Effects of different welding technologies on metallurgical anf mechanical properties of DP600 steel welded joints

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Considering the safety standards required in the automotive industry, dual phase (DP) steels have gained their popularity thanks to their higher tensile strength in conjunction with superior formability if compared to the steel grades of similar yield strength. Such properties are related to their microstructure which consists of soft ductile ferrite matrix, strengthened by hard martensitic phase.

It is well known that welding processes play an important role in the automotive industry. While the conventional arc-welding processes are well-established, flexible and easy to automate, high power density processes guarantee low distortions, narrow fusion and heat affected zones.

The performance evaluation of welded automotive components made in DP steels, with respect to durability or crashworthiness, involves the quantification of the properties change of the welded joint. This work is aimed at evaluating the effects of three different welding technologies (GTAW, PAW, EBW) on DP600 steel properties. In particular, the soundness, the fusion and heat-affected zone microstructure, and the mechanical properties of the welded joints are analyzed and compared in detail.

KEYWORDS: Advanced High Strength Steels, DP600, electron beam welding, gas tungsten arc welding, plasma arc welding, metallurgy, mechanical properties

INTRODUCTION

Advanced high strength steels (AHSS) were developed in order to meet the increasing requirements of weigh reduction in many engineering applications. Their final microstructure is usually a composite of relatively soft ferrite matrix with strengthening phases (martensite, bainite, precipitates). Thinner sheets can possibly be used in automobile bodies since AHSS have better impact energy absorbing capacity and resistance to plastic deformation with respect to conventional ferritic low-carbon sheet steels. In general, weigh reduction involves less material purchased, less production energy, less CO_2 emissions, less inertial loads and, finally, less environmental harm. The increased formability of these steels allows for greater part complexity, which leads to fewer individual parts (cost savings) and more manufacturing flexibility.

AHSS are typically produced by nontraditional thermal cycles and contain microstructural components whose mechanical properties can be altered by exposure to elevated temperatures. This temperature sensitivity could alter the mechanical behaviour of AHSS after welding. Thus, the weldability is one of the main technological properties that has to be investigated in order to correctly use such materials in structural and mechanical applications.

The fusion welding processes have historically been, and they are today, commonly used in manufacturing of automotive structures. Recently, the increased use of AHSS in automotive design posed a desire to evaluate the application of fusion welding processes relative to the joining of AHSS.

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Even if the weldability of DP600 is well known in the industrial world, works about this objective are difficult to find in the academic literature. Most of them deal with dissimilar joints or laser welded joints. This is due to the fact that, among the welding technologies, the high power density processes have received attention because of good mechanical and metallurgical properties of the welded metals (narrow heat affected zone (HAZ) and fusion zone (FZ), low deformations).

In their work, Rizzi et al. [1] have studied the effect of laser welding on the microstructure of three AHSS: transformation induced plasticity steel (TRIP), dual phase steel (DP) and martensitc steel. For all the samples, the FZ was constituted by martensite and a continuous change in microstructure was observed along the HAZ. Due to the solidification undercooling the formation of austenite as primary phase was expected. Another interesting work was performed by Kang et al. [2] who investigated the characteristics of Nd.YAG laser welded 600 MPa grade TRIP and DP steels with respect to hardness, microstructures, mechanichal properties and formability. In both steels the hardness of the weld zone was increased. Martensite, ferrite and bainite were observed in the weld metal of TRIP, while acicular ferrite, bainite and martensite was detected in FZ and grain boundary ferrite and bainite in HAZ near the FZ of DP welded joints. In a tensile test perpendicular to the weld axis, all specimens were broken at the base metal and the tensile strength and yield strength were higher than those of the raw material but the elongation was lower. Finally, formability was determined to be approximately 80% as compared with the raw material. Mingsheng Xia et al. [3] investigated the effects of heat input on HAZ softening of three dual-phase alloys with ultimate tensile strengths ranging from 450-980 MPa. It was found that HAZ softening was a

C	Mn	Si	S	P	Cr	Ni	Mo	Al	V	Cu	Sn	Ti	Co	W	Zn	N	Fe
0,051	1,025	0,287	0,002	0,009	0,406	0,139	0,059	0,035	0,001	0,160	0,014	0,003	0,009	0,002	0,003	0,001	Bal.

TAB. 1 ***Measured chemical composition (wt%) of the material analysed in this study.***
Composizione chimica dell'acciaio DP600 analizzato (wt%)

function of both martensite content and heat input. In particular, maximum HAZ softening was proportional to the martensite content, and the heat input controlled the completion of softening. A more recent experimental work on laser welded DP steel joints was carried out by N. Farabi et al. [4]. They evaluated the microstructural change of the alloy after laser welding and its effect on the tensile and fatigue properties. According to the previous works, it was found a ductility decrease and a yield strength increase after welding. Although the fatigue limit of the welded joints was slightly lower than that of the base metal, the fatigue life at the higher level of stress amplitudes was almost the same within the experimental scatter between the base metal and welded joints despite the presence of the soft zone. Tensile fracture and fatigue failure at higher stress amplitude occurred at the outer HAZ.
To the best knowledge of the authors of this article, specific works about electron beam welding, plasma welding and arc welding of DP600 steels are still lacking in literature. In this work metallurgical and mechanical investigations were carried out on DP600 welded joints produced by means of electron beam, plasma and arc welding. A comparison among the three different technologies is made in terms of heat input, induced microstructures and mechanical properties.

EXPERIMENTAL PROCEDURES

Material and welding processes

The chemical composition of the DP600 steel analysed in this work is reported in Table 1. Tensile and thermal properties of this material are summarized in Table 2, where T_m is the melting temperature and T_{Ac1} is the Ac1 temperature which has been estimated by using Eq. 1, given by Krauss [5]:

$$A_{c1} = 723 - 10.7\,Mn - 16.9\,Ni + 29.1\,Si + 16.9\,Cr + 290\,As + 6.38\,W \quad (1)$$

Mechanical properties	Yield strength	434 MPa
	Ultimate strength	630 MPa
	Elongation at break	16%
	Young modulus	200 GPa
Thermal properties	T_m	1530°C
	T_{Ac1}	725°C

TAB. 2 ***Tensile and thermal properties of DP600 base material analysed in this work.***
Proprietà meccaniche e termiche del materiale base.

DP600 steel plates (2x100x210 mm) were butt-welded using three different welding technologies: Gas Tungsten Arc Welding (GTAW), Plasma Arc Welding (PAW) and Electron Beam Welding (EBW). The process parameters are listed in Table 3, and the heat input (HI) was calculated using Eq. 2 [6]:

$$HI[kJ/mm] = \eta \frac{V[V] \times I[A]}{v[mm/s] \times 1000} \quad (2)$$

where V is the voltage, I is the amperage, v is the travel speed and η is the thermal efficiency of the process which was estimated equal to:
- 0.5 for GTAW and PAW [7]
- 0.8 for EBW [8]

As well known, it can be noted, in Table 2, that the EBW process is characterized by the lowest heat input and the highest travel speed, while GTAW has the highest heat input and the lowest welding speed.

Metallurgical and mechanical investigations

Preparation of metallographic sections transverse to the weld bead consisted of silicon carbide paper grinding followed by diamond paste polishing. 2% nital solution was used to reveal the microstructure. Microstructural investigations were executed by Light Optical Microscopy (LOM) and Environmental Scanning Electron Microscopy (ESEM). The grain size and volume fraction of ferrite and martensite was evaluated carefully by means of a software for image analysis (LEICA QWIN) interfaced with the LOM. The final value is the average of at least 3 measurements at 1000x for grain size and 500x for phase distribution, for each zone considered (FZ, HAZ, parent metal).
Tensile tests were performed on welded specimens in order to compare the mechanical resistance of the different joints. Welded samples were machined perpendicular to the welding direction, and the geometry of tensile test samples is given in Fig. 1, according to UNI EN 895 Standards. Tensile tests were performed at room temperature using a fully computerized universal tensile testing machine. At least three samples were tested for each welding process. The 0.2% offset yield strength, ulti-

Process	Shielding gas	Filler metal	Current: Current type and polarity	Current: Intensity [A]	Voltage [V]	Travel speed [cm/min]	Heat input [kJ/mm]
GTAW	Argon 99.99%	-	DC-SP	64	9,1	5	0,35
PAW	Argon 99.99%	-	DC-SP	120	24,5	28	0,31
Process	**Shielding gas**	**Filler metal**	**High voltage [kV]**	**Beam current [mA]**	**Focusing current [mA]**	**Travel speed [cm/min]**	**Heat input [kJ/mm]**
EBW	-	-	150 ± 2%	7.5 ± 5%	367 ± 2%	54	0,1

TAB. 3 ***Welding parameters.*** *Parametri di saldatura.*

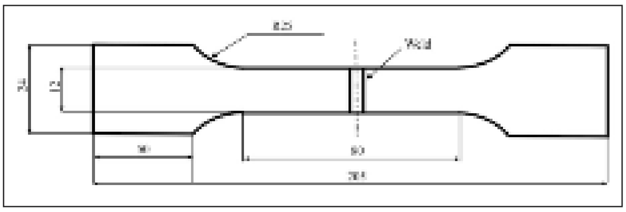


FIG. 1 ***Geometry of tensile test specimens used in the this study (dimensions are in mm).***

Geometria dei provini sottoposti a test di trazione utilizzati nel presente lavoro (dimensioni in mm).

mate tensile strength, and elongation at break were evaluated. Vickers microhardness tests were finally performed on the etched samples. A load of 100 g and a dwell time of 15 s were used during testing. The center point of the fusion zone was determined by carefully observing the weld geometry under microscope and all the indentations were adequately spaced to avoid any potential effect of strain fields caused by adjacent indentations.

RESULTS AND DISCUSSION

Metallurgical analysis

Aspect of the welded zones

In previous works about the weldability of DP steels, it was found that the sub-critical area of the heat affected zone softens during welding; this phenomenon (called HAZ softening) is caused by tempering of the pre-existing martensite in such zone [3,4,9,10].

Thus, to properly compare the effects of different welding processes on DP600 steel, the effects of different thermal cycles on bead geometry and HAZ softening must be taken into account. For this aim, the macrograph of each joint has been analyzed, and different zones were identified (Table 4):

- Fusion Zone (FZ): the area between the weld centerline and r_m, where the temperature exceeded the melting point (T_m);
- Heat Affected Zone 1 (HAZ-1): the area between r_m and r_{HAZ-1}, where the temperature reached values higher than the Ac1 temperature;
- Heat Affected Zone 2 (HAZ-2): the area between r_{HAZ-1} and r_{HAZ-2}, where the temperature didn't reach the Ac1 temperature;
- Parent Metal (PM): unaltered base material.

Table 4 shows that GTAW has the greatest influence on the welded joint macrostructure, while EBW assures the narrowest FZ and HAZ. The diagram reported in Fig. 2 shows the evolution of the geometric parameters collected in table 4 as a function of the calculated heat input.

A linear relationship between the calculated heat input and the corresponding extension of fusion and heat affected zones was found.

Microstructural analysis

The microstructures of the different welded joints are reported in Fig. 3 as a function of the welding technology and the distance from the weld centerline as indicated in table 4 (FZ, HAZ and PM).

PM has the typical dual phase structure, containing some islands of martensite (10-12% vol.) in a ferritic matrix (with an average grain size of 3 μm).

FZ and HAZ near the FZ (zone B in Fig. 3), are characterised by different structural micro-costituents (Figs. 3-4). A mixture of acicular ferrite, allotriomorphic ferrite and bainite was detected. As reported in literature, the acicular ferrite morphology is usually referred as a 'basket-weave structure' and it was observed to co-exist with other ferrite morphologies such as Widmanstätten ferrite, allotriomorphic ferrite and bainitic ferrite [14]. Due to the low heat input of the high density processes,

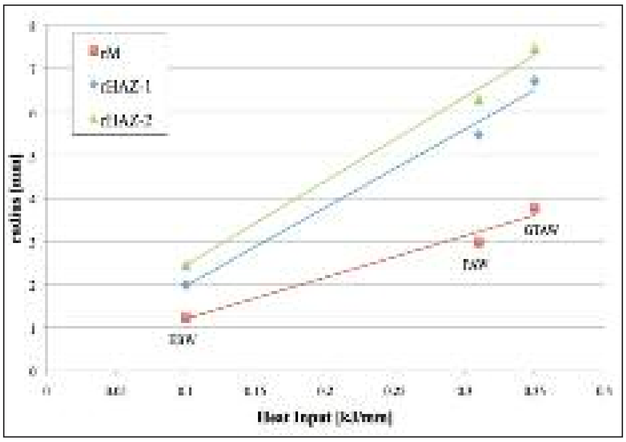


FIG. 2 ***Geometric parameters of cross sections vs welding heat input.***

Andamento dei parametri geometrici delle sezioni trasversali in funzione dell'apporto termico delle diverse saldature

TAB. 4 ***Cross sections and thermal/geometric parameters of the analyzed welded joints.***

Sezioni trasversali e parametri termici/geometrici dei giunti in esame.

	GTAW	PAW	EBW
r_m [mm]	3,8	3,0	1,25
r_{HAZ-1} [mm]	6,7	5,5	2,0
r_{HAZ-2} [mm]	7,5	6,3	2,49

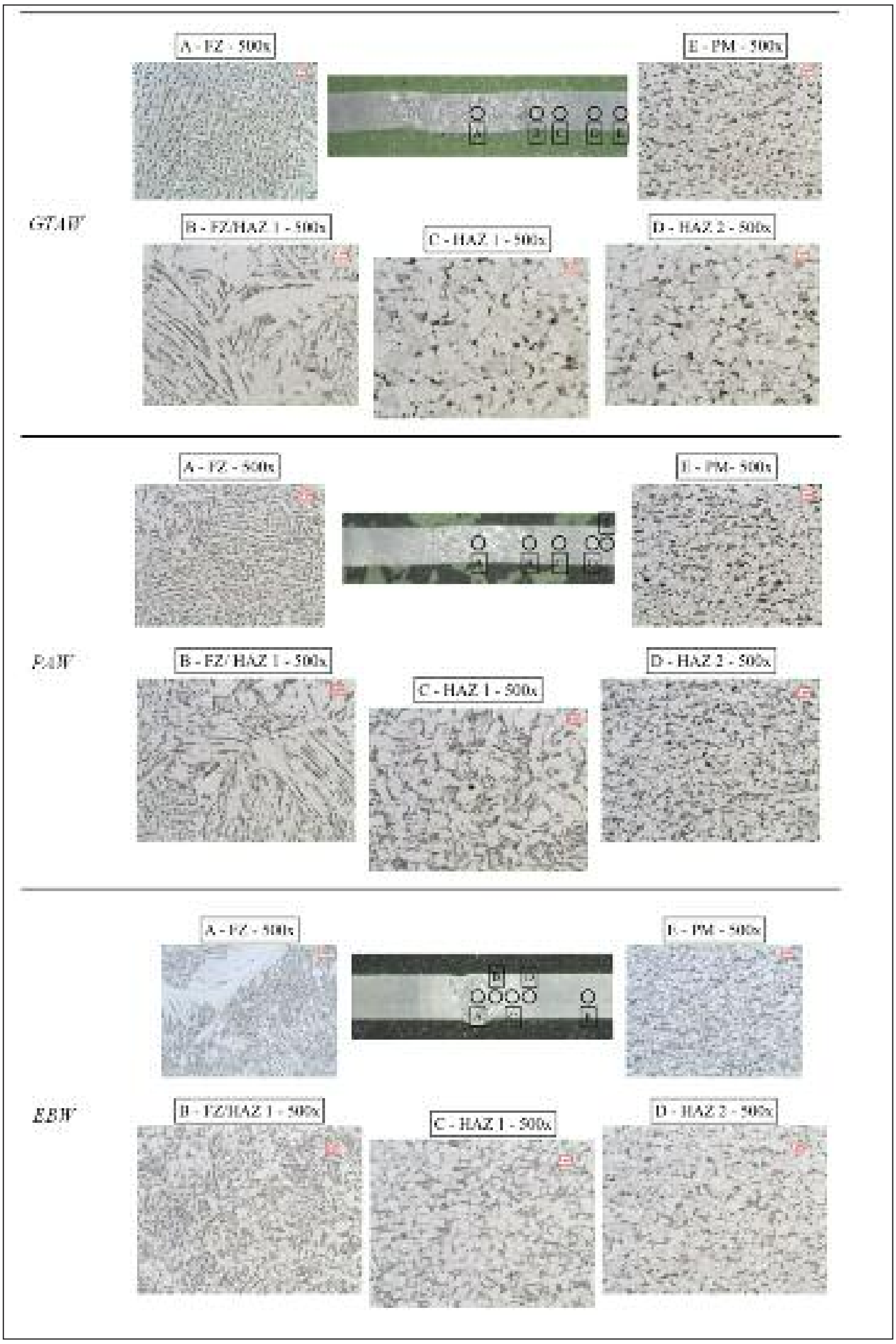


FIG. 3
Microstructure characteristics of the analyzed welded joints (FZ = fusion zone, HAZ = heat affected zone, PM = parent metal).

Caratteristiche microstrutturali dei giunti analizzati (FZ = zona fusa, HAZ = zona termicamente alterata, PM = metallo base).

FIG. 4 ***Fusion zone microstructure: a) GTAW, b) PW, c) EBW.*** *Microstruttura della zona fusa: a) GTAW, b) PAW, c) EBW.*

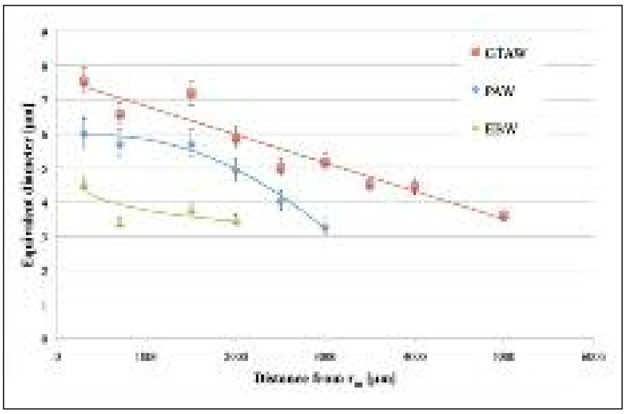


FIG. 5 ***Grain size evolution as a function of the distance from FZ.***

Evoluzione della dimensione del grano in funzione della distanza dalla zona fusa.

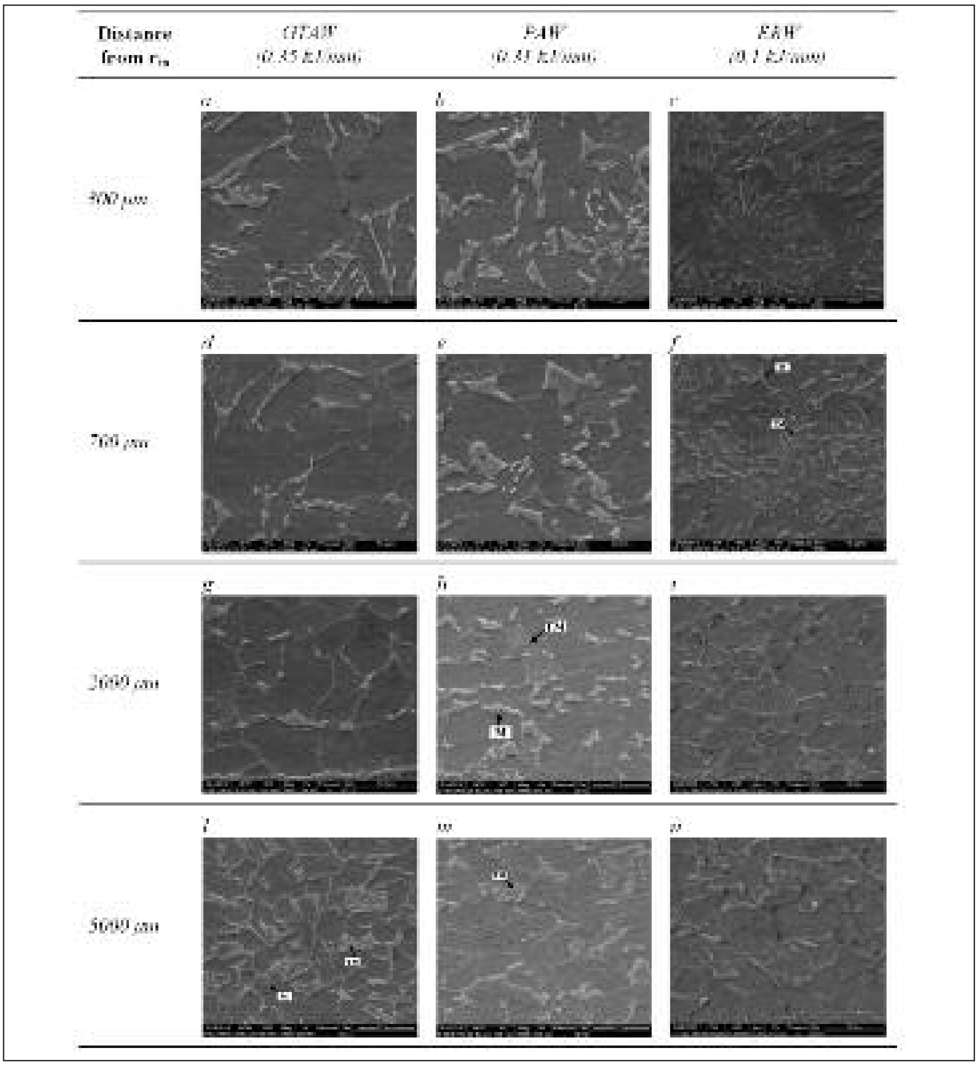
only a partial austenitization was observed in zone B of the electron beam welded joint.
In particular, in Fig. 4, thanks to the presence of allotriomorphic ferrite, a coarser primary austenitic microstructure can be observed in FZ of arc welded joints which promoted a greater percentage of acicular ferrite compared to the others welded samples [14-16]. It is important to note that acicular ferrite has been known to be the most desirable microstructural constituent in steel weld metals because its presence directly correlates with improved toughness [15]. The presence of acicular, bainitic and allotriomorphic ferrite in FZ is probably due to a rapid cooling rate combined with the low carbon content of the analysed alloy, compared to other DP600 steels chemical composition [2,4]. Ferrite grains result to be coarser in correspondence of HAZ-1, especially for the samples obtained with GTAW, which is characterized by the highest heat input; on the other hand, EBW guarantees the minor upsetting of the welded joint microstructure. Such differences are plotted in the diagram of figure 5, which shows the evolution of the equiaxed ferritic grain size as a function of the distance from fusion zone for each welding process.
It can be noted the lowest impact on the initial dimension of ferrite grains induced by EBW. On the other hand, according to the heat input, GTAW induces the largest variation of the grain size. The HAZ microstructure as a function of the distance from FZ is also shown in the ESEM images of Fig. 6.
In each sample, HAZ microstructure is constituted by ferrite and martensite islands; some tempered martensite has been also detected in all the specimens, at different distances from r_m, depending on the welding process (see Figs. 5 f-h-l-m) [4].

Mechanical properties

Fig. 7 shows the micro-indentation hardness profiles of the joints analysed. The obtained results are coherent with the metallographic observations. The highest hardness values in FZ are due

FIG. 6
Secondary Electrons (SE) micrographs showing the microstructural change of the analyzed welded joints as a function of the FZ distance - 7000x (M = martensite, TM = tempered martensite).

Micrografie ESEM che illustrano le variazioni microstrutturali nei giunti saldati analizzati in funzione della distanza dalla zona fusa - 7000x (M = martensite, TM = martensite rinvenuta).



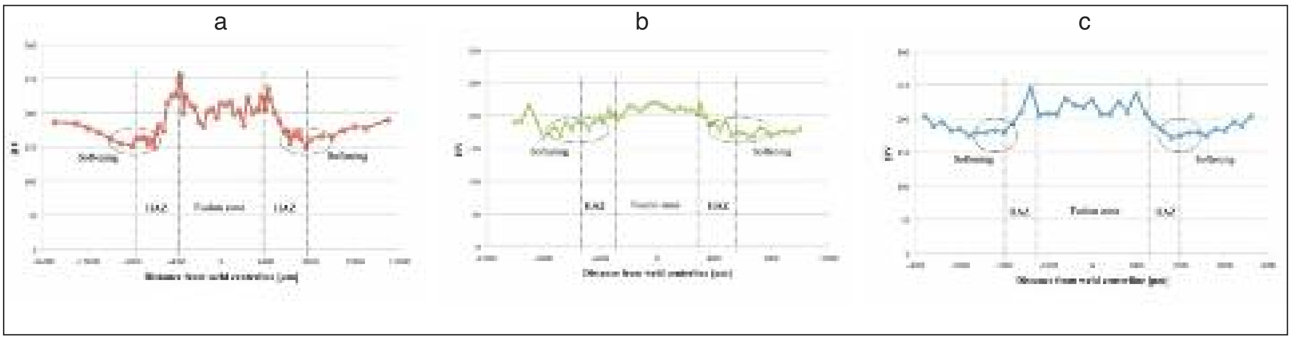


FIG. 7 ***Typical microhardness profiles of the analysed welded joints (a - GTAW, b - PAW, c - EBW).***
Profili di microdurezza dei giunti saldati in esame (a - GTAW, b - PAW, c - EBW).

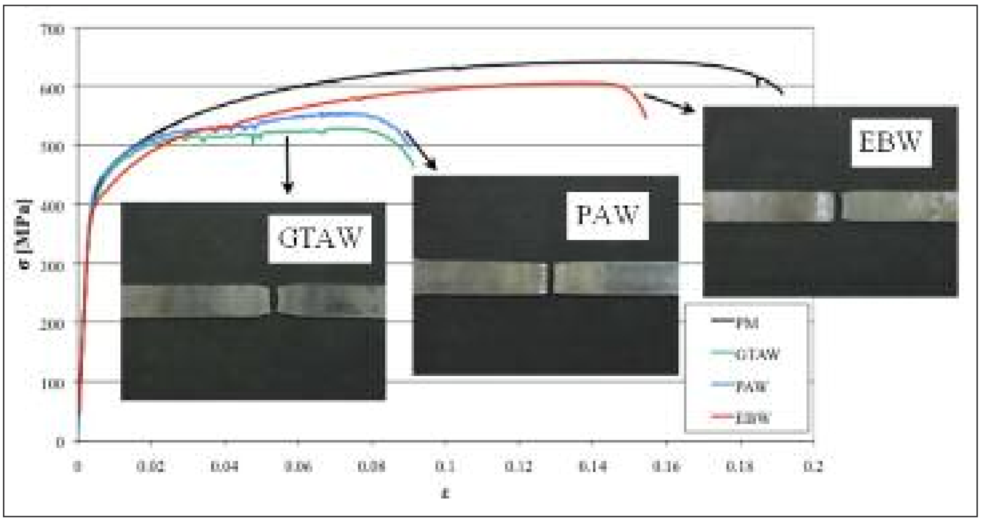


FIG. 8
Stress- strain curves of DP600 steel welded joints and parent metal (PM).
Curve tensione-deformazione ingegneristiche dei giunti saldati analizzati e del metallo base.

to its mixed microstructure formed by acicular ferrite and bainite. The lowest values of hardness are induced by the typical softening effect of tempered martensite in addition to the coarsening of ferritic grains [2,3,11,12,13].
The hardness values in the parent metal were observed to be nearly constant throughout the material (about 190-200 HV), corresponding to the microstructure of the base metal containing islands of martensite (10-12% vol.) in the ferrite matrix.
Fig. 8 shows the stress–strain curves obtained from the different welded joints, while Table 5 lists the measured tensile properties.
Fig. 8 shows that rupture took place in the HAZ-2 of all the specimens, where the softening phenomenon results to be marked (Fig. 7).
In Fig. 8 and Table 5, it is easy to observe that the welding process decreases the mechanical properties of the joints if compared with the parent metal; while EBW assures the best tensile behavior, both in terms of UTS and elongation at break, GTAW and PAW decrease appreciably the mechanical properties of the DP600 steel examined. GTA and PA welded joints show similar YS and elongation at break values, while the UTS of the PA welded joint is slightly higher if compared with the GTA welded one. Tensile tests confirm that both the softening phenomenon and grain coarsening are the most important factors which affect the mechanical behavior of DP600 steel welded joints. The best resistance has been obtained by using EBW process, which guarantees the narrowest heat affected zone (both in terms of softening and grain coarsening); however, this technology is characterized by higher investment costs, higher set-up times and less flexibility, in terms of geometrical constrains, which are directly connected with the dimensions of vacuum camera.
On the contrary, GTAW and PAW processes are well-established, flexible and easy to automate, but they involve an higher alteration of the parent dual-phase microstructure.

	GTAW	PAW	EBW
UTS [MPa]	530	559	607
YS [MPa]	428	441	414
Elongation at break %	7	7	13

TAB. 5 ***Tensile properties of the tested welded joints.***
Proprietà meccaniche dei giunti sottoposti a test di trazione.

CONCLUSIONS

The effects of different welding technologies on a low carbon DP600 steel were studied in terms of both metallurgical and mechanical properties. Independently from the welding technology, each joint showed:

- a FZ microstructure constituted by a mixture of acicular, bainitic and allotriomorphic ferrite;
- a coarse grain zone near the FZ/HAZ interface;
- a soft zone due to the formation of tempered martensite and ferritic grain coarsening;
- necking near the HAZ-2.

By comparing the effects of the different welding technologies on the properties of the joints, the following differences were found:

- FZ and HAZ width increases with the increase of heat input;

- grain coarsening effect increases with the increase of heat input;
- the softening effect is more marked in gas tungsten arc welded samples than plasma and electron beam welded joints both in terms of minimum hardness values and HAZ-2 width.

As a consequence of the differences cited above, electron beam welded joints showed better mechanical properties compared to the gas tungsten and plasma arc welded samples.
It can be concluded that the main advantage of high power density technologies in welding such kind of steels is above all due to the very narrow HAZ if compared to the other conventional welding processes. This result can be probably extended to laser welding with a great advantage in terms of productivity and costs.

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Abstract

Effetto delle diverse tecnologie di saldatura sulle proprietà meccaniche e metallurgiche di giunti saldati in acciaio DP600

Parole chiave: acciai altoresitenziali avanzati, DP600, saldatura a fascio elettronico, saldatura ad arco, saldatura al plasma, metallurgia, proprietà meccaniche

Il mondo dell'industria, e in particolare il settore automotive, è particolarmente sensibile alle attuali esigenze riguardanti la riduzione delle emissioni inquinanti, la riduzione dei consumi e la sicurezza dei veicoli; tali richieste hanno spinto molti produttori e ricercatori a sviluppare nuove leghe metalliche in grado di contribuire a migliorare le prestazioni dei componenti in relazione ai suddetti scopi.
Gli acciai altoresistenziali avanzati (Advanced High Strength Steels - AHSS) costituiscono una nuova categoria di materiali in grado di far fronte alle nuove suddette necessità; essi si suddividono in diverse famiglie a seconda della microstruttura e dei processi produttivi secondo i quali vengono ottenuti.
In particolare, gli acciai Dual Phase (DP), caratterizzati da una matrice ferritica, rafforzata dalla presenza di isole di martensite, rispettano i requisiti specifici dei materiali destinati ad un impiego nell'ambito automotive. A livello microstrutturale infatti, la ferrite garantisce duttilità e quindi ottime capacità di formatura; d'altro canto, la martensite è caratterizzata da elevata durezza la quale conferisce alla lega un'eccellente resistenza meccanica soprattutto in termini di tensione di snervamento e di rottura. Quest'ultima caratteristica degli acciai DP permette una riduzione degli spessori dei componenti strutturali e conseguentemente una riduzione del peso globale dei veicoli, rispetto a materiali tradizionali quali acciai al carbonio e i classici acciai ad elevata resistenza microlegati (HSLA). Infine la buona combinazione fra duttilità e resitenza meccanica rende questi acciai adatti alla produzione di componenti strutturali con elevata capacità di assorbimento di energia all'urto.
Come spesso accade nello sviluppo di materiali innovativi però, possono insorgere alcuni problemi tecnologici, legati per esempio alla saldatura dei componenti. Nel caso degli acciai DP, l'operazione di saldatura è particolarmente delicata: da una parte le esigenze di produzione richiedono processi veloci ed automatizzabili, dall'altra le richieste applicative e le specifiche di progetto necessitano del mantenimento delle ottime proprietà meccaniche tipiche di questi acciai, e di conseguenza una contenuta alterazione metallurgica del materiale base durante il procedimento di giunzione.
Scopo di questo lavoro è il confronto degli effetti di diversi processi di saldatura su un acciaio altoresistenziale DP600 in termini di alterazione microstrutturale e proprietà meccaniche del giunto finale. I procedimenti di saldatura considerati sono stati sia quelli ad arco elettrico (GTAW - Gas Tungsten Arc Welding e PAW – Plasma Arc Welding) sia quelli maggiormente innovativi come, in questo caso, la saldatura a fascio elettronico (EBW – Electron Beam Welding). Mentre i processi più convenzionali ad arco costituiscono oramai delle tecnologie consolidate, sono flessibili e facilmente automatizzabili, i processi ad alta densità di energia

garantiscono minori distorsioni termiche ed una contenuta zona termicamente alterata.
Sono state analizzate e confrontate in dettaglio le variazioni microstrutturali nella zona fusa e nelle zona termicamente alterata (ZTA), i profili di microdurezza e le proprietà di resistenza a trazione dei giunti saldati in relazione al tipo di processo.
I risultati illustrano come tutti i campioni ottenuti siano caratterizzati da una zona fusa costituita da ferrite aciculare, bainitica e allotriomorfa, e un fenomeno di softening in ZTA dovuto sia ad un ingrossamento del garno ferritico sia al rinvenimento della martensite (come già ampiamente documentato in letteratura). Si è verificato come l'ingrossamento del grano in ZTA sia proporzionale all'apporto termico; il fenomeno di softening è quindi più accentuato nelle saldature ad arco e di conseguenza il comportamento a trazione di tali giunti risulta essere peggiore rispetto a quelli saldati a fascio elettronico.
Sulla base di ciò, è stato possibile concludere che la saldatura a fascio elettronico garantisce una minore variazione delle proprietà metallurgiche e meccaniche del metallo base, in particolare se confrontata con i procedimenti tradizionali ad arco. Questo risultato potrebbe essere probabilmente esteso anche alla saldatura laser la quale risulta più flessibile rispetto alla saldatura a fascio elettronico, aspetto che consentirebbe un vantaggio in termini di produttività e quindi di costo dei componenti realizzati.