



## Fatigue endurance of new high-strength car-body steels

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**ABSTRACT.** Advanced, high-strength steel sheets are increasingly used to make lighter and safer car-bodies. The main mechanical requirements of these steels in service are high fracture strengths and energy absorptions, relevant for crash tests, and fatigue endurances, relevant for ordinary car usage. The steel sheets are made by continuous casting, hot rolling, cold rolling and continuous annealing, or other continuous final heat treatments, and are then cold formed and welded to fabricate the car bodies. Two new high-strength car-body steels are examined here: a TWIP (TWinning Induced Plasticity) steel, which is already industrially available, but not yet widely used, and a Q&P (Quenching and Partitioning) steel, which was recently produced industrially as a prototype. The new steels are compared with a widely used, high-strength, DP (Dual-Phase) automotive steel grade. Automotive TWIP steels are high-Mn austenitic steels, with a medium-high C content, which exhibit a promising combination of strength and toughness, arising from the ductile austenitic structure, which is strengthened by C, and from the TWIP (TWinning Induced Plasticity) effect. The low-alloy Q&P steels are subjected to the Quenching and Partitioning (Q&P) final heat treatment, which consists of: 1) full or partial austenitizing; 2) quenching to the  $T_q$  temperature, comprised between  $M_s$  and  $M_f$ ; 3) soaking at the  $T_p$  “partitioning” temperature, equal to or slightly higher than  $T_q$ , allowing carbon to diffuse from martensite to retained austenitized; 4) quenching to room temperature. The final microstructure consists primarily of low-carbon martensite, high carbon martensite, and carbon stabilized austenite. The fatigue behavior of these steels is examined both in the as-fabricated condition and after pre-straining and welding operations, which are representative of the cold forming and assembling operations performed to fabricate the car-bodies. Moreover, the microscopic fracture mechanisms are assessed by means of fractographic examinations.

**SOMMARIO.** Lamiere di acciai altoresistenziali avanzati sono usate sempre più spesso per fabbricare scocche automobilistiche più leggere e più sicure. I principali requisiti meccanici di questi acciai in opera sono alta resistenza a frattura ed elevato assorbimento di energia, importanti per le prove di urto stradale, e la resistenza a fatica, importante per l'uso ordinario della vettura. Le lamiere di acciaio sono fabbricate mediante colata continua, laminazione a caldo ed a freddo e ricottura continua, o altro trattamento termico finale realizzato in modo continuo; esse sono poi imbutite e saldate per fabbricare le scocche. Sono qui esaminati due nuovi acciai ad alta resistenza: un acciaio TWIP (TWinning Induced Plasticity), già disponibile a livello industriale, ma non ancora di uso comune, ed un acciaio Q&P (Quenching and Partitioning), recentemente prodotto industrialmente come prototipo. Questi nuovi acciai sono confrontati con un acciaio DP (Dual-Phase) ad alta resistenza di uso comune. Gli acciai TWIP per costruzioni automobilistiche sono acciai ad alto tenore di Mn, con una percentuale rilevante di C, i quali presentano una combinazione promettente di resistenza e tenacità,



derivante dalla loro struttura austenitica, rafforzata dal C e dall'effetto TWIP. Gli acciai Q&P, a basso tenore di elementi di lega, sono sottoposti al trattamento termico finale di tempra e partizione, che consiste di: 1) austenitizzazione completa o parziale; 2) tempra fino alla temperatura  $T_q$ , intermedia tra  $M_s$  e  $M_f$ ; 3) mantenimento alla temperatura di partizione  $T_p$ , uguale o poco superiore a  $T_q$ , per permettere al carbonio di diffondere dalla martensite all'austenite residua; 4) tempra fino alla temperatura ambiente. La microstruttura finale consiste principalmente di martensite a basso tenore di carbonio, martensite ad alto tenore di carbonio ed austenite stabilizzata dal carbonio. Il comportamento a fatica di questi acciai è esaminato sia allo stato di fabbricazione, sia dopo operazioni di predeformazione e di saldatura, rappresentative dei processi di imbutitura e di assemblaggio eseguiti per fabbricare le scocche. Inoltre, i meccanismi microscopici di frattura sono valutati mediante analisi fratto grafiche.

**KEYWORDS.** Automotive; Steel sheets; TWIP; Quenching and partitioning.

## INTRODUCTION

In recent years car-bodies are more and more frequently built with innovative high-strength steels, both to reduce vehicles weight and to improve passenger safety. The main service requirements of these steels are high fracture strength and good energy absorption, in relation to the possibility of car crashes, and good fatigue resistance, as it regards the vehicles normal use [1].

In general, the high-strength steels, used so far, in comparison with the conventional deep-drawing steels, show resistance characteristics three or four times higher, but a lower formability, evidenced by a smaller elongation in the tensile tests.

The steel sheets for automotive applications are normally manufactured by means of continuous casting, hot and cold rolling, continuous annealing (or other continuous heat treatment) and, in some cases, anticorrosive coating (hot dip Zn coating may be performed during the cooling stage after the final heat treatment). Steel sheets are then cold-formed (i.e., deep-drawn) in order to fabricate the car-body components. Eventually, the car bodies are constructed by assembling many deep-drawn components, often made of different steels, by using the Resistance Spot Welding (RSW) process, in which two or three superposed sheets are welded due to local heating caused by the Joule effect [2]. Laser beam welding (LBW) [3], in which a laser beam is employed to form a butt weld, is used less frequently.

Welding processes cause both microstructural and geometric effects, which can influence the fatigue behavior. In particular, the geometry of a weld spot causes a complex notch effect, which has a relevant negative influence on the fatigue performance of the welded component [4].

Two new high-strength car-body steels are examined here: a TWIP (TWinning Induced Plasticity) steel, which is already industrially available, but not yet widely used, and a Q&P (Quenching and Partitioning) steel, which was recently produced industrially as a prototype. The new steels are compared with a widely used, high-strength, Dual-Phase (DP) steel.

Automotive TWIP steels are high-Mn steels with a medium-high percentage of carbon, which exhibit a promising combination of strength and toughness, arising from the carbon strengthened ductile austenitic structure and by the possibility to deform via mechanical twinning [5-10].

The low-alloy Q&P steels are subjected to the Quenching and Partitioning (Q&P) final heat treatment, which consists of: i) full or partial austenitizing; ii) quenching to the  $T_q$  temperature, comprised between  $M_s$  and  $M_f$ ; iii) soaking at the  $T_p$  "partitioning" temperature, equal to or slightly higher than  $T_q$ , allowing carbon to diffuse from martensite to retained austenite; and iv) quenching to room temperature. The final microstructure consists primarily of low-carbon martensite, high carbon martensite, and carbon stabilized austenite [11, 12].

Dual-Phase (DP) steels exhibit a mixed ferrite-martensite microstructure, which is obtained after heating to an intercritical temperature followed by a rapid cooling [13, 14].

This work is a part of a larger research project [15, 16], whose goals are: to characterize and compare mass-produced, innovative high-strength steels for car weight reduction, as well as to facilitate the industrialization of the new steels still in the experimental stage, with regards to both the production processes and the service requirements. In this framework, a study of the fatigue behavior of the same steels in the as-fabricated condition and after pre-straining and welding operations, which are representative of the cold forming and assembling operations performed to fabricate the car-bodies, was undertaken, and is here reported.

## MATERIALS AND METHODS

### Examined steel sheets

All the examined steels have a nominal ultimate yield strength of about 1 GPa and were produced with industrial plants, by continuous casting, hot and cold rolling, and continuous final heat treating (the TWIP and DP steels were also coated with Zn). The latter as-fabricated steels conditions are those which are expected to occur immediately before cold forming. The thickness of the TWIP, Q&P and DP steel sheets was 1.4, 1.8 and 1.2 mm, respectively. The steels chemical composition, given in Tab. I, was determined by direct optical emission spectroscopy, with the exception of the Mn, Cr, Ni, Al and Cu contents of the TWIP steel, which were determined by acid dissolution and subsequent optical absorption spectroscopy.

It was previously ascertained that the TWIP steel consists of fine grained austenite, with a grain size of about 4  $\mu\text{m}$  (even if a small fraction of sub-micron-sized carbides may also be present), with evident bands in the rolling directions, and its hardness is 235 HV, whereas the DP steel consists of dispersed martensitic regions within a quasi-continuous ferritic matrix, with a ferrite grain size of about 8  $\mu\text{m}$ , small fractions of bainite and retained austenite, and its hardness is 290 HV [15, 16].

steel	C	Mn	Al	Si	B	Ni	Cr	Cu	V	Mo	P	S	Nb	Ti
TWIP	0.65	18.3	1.5	0.05	n. m.	0.41	0.02	0.05	0.04	n. d.	0.02	0.01	n. m.	n. m.
Q&P	0.20	1.8	0.04	1.4	0.0015	0.01	0.03	0.01	0.004	0.02	0.02	0.006	0.002	n. d.
DP	0.18	2.3	0.03	0.18	0.0007	0.02	0.51	0.01	0.002	<0.001	0.01	<0.001	0.025	0.002

Table 1: Chemical composition of the examined steels (weight percent; n. m.: not measured; n. d.: not detected).

### Tensile and fatigue testing of as-fabricated specimens

Full thickness, constant-section tensile specimens, whose calibrated section was 20 mm wide and 110 mm long (Fig. 1a), were machined from the steel sheets and used for quasi-static tensile tests at room temperature.

The latter specimens were also used to perform stress-life fatigue tests on the TWIP and DP steels, according to the staircase method [17, 18], in order to determine the 1 million cycles fatigue strength, with zero load ratio. The test frequency was 15 Hz and the failure criterion was total specimen fracture.

Finally, a series of stress-life fatigue tests was performed on as-fabricated Q&P steel sheets, by using full thickness hourglass specimens, with 16 mm minimum width and 80 mm fillet radius (Fig. 1d), resulting in a stress concentration factor equal to 1.06 [19]. The latter fatigue tests were performed with a 0.1 load ratio and 30 Hz frequency, up to the total specimen fracture, and were aimed to determine the Wöhler curve.

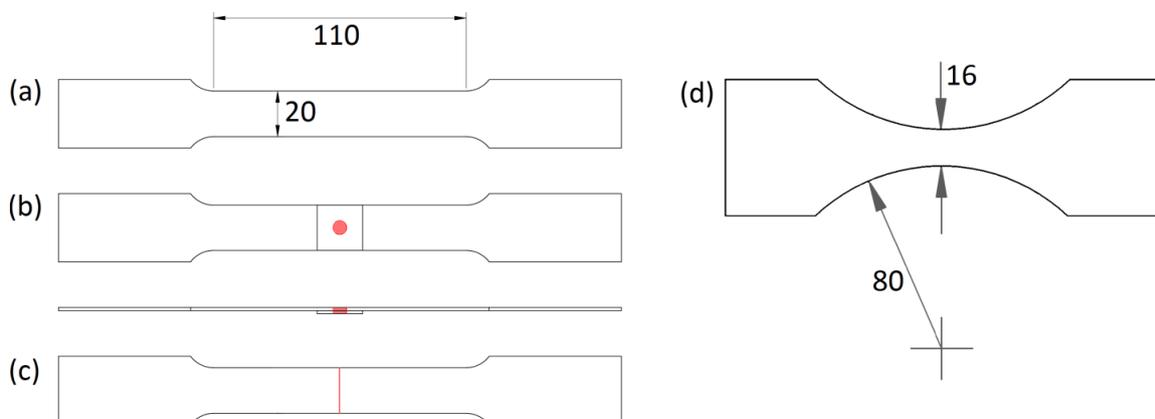


Figure 1: Constant-section specimens: plain (a), with one RSW welding spot (b) and with a simulated LBW line (c). Hourglass specimens (d). Dimensions in mm and welded joints in red color.

### *Pre-straining and welding procedures and subsequent mechanical testing*

Some DP steel tensile specimens were pre-strained up to 7% engineering strain (as measured with a clip-gage extensometer), and then unloaded, to simulate the deep drawing, appropriate for this kind of steel, given its stress-strain curve (as reported below). Other TWIP tensile specimens were also pre-strained in the same manner for the sake of comparison.

TWIP and DP steel tensile specimens, either as-fabricated or pre-strained, were resistance spot welded at mid-length, with one spot, to a 20 mm homologous sheet square (Fig. 1b). The welds were performed with an industrial RSW equipment, with 3 mm electrode radius and with the following parameters: 3.5 kN clamping force, 7 kA electric current and 260 ms duration for the TWIP steel; or 4 kN, 10 kA and 260 ms for the DP steel.

Moreover, another series of tensile test samples, with the same shape and size, were cut from one TWIP steel sheet, on which a simulated Laser Beam Welding (LBW) line had been previously performed with an industrial apparatus, by means of a NdYAG laser with 3 kW rated power and by using helium as the protective gas, with the following process parameters: feed rate from 2.2 to 2.7 m/min and power input from 2.4 to 2.8 kW. Specimen blanks were cut to obtain the welded line as perpendicular to the specimen tensile axis and located at its mid-length (Fig. 1c).

The microstructures and microhardness of these welded joints were previously reported [16] and are summarized here. The molten zone of the RSW joints between the DP steel sheets consists mostly of martensite, lower bainite and retained austenite, with a much higher hardness than the base metal (about 430 HV), and with intermediate properties in the HAZ. On the contrary, in both the RSW joints and the simulated LBW joints, performed on the TWIP steel, the molten zone and the HAZ are fully austenitic, like the base metal, and the hardness throughout the joints is not much different than in the base metal.

The welded, or pre-strained and welded, tensile specimens were then tested with the same procedures used for the as-fabricated sheet specimens. In both the tensile and fatigue tests the apparent stress and strain were calculated on the basis of the specimen cross-section away from the welded region. Thus, both the modification of the cross-section, and the notch effect, caused by welding, were not taken into account; for such a reason, we will refer to “apparent” stresses and strains.

## RESULTS

### *Tensile tests*

The tensile curves of the as-fabricated steel sheets and the apparent tensile curves of the welded specimens are shown in Fig. 2.

The Yield Stress (YS), Ultimate Tensile Stress (UTS), and elongation-to-fracture of the as-fabricated TWIP steel, are: 465 MPa, 960 MPa and 47%, in the rolling direction; the analogous properties for the Q&P steel are: 733 MPa, 1007 MPa and 18 %; finally, for the DP steel they are: 705 MPa, 1013 MPa and 13%. The TWIP steel exhibits series of serration on its tensile curve, which are due to the Portevin - Le Chatelier effect [8-12].

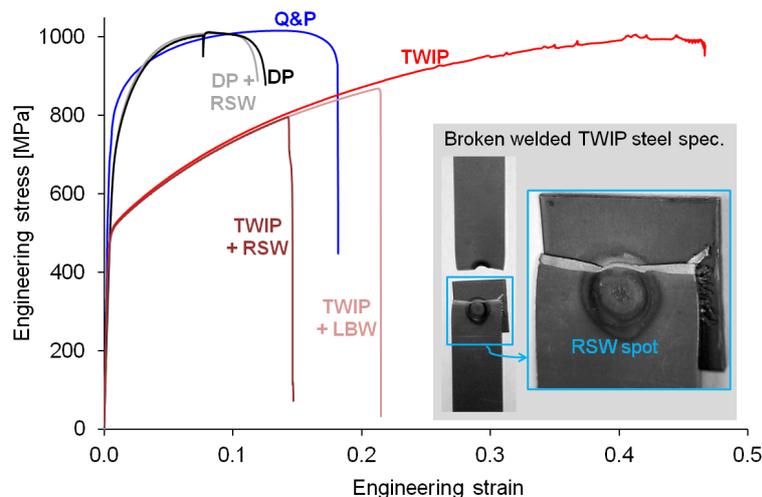


Figure 2: Tensile curves of the TWIP, Q&P and DP sheet steels, either as-fabricated or after welding with the RSW or LBW technique, and detail of a fractured specimen.



The DP steel samples, welded with one RSW spot, which were tested in traction, broke far away from the weld spot itself and their apparent tensile curves are almost identical to the tensile curve of the as received DP steel.

The welded TWIP steel specimens, on the contrary, did always break close to the welded joint; their apparent tensile curves are initially almost identical to the tensile curve of the as received TWIP steel, with an earlier rupture occurring in the weld regions at fracture stress and elongation-to-fracture equal to 796 MPa and 14 %, for the sample with the RSW spot, and to 868 MPa and 21 %, for the sample with the simulated LBW line, respectively (Fig. 2).

### Fatigue

The stress-life fatigue tests results, pertaining to the as-fabricated and welded samples, are summarized in Fig. 3; the DP and TWIP steels fatigue strength (defined here as the stress amplitude, leading to 50% survival probability after 1 million cycles, with zero load ratio) is 570 and 410 MPa, respectively, as obtained by unnotched specimens.

Notwithstanding the slight difference in the load ratio (0.1 instead of 0), and even if the tested stress levels were chosen with different criteria, it is apparent that the stress-life fatigue behavior of the Q&P steel is at least equal, and probably better, than that of the DP steel (which, in turn, is better than the TWIP steel, as stated above).

The apparent fatigue strength of the TWIP steel samples with the simulated LW line, namely 400 MPa, is almost equal to the fatigue strength of the as received TWIP steel; this is further confirmed by the fact that two of these samples (not used to calculate the fatigue limit and not shown in Fig. 3) were broken by fatigue away from the welded joint.

The sheet samples with RSW spots, on the contrary, show considerably lower fatigue resistance, i.e. 210 MPa for the TWIP steel and 190 MPa for DP steel, and did always break within or around the weld spots.

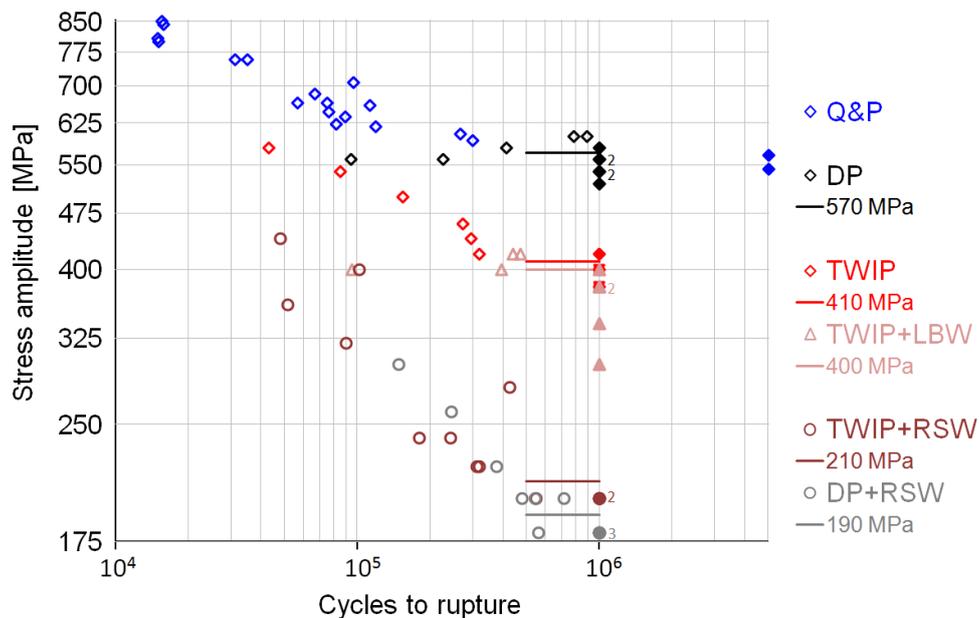


Figure 3: Stress-life fatigue test results of the TWIP, Q&P and DP steels, either as-fabricated or after welding by the RSW or LBW technique, and calculated 1 million cycles fatigue strength values. The load ratio was 0.1 for the Q&P steel and 0 in all the other cases. Unbroken specimens are shown with filled symbols and number of repetitions.

The effect of the 7% pre-straining operation on the apparent stress-life fatigue behavior of the resistance spot welded samples is shown in Fig. 4. The fatigue strength of the TWIP steel, after pre-straining and welding, is remarkably lower than after welding alone (150 vs. 210 MPa), whereas in the DP steel case pre-strain and RSW do not sensibly modify fatigue strength, in respect to simple RSW.

The fatigue crack of the resistance spot welded specimens was generally nucleated on the edge of the welding spot and then grew in both directions, at first along the same edge, and then toward the short sides of the specimen cross section; the fatigue fracture surface was tangent to the edge of the welding spot and perpendicular to the tensile axis, whereas the final overload fracture surface was inclined by about 45° in respect to both the tensile axis and the sheet plane (Fig. 4b); the latter feature most often occurred at both ends of the fracture path, but in some specimens it was evident at one end only. In particular, the more detailed SEM investigation of one TWIP specimen (Fig. 4a to 4f) evidenced that the fatigue crack was likely nucleated from a shrinkage porosity (Fig. 4c,d) and that the fatigue fracture surface of the heat affected

zone and of the adjacent material unaffected by the welding process are microscopically different (Fig. 4e,f), even if both exhibit fatigue striations, because in the latter case the striations are more evident and less influenced by the microstructure.

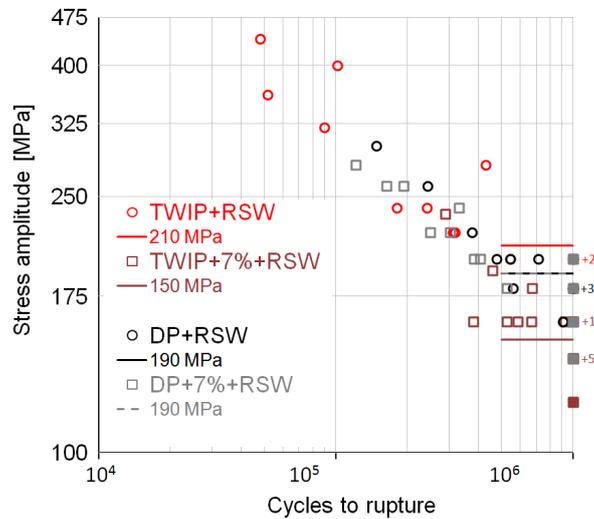


Figure 4: Stress-life fatigue test results of the TWIP and DP steels, after resistance spot welding (RSW), or after 7% pre-straining and RSW, and calculated 1 million cycles fatigue strength values. The load ratio was 0. Unbroken specimens are shown with filled symbols and number of repetitions.

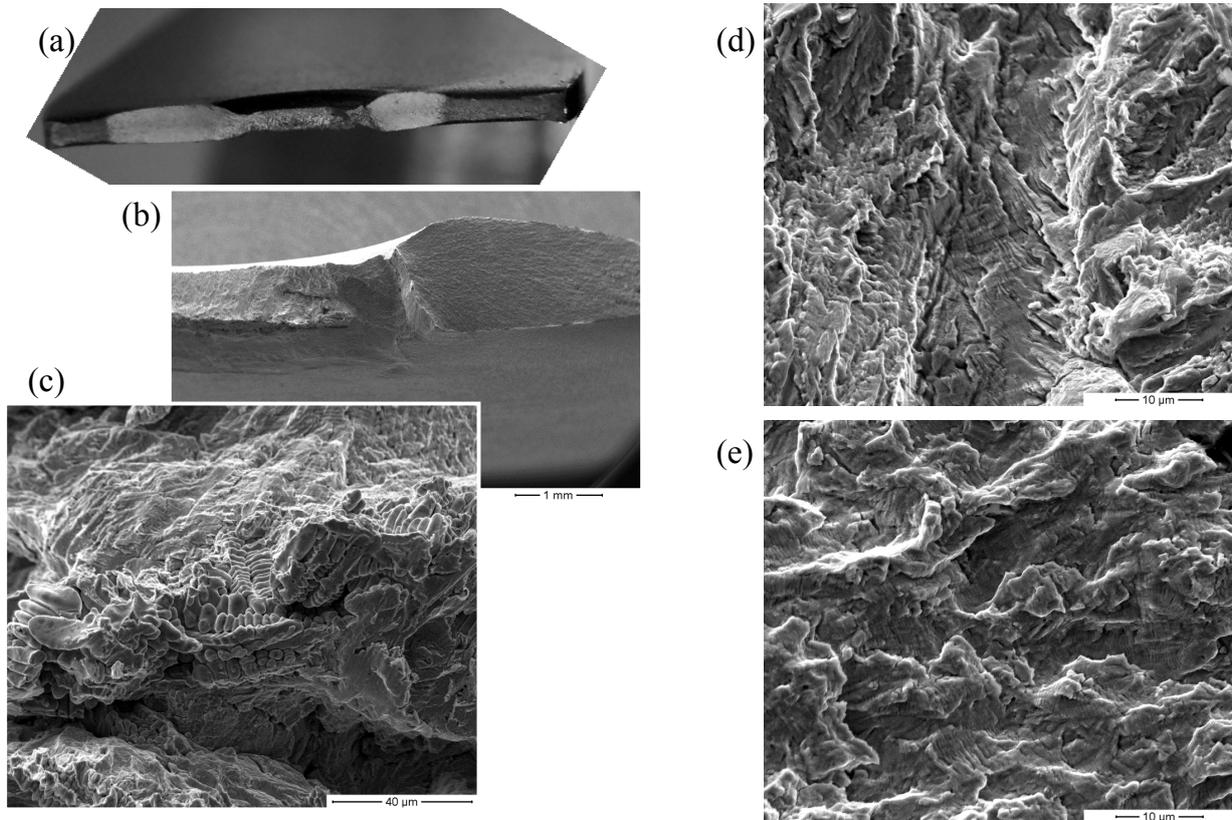


Figure 4: Fracture surface of a TWIP steel specimen, subjected to RSW and broken after 48,016 fatigue cycles from 0 to 440 MPa (top half with respect to the enclosure in Fig. 2). Overall view and successive enlargements of the fatigue crack initiation region (a, b, c); fatigue crack growth surface of the heat affected zone (d) and of the base metal (e).



## DISCUSSION

**D**P and Q&P steels are both characterized by a two-phase microstructure, with austenite in place of ferrite in the latter one. Even if neither ferrite nor austenite are able to exhibit their full ductility properties, due to a local situation of constrained ductility, [20] austenite is definitely more ductile than ferrite and induces larger elongations-to-fracture in the as-fabricated Q&P steels, as compared to DP steels.

As it regards fatigue test results of the as fabricated-steels, fatigue strengths are in the same order as the steels yield strengths, with DP and Q&P steels exhibiting similar values, close to 570 MPa, and the TWIP steel lower values (400 MPa ca.). This fact may be explained by considering the FCC crystal structure and the lower yield stress of the TWIP steel, which imply that the microplasticity phenomena, which promote the fatigue crack nucleation, may occur at lower stress in the TWIP steel, in comparison with the DP and Q&P steel.

RSW induces the formation of martensite structures in the spot welded regions of DP steels, thus causing welded specimens to deform and break in the unwelded regions, which obviously exhibit a behavior similar to as-fabricated specimens. TWIP steels specimens, instead, do not show a different phase constitution in welded or not welded areas; thus, variation in tensile behavior is dictated by the large notch effect induced by spot welding. LBW induces a much lower notch effect; therefore LBW tensile behaviors are controlled by the different grain sizes and/or by the solidification flaws produced by welding.

RSW induces in both DP and TWIP steels large reductions of fatigue strengths due to the notch effect caused by spot welding, confirming previous literature results [4]. In these cases, the geometrical stress concentration is more important than the local microstructural variations. This is the reason of the adequate behavior of the LBW fatigue specimens, where neither a relevant notch effect, nor a phase constitution variation, are introduced by the welding procedure, as compared to the as-fabricated material.

## CONCLUSIONS

**T**wo new high-strength car-body steels have been examined: a TWIP (TWinning Induced Plasticity) high-Mn austenitic steel, and a Q&P (Quenching and Partitioning) steel. The new steels are compared with a widely used, high-strength, DP (Dual-Phase) automotive steel grade.

Both TWIP and Q&P steels exhibit 1 GPa UTS, similar to the DP steel, but a better ductility; 45 and 18 %, respectively, as compared to 13 % for the DP steel.

The stress-life curve of the Q&P steel is comparable with the reference DP steel, whereas, on the contrary, the stress-life curve of the TWIP steel is remarkably lower.

The DP steel exhibit a higher fatigue strength at 1 million cycles than the TWIP steel, i.e. 570 MPa versus 410 MPa.

The TWIP welded samples exhibit similar tensile curves, but premature failures, in respect to the as-fabricate material, whereas the DP steel tensile curves are not affected by welding, since the fracture occurs outside the weld region.

After homologous resistance spot welding, both DP and TWIP steels show a much lower apparent fatigue strength, i.e. 190 and 210 MPa.

The fatigue behavior of the pre-strained and welded samples, fabricated with the DP steel, is not sensibly different from the behavior of the specimens which were simply welded; instead, the fatigue strength of the TWIP steel, after pre-straining and welding, is remarkably lower than after welding alone (150 vs. 210 MPa).

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