobalt, Co	-	-	-	-	-	0.009	-	-	-	-
Tungsten, W	-	-	-	-	-	0.002	-	-	-	-
Zinc, Zn	-	-	-	-	-	0.003	-	-	-	-

*This reference uses RS590CL steel, with practically the same chemical composition of DP600 steel (Except by the Molybdenum); on welding toughness tests, both have nearly the same behaviors.

1. Milan et al. (2010)
2. Avramovic et al. (2009)
3. Surajit et al. (2015)
4. Rosenberg et al. (2013)
5. Tiziani et al. 2011
6. Mihaliková et al. 2015
7. Chenyao et al. 2016
8. Revilson et al. (2011)

Kuziak et al. (2008) demonstrate that Carbon is important to control the hardening capability of DP steel, it also determines morphological properties of Martensite. On DP steels, between 0.060% and 1.500% Carbon content by weight is a typical interval, because of welding capabilities: the more Carbon content, the more brittle welded region. Table 1 shows pretty the same interval range (0.050% - 0.120%).

Kuziak et al. (2008) state that Manganese is usually present on chemical composition of DP steels, if not, same content of Nickel can be found (sometimes both; Manganese is cheaper than Nickel). Both elements perform like Austenite stabilizers. On literature, the interval of content by weight is 1.500% and 2.500%. Table 1 Manganese content is between 1.025% and 2.000% apparently different from literature data; however, Nickel content is 0.139%, certainly the manufacturer criteria were achieve a combined effect of both stabilizers elements. Calcagnotto et al. (2012) made some practical tests showing that insufficient quantities of Manganese and/or Nickel affects the hardening capability and allow a faster Ferrite grain growth at the intercritic tempering process (worst energy absorption capability). On the other hand, the contrary case is also negative, do not allowing Ferrite grain to growth, increasing the Martensite segregation.

Güngor et al. (2010) studied Chrome and Molybdenum, until 0.400% they perform like Ferrite stabilizers and Perlite/Bainite formation delayers. These two elements allow a high hardening capability. Table 1 shows Chrome exceed at two opportunities reference data, the first time with 0.550% and the second time with 0.406%.

Marra et al. (2008) defined as reference data: Vanadium at 0.060% and Niobium at 0.040%, both as Ferrite stabilizers. The first hardens the material by allowing aging, and the second one allows a very fine microstructure. Table 1 shows smaller percentages by weigh in both cases, compared with reference data.

Marra et al. (2008) also defined as reference data: Silicon at 1.000%, which downs Carbon solubility on Ferrite, and allows a denser melted metal on welding process. Table 1 shows almost the same values from reference data.

2.1.3. Mechanical properties and Metallography

Adaptation from Surajit et al. (2015) exposes Figure 2. Using a SEM, it shows Martensite morphology variation depending of their volumetric fraction. These variations, as mentioned, are strongly related with mechanical behavior.

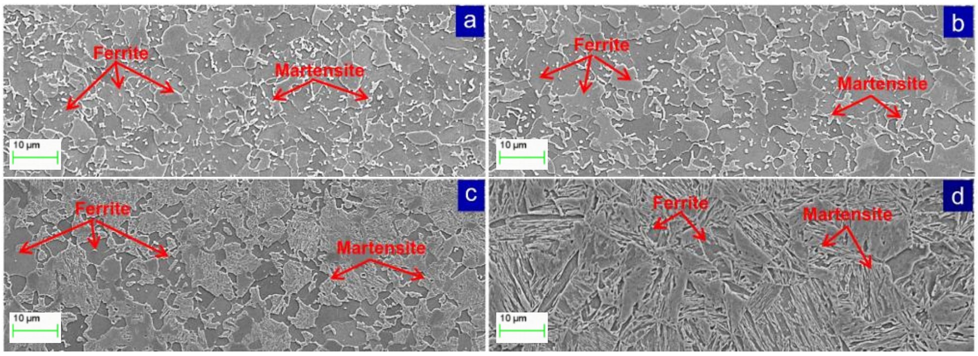

Figure 2: DP600´s microstructure, four Martenite contents: A) 13%, B) 20%, C) 49% and D) 88%

Table 2 presents DP600´s mechanical properties compilation from different authors.

Table 2: DP600´s mechanical properties compilation

MECHANICAL PROPERTIES	1	2	3	4			5	6	7
				B	C	D			
Yield Tensile Strength [MPa]	350 450	380 470	-	350 400	500 550	750 800	410	300 380	347
Ultimate Tensile Strength [MPa]	575 595	580 670	660 670	750 800	950 1000	1200 1250	617	620 655	561
Uniform Strain [%]	29 32	24	-	8 9	11 12	15 16	29.5	27	-
Martensite [%]	-	-	31.9	20	49	88			11.6

1. Chenyao et al. (2016)
   - RS590CL steel.
2. Milan et al. (2010)
3. Rodrigues et al. (2014)
4. Surajit et al. (2015)
   - **A** steel is not presented.
5. Rosenberg et al. (2013)
6. Revilson et al. (2011)
7. Mihaliková et al. (2015)

Confirming reference data, and as showed on previous table, 600 Grade DP steels have its name because of their approximately ultimate tensile stress of 600 [MPa]. Filho et al. (2011) state: The higher Martensite volumetric fraction, the higher the tensile strength; up 20% volumetric fraction of Martensite steels have a higher grade, for example DP780. From practical data, using a SEM, DP600 steel has around 19% volumetric fraction of Martensite.

2.2. Flash-Butt Welding

2.2.1. DP steel welding

Ramazani et al. (2013) deduce that three basic regions can be distinguished on metallic materials welding: Base Metal/Material (BM), which is the unaffected material (in some point only heated but with no phase changes); Heat Affected Zone (HAZ), not melted region but with microstructural changes; and Melted Zone (MZ), or also called Fusion Zone (FZ). Figure 3 shows schematically regions/zones distribution on a Laser welded metal:

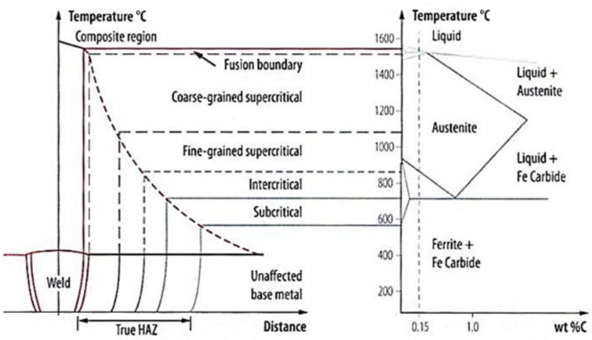

Figure 3: DP600´s laser welded regions

There is no difference between heat affected regions distribution, because heat dissipation is kindly the same independent from the welding method; some proportions may change, but generally this distribution is pretty the same. Diogo et al. (2012) made a comparison with Fe-C phase diagram, as Figure 3 shows; here it is made a reference to the microstructural changes according with the temperature path, which depends of the welding heat input.

2.2.2. DP steel Flash-Butt welding characteristics

Chenyao et al. states that Flash-Butt welding method is highly efficient. Nowadays it is applied on automobile industry, train railroad repairing and other diversely applications. However, until today exists some issues to be resolved, especially related to defects and brittlening on welding regions. Çentikaya et al. (2006) determine that some important parameters involved on welding quality are these: Applied electric current; Flash modulation; pressing/forging applied force; and effective welding interface dimensions. These parameters are also complexly involved with defects and inclusions. Weld toughness is strongly compromised depending on Çentikaya´s parameters.

Recently Prince (2016) studied that joining pieces using FB welding occurs by the combination of the generated heat input because of Joule effect (high electric current, small interface resistance) and the applying force (like pressing) between piece´s faces; basically, joining is possible by forging melted faces.

Chenyao et al. (2016) generate Figure 4, which shows schematically the steps on FB welding process. Heat input, generated by passing high electric current (generally at low voltages), redefines the microstructure on the HAZ but especially on the remaining FZ (there is some lost material: some melted, some expulsed in form of sparks). When flashing, temperature increases exponentially, then the pieces are pressed together being permanent deformed (plastic deformation), new interatomic junctions are formed (this can be assumed as forging).

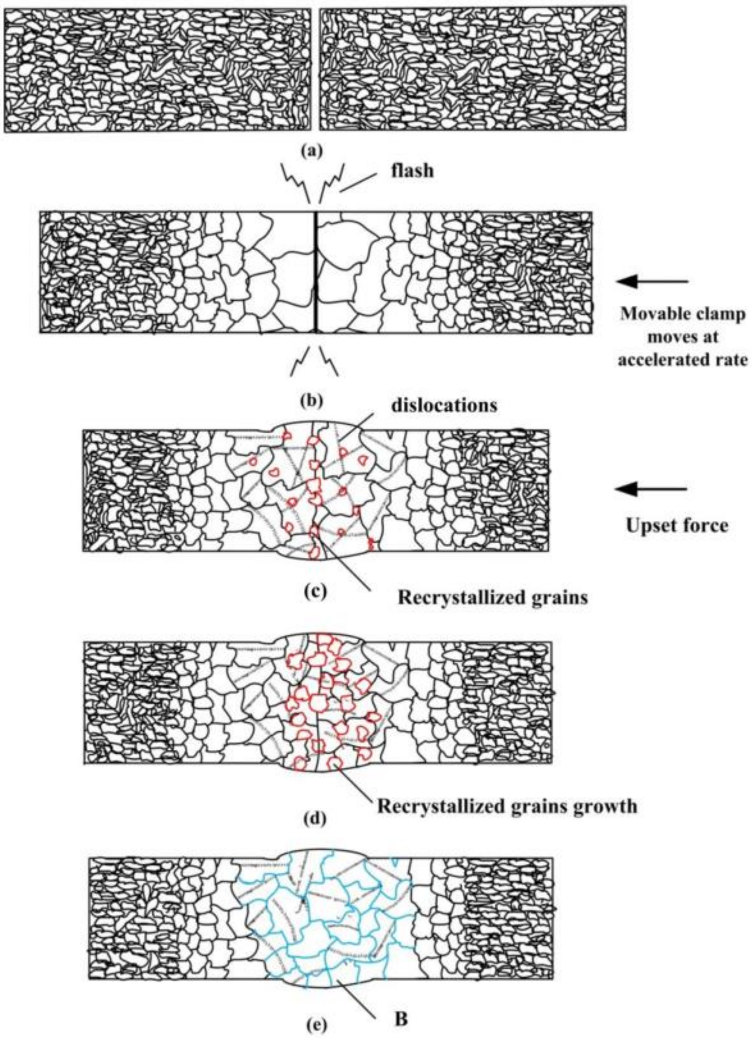

Figure 4: Flash-Butt welding schematic steps

Commonly, micro hardness distribution of welded steels shows this "hat" pattern (depending of the steel type and some conditions the hat shape must change). According to Chenyao et al. (2016) on Figure 5, WZ means Welded Zone, and FZ corresponds to the HAZ before the only heated base metal. It can be noted that micro hardness is not very much sensible to applied upset force variation (Fu). Qiu et al. (2004) states that in practice, micro hardness distribution can be assumed as symmetrical from the welding interface.

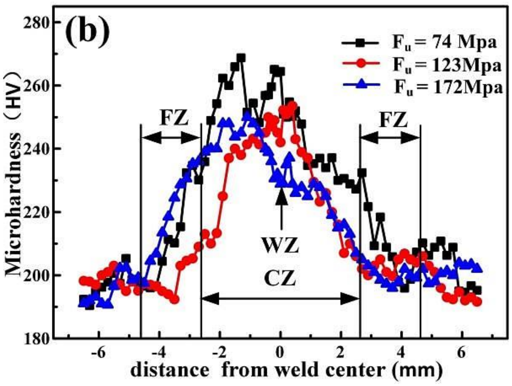

Figure 5: Micro hardness distribution by changing the upset force

Zrilic et al. (2007) state that tensile strength and other mechanical solicitations (e.g. Fatigue) are limitative patterns on welding quality. In order to clarify this last affirmation, Figure 6 and Figure 7 are presented; these show the typical morphology of failures on ductile case (Base Metal) and brittle case (Fusion Zone and/or Heat Affected Zone).

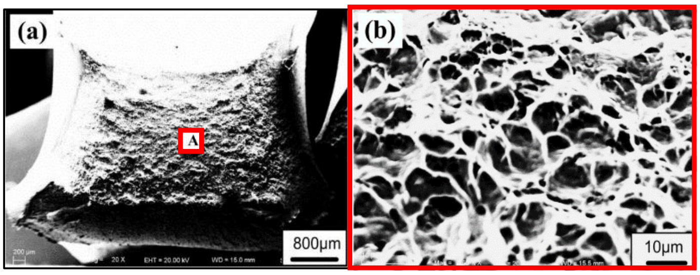

Figure 6: Ductile failure, base metal region

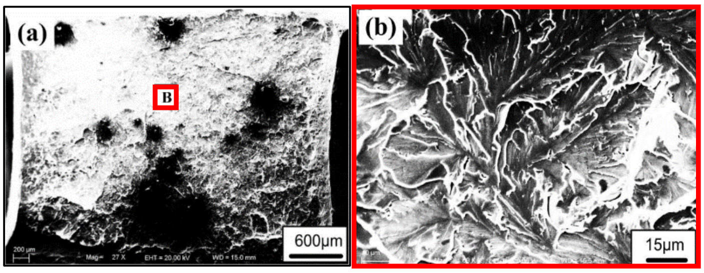

Figure 7: Brittle failure, fusion zone on FB welding

According to Chenyao et al. (2016), Figure 6 a) shows a fibrous failure face, at boundaries can be distinguished a considerable plastic deformation. At zoom **A**, Figure 6 b), are shown the micro dimples of fibrous morphology. In contrast, Figure 7 a) shows a pure brittle failure, also commonly known as cleavage cracking morphology. Ichiyama et al. (2007) focus the problem on HAZ and FZ – weld defects and welder machine calibration are important – there are studies about that, but only few can describe precisely the toughness on welded regions.

2.3. Cracking considerations

2.3.1. Effect of chemical composition

Ichiyama et al. (2007) studied that high Carbon content allows brittle formations on the HAZ and FZ. Manganese (which improves hardenability), Silicon (which improves the regulation of Carbon solubility on Ferrite), and Aluminum, allows brittle oxides formation, harming welding quality. These oxide formations are formed when flashing, fraction of them stay on welding faces until upset force is applied; even when pressing, a few oxide formations can´t be ejected, solidifying as defects and allowing a brittle welded region behavior.

2.3.2. Effect of impurities and inclusion on microstructure

Practically, cracks can be generated by two factors: Limitation of mechanical properties and/or microstructure defects, that harms mechanical properties; on this paper, impurities and inclusions are defined as microstructure defects. An inclusion is an undesired formation of alloying elements, like oxides or non-homogenous Martensite/Ferrite grain growth; an impurity consists on estrange elements, different from alloy constituents.

According with Herbert et al. (2006), when welding using electrodes, there are some impurities on electrode´s coating, contaminating and brittlening the welding zone; however, even on FB welding there are no electrode´s coating, it is very difficult to handle a complete control of impurities on steel fabrication process. Oils, coatings, and other combined compounds are potential contaminants on welding process; they are fonts of diffusive hydrogen that allows impurities and a huge sort of brittle undesirable formations.

Recently, Chenyao et al. (2016) generated Figure 8, which is related whit Figure 7 b), that shows the morphology of two different cracked faces on the ZF of DP600 FB welding. Oval form oxide formations can be distinguished; an Energy-dispersive X-ray Spectroscopy (EDS) determine the presence of Oxygen and Iron on Figure 8 c) oxide formation, and the same but additional Aluminum on Figure 8 d). Oxides and inclusions are very brittle performing like stress concentrators. Therefore, reduced toughness on welding can be caused by retained oxide formations (retained because of they are not properly ejected on flashing), coarse grain Bainite (as an undesirable formation), and other dismissing inclusions and impurities.

Ichiyama et al. (2007) state that when flashing, little cavities are formed, which contains melted metal and possibly impurities and formations; if welding energy on flashing is properly managed (by an automatic feedback control system) these undesirable formations can be ejected. When pressing is applied, the undesirable formations (those that could not be ejected on flashing) are expelled through melted metal.

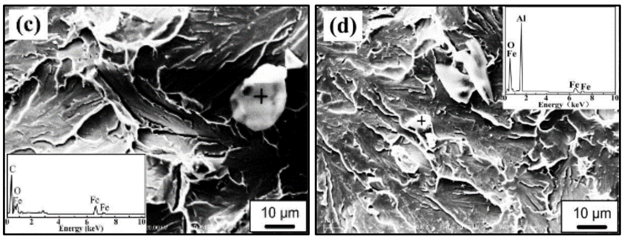

Figure 8: Fusion zone failure morphology

2.3.3. Effect of heat input and cooling rate

According to Herbert et al. (2006), on FB welding, thermal cycles affect HAZ (and obviously FZ) that changes the microstructure and the mechanical behavior. Chemical composition, cooling rates (at Austenitic-Martensitic transformation range) and heat treatment have a huge influence on microstructure.

Ichiyama et al. (2007) state that pre-heating also has a considerable impact on heat affected zones microstructure. Figure 9 shows the favorable effect of pre-heating (heating before Flash-Butt welding). Mechanical behavior of final material (BM + HAZ + FZ) presents a better resistance against crack growth.

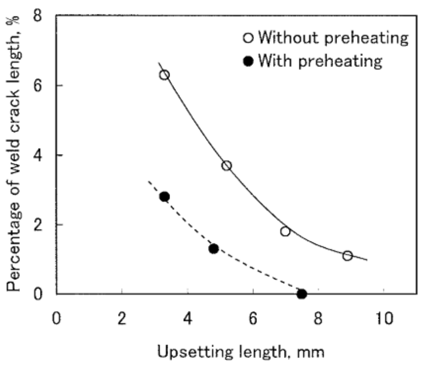

Figure 9: Percentage of weld crack length vs upstting length for different pre-heating

Ichiyama et al. (2007) also generates Figure 10. which presents a comparison between cross-sectioned welded regions with and without pre-heating; both were pressed with the same upsetting force. A third lip appears on the burr when pre-heating is applied; this helps to oxide (or other impurities and/or inclusions) ejection. Furthermore, according to the same author, at the same figure can be perceived the next facts: Grain Growth; Coarse Bainite Formation; and crystalline texture with grain orientation change.

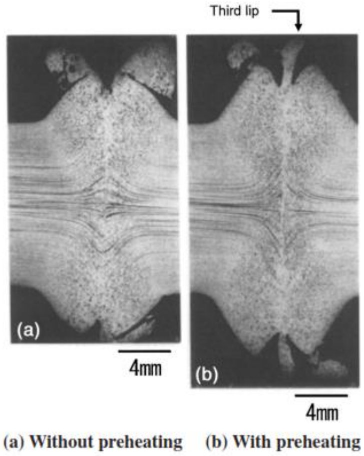

Figure 10: Pre-heating effect and burr lip formation

3. DISCUSSIONS

Describing welding parameters effect on welding toughness behavior is a complex work. An optimal combination of flashing input energy (electric energy input, presented in form of heat), upsetting force/length (mechanical energy input), and effective times (times between operations) can perform in a favorable way, in order to eject impurities/inclusions, promoting a high quality FB welding. In practice, this issue is quantitatively complex to develop.

Perhaps, even the complex model, FB welding needs to control internal processes like Martensite and retained Austenite formation/dissolution. In order to simplify the problem, it can be stated that controlling the input energy, to generate a specific temperature profile on time, micro structural phase transformations are indirectly controlled; final welding microstructure defines its mechanical behavior (frequency of cracking).

Heat treatment allows better micro structure organization, which means better mechanical behavior against any solicited stress field. Normalizing, or other kind of heat treatment can emerge as a potential solutions avoiding cracks.

3.1. Final remarks

About DP600 steel: Mechanical behavior depends exclusively of micro constituent's interaction: Martensite and Ferrite matrix; while and after welding, this mechanical behavior may change, because a different proportion between these phases and the heterogeneity through all heat affected regions. Cracking tendency turns worse than initial condition.

Before welding, microstructure and micro constituent´s morphology depend of chemical composition (alloying elements addition) and thermo mechanical cycles (fabrication process); while and after welding, chemical composition can be assumed to remain constant (even this fact is not necessary true at all points), but microstructure and phases morphology may change because welding thermo mechanical cycles. Cracking tendency is related to these cycles.

It is not intended to change DP fabrication process, either mechanical behavior or microstructure; these are starting points to develop future evaluations, focused on cracking tendency. Values from Table 1 and Table 2 (and related insinuated data) should be a reference to describe base material properties before welding.

About DP600 steel FB welding: Mechanical behavior, microstructure and morphology may change before while and after welding; chemical composition is assumed to maintain a constant proportion. These changes are strongly related to welded region quality (frequency of cracks); temperature profile (thermo mechanical cycles), which generates phase changes distributed in heat affected regions, is directly related with welding toughness; in practice, is reasonable to modify welding parameters than modify steel properties.

Electric energy input (as generated heat) is strongly related to final hardness and frequency of cracking, not only the quantity, but also the way that this energy is applied; good calibration of electric welding parameters should improve the quality of welded regions, particularly on brittle regions. Mechanical energy input (as pressing) is weakly related with hardness. Even do, both belongs to a complex thermo mechanical process. Future works will tend to simulate this process.

About failure and cracking: Some alloying elements allow undesirable micro formations, which harm welded region quality. But as briefly stated, it is not intended to change steel initial properties, either chemical composition; the solution to cracking issues begins from optimizing welding parameters and techniques.

If flashing or pressing procedures are optimized, most (if not all) of undesirable while welding formations will be expelled. These procedures are strongly dependent of the welder machine and its calibration. A smart manage of heat input (quantity of energy and way of application), can prevent inclusions; but not impurities completely. Good welding techniques (as clean dies, electrodes in good condition of operation, dry environment by shielding or by gas burning, no coats either protective oils, etc.) can improve impurities formation.

If inclusions and impurities issues were satisfactory resolved, remain problem resumes on after welding brittle phase formations. Relative fast cooling rates promotes brittle formations like Martensite. Localized heat treatment (on heat affected zones and fusion zone only), as Pre and Post procedures (heating or retarded cooling procedures), are potential effective solutions in order improve welding toughness avoiding brittle phases formation.

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