The Digital Image Correlation technique applied to the deformation behavior of welded sheet joints

G. Silva, B. Rivolta, E. Zappa, R. Gerosa, A. Silvestri, P. Mazzoleni, S. Gualtieri

The existence of a welded zone generally influences the local strain and stress distribution especially in case of welding defects. A method able to measure the local deformability can hence give many important information about the real stress and strain fields useful to improve the welded structure design. In this experimental work, some new generation automotive steels have been considered, because of the well known welding problems due to their unstable microstructural condition. Such materials, known as Q&P steels and available only as thin sheets, require a suitable quenching process able to give high mechanical resistance and satisfying deformability. Some sheet samples were welded by electron beam technique, because it is able to reduce the width of the heat affected zone where the main microstructural changes are concentrated. From such samples, tensile specimens were machined. During the tensile tests, the deformations were measured both by a traditional extensometer and by a 3D Digital Image Correlation (3D DIC) technique. A preliminary investigation of the melted and the heat affected zones resulted in small dimensions (about 10 mm) and hence the measuring setup has been optimized in order maximize the achievable measuring resolution minimizing the resulting uncertainty. This result can be achieved by a pattern generated by a suitable software and by an accurate preparation of the surface where the pattern will be deposited on.

Keywords: welding, mechanical resistance, innovative strain measurements

INTRODUCTION

The execution of a welding in a metal generally induces microstructural variations depending on many factors such as the welding technique and parameters, the base material and its metallurgical conditions (strain hardening degree, previous thermal history…). The local mechanical properties are expected to change from the melted to the heat affected zone and generally they will be different from the base material ones [1].
One of the most common methods to evaluate the local properties of a welded joint is based on micro-hardness tests, whereas the determination of mechanical parameters such as the yield stress, the UTS and the elongation to fracture require a standard tensile test. One way to measure the deformation is based on the Digital Image Correlation. Such technique doesn't require a physical contact with the surface of the component and works comparing images of the surface acquired during the test with a reference one of the unloaded specimen. This results in the definition of a full-field displacement map and finally in an accurate surface state of strain. It was developed for the first time at the University of South Carolina in the '80 [2], but in the following years many enhancements were obtained resulting in a measuring uncertainty of the order of magnitude of few hundredths of pixel. Such method was already studied and appreciated by the authors in other experimental works [3-6]. In the present investigation some new generation sheet steels for the automotive world have been considered and some weldings were performed by electron beam technique in order to study the microstructural and the mechanical modifications induced by the heat input. Tensile specimens were machined from the welded sheets and the deformation during the tensile tests were measured both by a traditional extensometer and by 3D Digital Image Correlation for a comparison among the two approaches.

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MATERIALS AND METHODS

The investigated materials belong to new generation steels, known as Q&P (Quenched & Partitioned), developed for the automotive industry. Their chemical compositions are reported in table 1.
The materials were delivered as 1mm thick sheets produced (both the melting, the casting, the rolling and the final heat treatment) by a thermo-mechanical simulator Gleeble 3800. Such steels are characterized by high silicon content and by a suitable heat treatment optimized for the

	%C	%Mn	%Si	%P	%S	%Cr	%Ni	%Mo	%Cu	%V	%Al
B1	0,217	1,647	1,628	0,0155	0,014	0,03	0,013	0,003	0,011	0,005	0,05
B2	0,208	1,824	1,634	0,0161	0,016	0,039	0,017	0,167	0,013	0,006	0,006

Tab. 1. Chemical composition of the investigated steels.

Tab. 1. Composizione chimica degli acciai investigati.

Steel	Taust. [°C]	t [s]	QT [°C]	t [s]	PT [°C]	t [s]
B1	900	180	240	10	350	10
B2	850	180	220	20	350	60

Tab. 2. Heat treatment temperatures and times.

Tab. 2. Tempi e temperature di trattamento.

specific chemical composition. The chemical composition of the investigated steels is very similar, except for the molybdenum that is higher in steel B2. The heat treatment is generally complicated, because it requires an austenitization and a following cooling till a temperature (quenching temperature - QT) included among M_s and M_f; after a soaking, the temperature increases (partitioning temperature - PT) and a new soaking is required before the final cooling to room temperature. During the soaking at the partitioning temperature the hardness of the martensitic fraction decreases and at the same time a stabilization of the austenitic fraction occurs [8,9].
The heat treatment parameters are reported in table 2.
The described materials have already been studied in previous paper under many aspects [7]. Nevertheless their weldability is still not well known. For this reason some samples have been machined from electron beam welded sheets for a mechanical characterization of the welded joints by micro-hardness and tensile tests. During the tensile tests the strains were measured both by a traditional extensometer and by 3D Digital Image Correlation for a comparison among the two approaches.
In table 3 the tensile specimens dimensions are reported.
In table 4, the welding parameters are summarized.
One of the aims of the present paper is a comparison among two measurement techniques: one is very well known (the extensometric one) and one is instead innovative (the 3D Digital Image Correlation) and hence it must

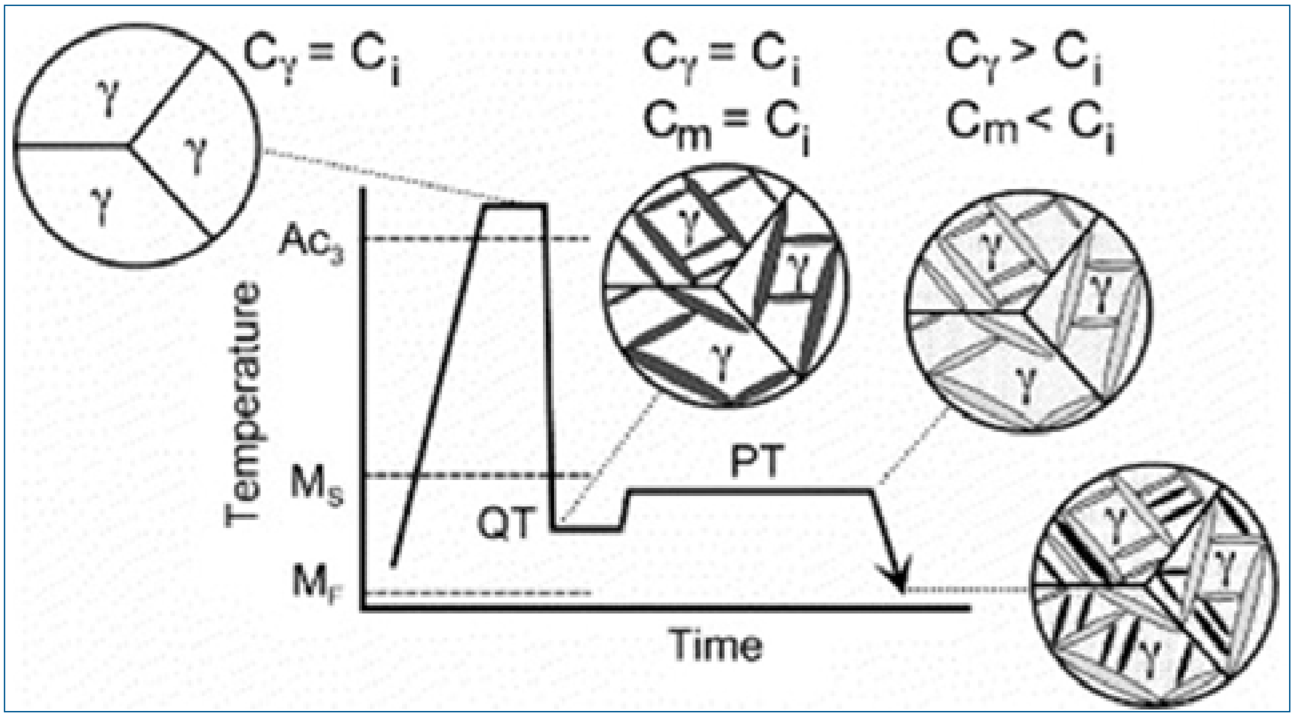


Fig. 1. Heat treatment of a Q&P steel. C_i, C_γ and C_m are the initial amount of carbon and the carbon content of the austenitic phase and of the martensite.

Fig. 1. Trattamento termico di un acciaio Q&P. C_i, C_γ e C_m sono rispettivamente la quantità iniziale di carbonio e le percentuali di carbonio delle fasi austenitica e martensitica.

S_o [mm]	b_o [mm]	L_c [mm]	r [mm]	h [mm]	l_f [mm]	L_t [mm]
1	9	75	25	14	25	140

Tab. 3. Tensile specimens dimensions.

Tab. 3. Dimensioni dei campioni di trazione.

Current [A]	Feeding speed [mm7min]	Gas
80	800	Argon

Tab. 4. Welding parameters.

Tab. 4. Parametri di saldatura.

be better described. The acquisition of the displacements of different points of a surface during a deformation requires the creation and the deposition of a suitable pattern able to maximize the spatial resolution. The patterns employed in this experimental work were generated by a software; then, they were printed on a suitable paper selected for its ability to transfer the pattern on the sample surface with great precision. The transfer operation was obtained using a certain pressure and temperature. Since the pattern shall be recognized by optical instruments, the sample surface finishing is a critical parameter: it must be bright, but not reflective. Such finishing was obtained by a controlled sandblasting after some preliminary tests.
Finally, the optical acquisition was concentrated on the whole welded zone.

RESULTS

The microstructure of the base material of the specimens after the described heat treatments are reported in figure 5.
Both the microstructure are characterized by different micro-constituents, but prevalently made of ferrite and martensite. Few amount of retained austenite was found (<5%). The presence of ferrite is due to an inter-critical quench as demonstrated by some dilatometric tests aimed to determine the phase transformation temperatures A_{c1} and A_{c3} (A_{c1}=730°C-740°C and A_{c3}=910°C-920°C for both the steels). Moreover, the ferrite content is higher and the morphology finer in steel B2 being lower its austenitization temperature. In table 5, the tensile results are reported.
The features of the whole welding, from the melted zone to the base metal, were investigated by HV0.5 micro-hardness profiles as shown in figure 6.
For both the steels, the microstructure in the melted zone (M.Z.) is martensite, whereas in the heat affected zone (H.A.Z.) an increasing fraction of ferrite appears moving toward the base metal (B.M.) where the microstructure is the same of the one described in figure 5.
By 3D DIC analysis, a different deformability was found in the welded joint and the fracture, located in the heat affected zone, was clearly detected as shown in figures 7 and 8.
The comparison among the deformation measured by the extensometer (gage length 12mm) and by the 3D DIC system (the strains were evaluated on a gage length of 12mm – sections D-D and E-E) resulted in a satisfying agreement between the two methods as clearly shown in figure 9 for B1 steel.
Finally, using the strains measured by the 3D DIC technique and the forces measured by the load cell, the Young modulus was evaluated too. In table 6 a comparison between the elastic moduli calculated using the extensometer data and the 3D DIC analysis is presented.

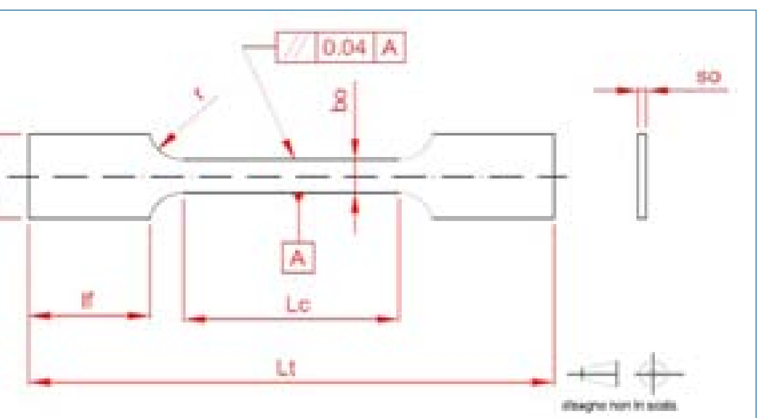


Fig. 2. Tensile specimen.

Fig. 2. Campione di trazione

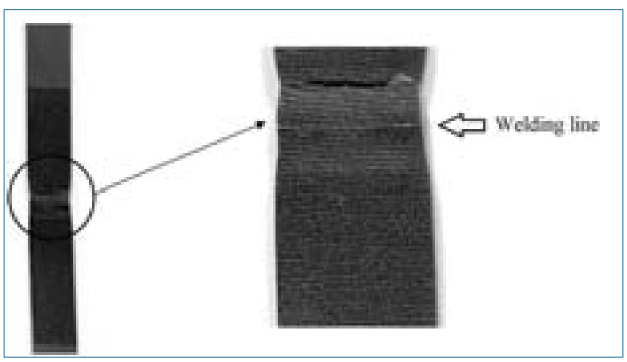


Fig. 3. Speckle pattern generated by means of a PC and transferred on the specimen surface.

Fig. 3. Schema a punti generato via PC e trasferito sulla superficie del campione.

Steel	$R_{p0.2}$ [MPa]	R_m [MPa]	E [MPa]
B1	714	1076	180000
B2	648	1027	189000

Tab. 5. Tensile properties.

Tab. 5. Proprietà tensili.

Steel	E - Extensometer [Mpa]	E - 3D DIC [Mpa]
B1	180000	175000
B2	189000	186000

Tab. 6. Average values of the calculated elastic moduli.

Tab. 6. Valori medi dei moduli elastici calcolati.

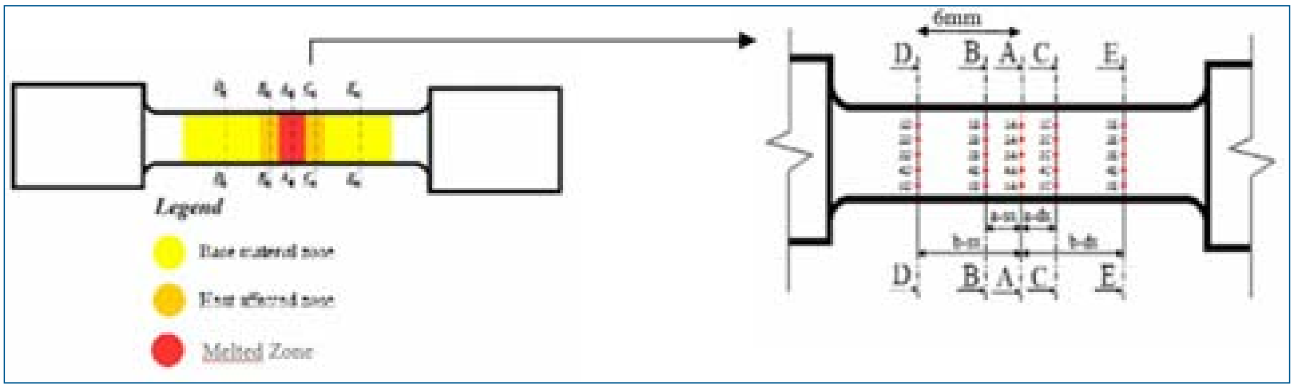


Fig. 4. Scheme of the measurement points.

Fig. 4. Schema dei punti di misura.

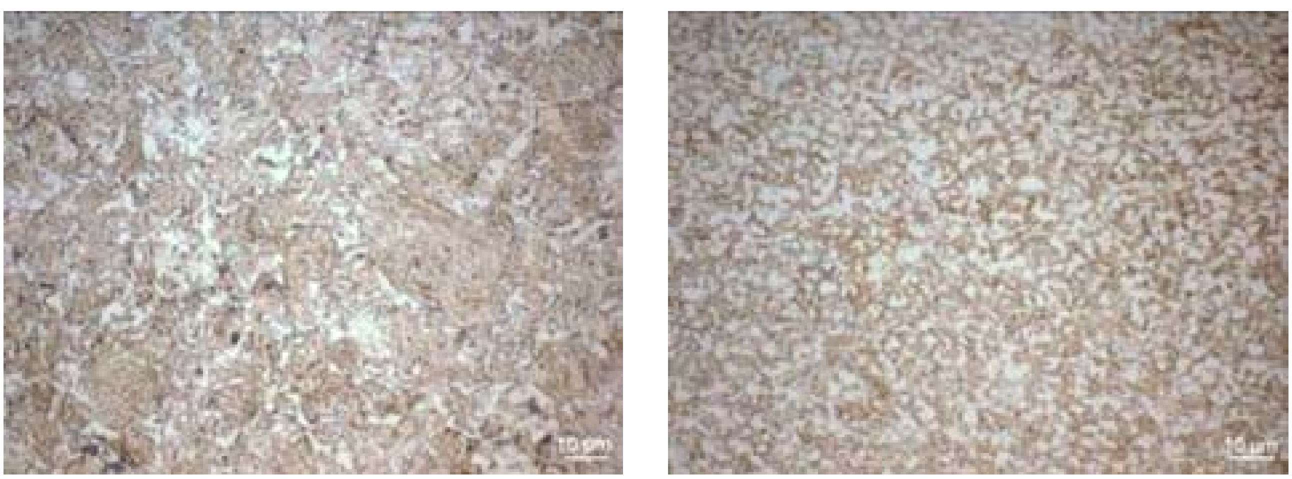


Fig. 5. Microstructure observed in steel B1 (a) and B2 (b) after the heat treatment and before the welding.

Fig. 5. Microstrutture osservate nell'acciaio B1 (a) e B2 (b) dopo il trattamento termico e prima della saldatura.

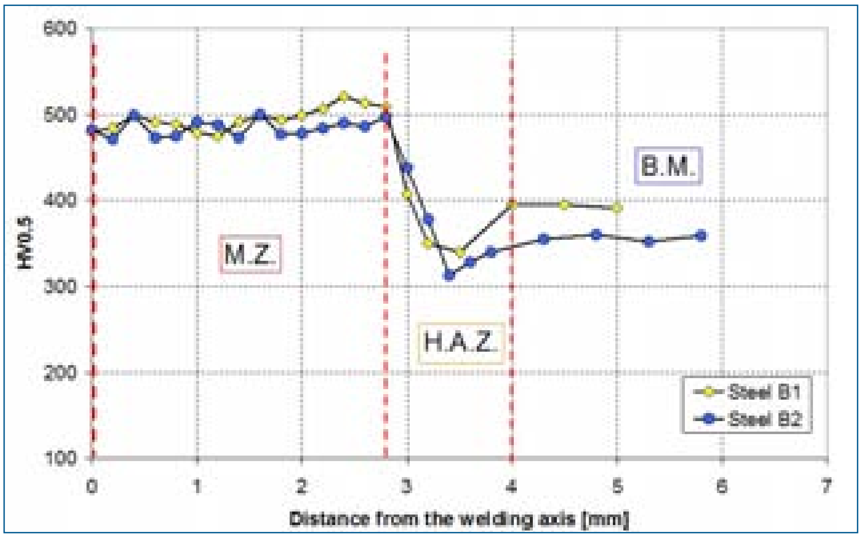


Fig. 6. Comparison among the micro-hardness profiles of steels B1 and B2.

Fig. 6. Confronto tra i profili di micro-durezza rilevati sugli acciai B1 e B2.

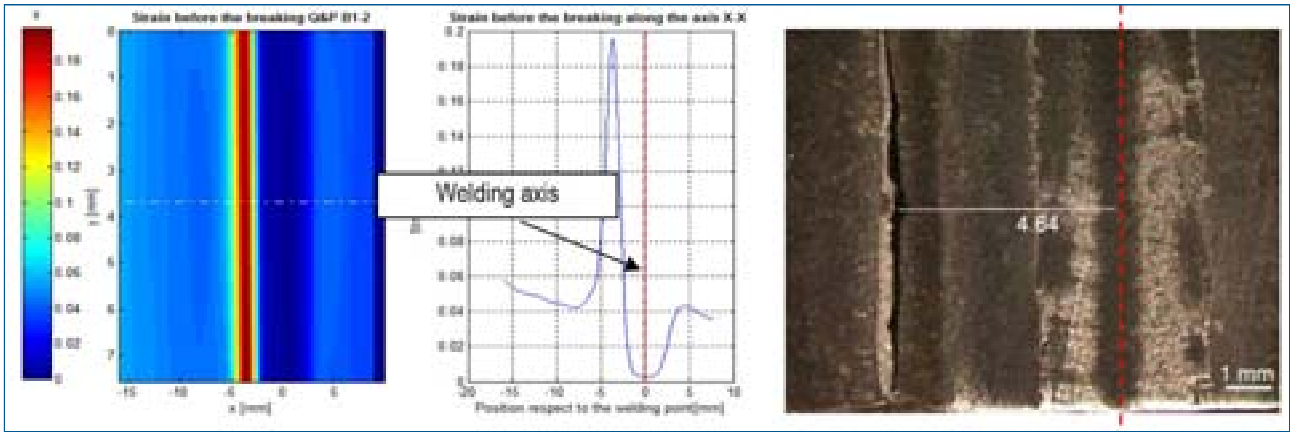


Fig. 7. Deformation of the welded zone of steel B1.

Fig. 7. Deformazione della zona saldata dell'acciaio B1.

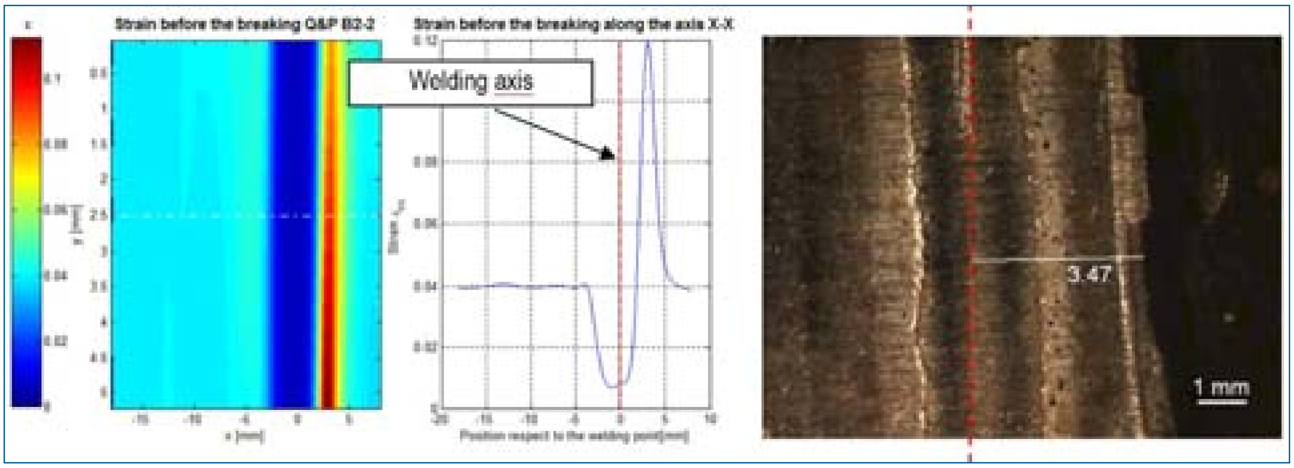
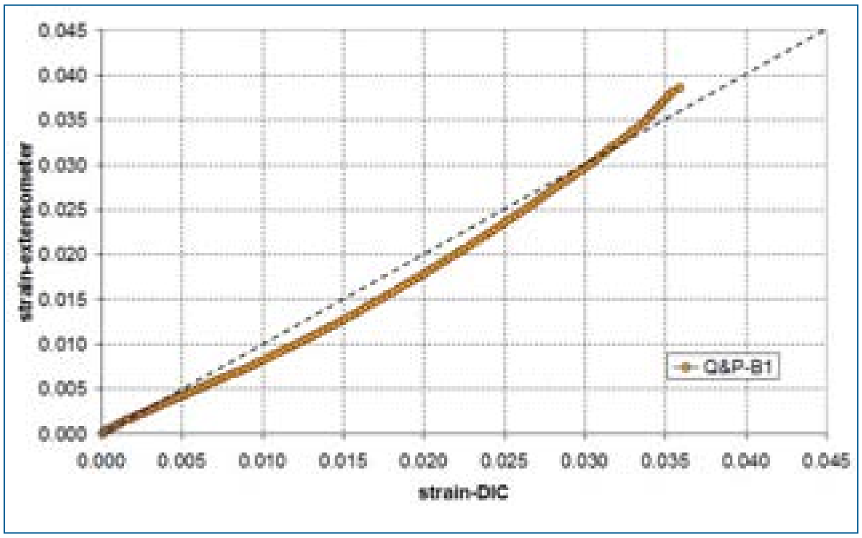


Fig. 8. Deformation of the welded zone of steel B2.

Fig. 8. Deformazione della zona saldata dell'acciaio B2.

Fig. 9. Comparison among the deformation measured by extensometer and by 3D DIC.

Fig. 9. Confronto tra la deformazione misurata tramite estensometro e tecnica 3D DIC.



CONCLUSIONS

The results presented in this paper justify the following conclusions:

- from the microstructural point of view, both the materials are characterized prevalently by ferrite and martensite. The amount and the morphology of such micro-constituents is strongly related to the heat treatment parameters and especially to the austenitization temperature;
- the microstructure in the melted zone (M.Z.) is martensite, whereas in the heat affected zone (H.A.Z.) an increasing fraction of ferrite appears moving toward the base metal (B.M.);
- the welded joints showed no cracks or welding defects and the mechanical resistance is satisfying;
- by 3D DIC approach, the local strains were determined in both the melted and the heat affected zone and the fracture zone was clearly identified;
- the comparison between the two measurement techniques, by extensometer and by 3D DIC, resulted in a good agreement.

ACKNOWLEDGMENT

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La tecnica della Digital Image Correlation per studiare la deformazione di giunti in lamiera saldata

Parole chiave: saldatura, resistenza meccanica, metodo di misura delle deformazioni innovativo

La presenza di una zona saldata all'interno di componenti meccanici, influenza la distribuzione delle deformazioni e quindi degli sforzi a livello locale. L'eventuale presenza di difettosità, quali cricche, porosità, mancata o parziale penetrazione, è da considerarsi un ulteriore fattore di disturbo nella distribuzione delle sollecitazioni. La possibilità di misurare le deformazioni a livello locale è pertanto molto importante anche a livello progettuale al fine di ottenere un ottimale dimensionamento del giunto saldato. In questo lavoro sono stati considerati materiali di recentissima introduzione destinati all'industria automobilistica che notoriamente mal si prestano all'operazione di saldatura a causa delle loro instabili condizioni microstrutturali. Questi acciai sono commercialmente noti come Q&P e richiedono un processo di tempra particolare che conferisce loro ottime caratteristiche meccaniche e discreta deformabilità. I materiali sono stati forniti in forma di lamiera. Dopo aver realizzato saldature mediante tecnica Electron Beam, scelta perché in grado di limitare l'alterazione termica e quindi quella microstrutturale, sono stati ricavati campioni di trazione in modo che il giunto saldato si trovasse al centro. Durante la prova di trazione le deformazioni sono state misurate sia tramite tradizionale estensometria sia mediante tecnica di 3D Digital Image Correlation (DIC) concentrando l'attenzione nella zona del giunto saldato e comparando i risultati ottenuti con le due tecniche. L'utilizzo di un sistema di visione stereoscopico risulta fondamentale data la non perfetta planarità dei provini a seguito della saldatura e la conseguente presenza di moti fuori piano durante la prova di trazione. Da analisi preliminari la larghezza della zona di saldatura e quella della zona termicamente alterata sono risultate essere piuttosto ridotte (circa 10mm). Questo ha richiesto lo sviluppo di una nuova tecnica per la generazione del pattern superficiale del provino in modo da massimizzare la risoluzione spaziale delle misure fatte con la DIC. La tecnica proposta è basata sulla generazione al calcolatore del pattern richiesto, la stampa su carta lucida appositamente selezionata e il riporto del pattern dalla carta sul provino per mezzo di pressione ad elevata temperatura. Al fine di valutare le proprietà locali del giunto saldato, sono stati inoltre eseguiti profili di micro-durezza dalla zona fusa fino al metallo base. Dal punto di vista microstrutturale entrambi gli acciai risultano costituiti da ferrite e martensite la cui morfologia e quantità sono strettamente legate ai parametri di trattamento e specialmente alla temperatura di austenitizzazione. Nella zona fusa la struttura è completamente martensitica, mentre nella zona termicamente alterata appare una quantità crescente di ferrite muovendosi verso il metallo base. Nel giunto saldato non sono stati rilevati difetti o cricche e la resistenza meccanica è stata soddisfacente. Infine, è stato confrontata la tecnica di misura tradizionale con estensometro e la nuova metodologia 3D DIC ottenendo un buon accordo.

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