

DUAL PHASE STEEL - HIGH STRENGTH FASTENERS WITHOUT HEAT TREATMENT

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Abstract

The mechanical and physical properties of steel fasteners are specified by international standards such as EN ISO 898 1999. These standards give details of the strength requirements for various property classes. For high strength fasteners graded 8.8 and above EN ISO 898 1999 also states the requirement for quench & temper processing and the necessary tempering temperature. However, steelmakers have been developing improved cold heading grades with combinations of strength and ductility that allow high strength properties to be achieved in the as-formed condition, thus eliminating the need for expensive heat treatments.

Dupla™ a newly developed steel from Corus is a ferrite plus martensite dual phase cold heading steel developed to take costs out of the high strength fastener manufacturing process. Tight composition, process and microstructural control provide a consistent rod product that requires neither spheroidisation annealing nor quench & temper heat treatments. The required strength levels are achieved by drawing to size, with cold heading performed on the as-drawn wire. The formability and achievement of high strength product specifications have been demonstrated on a variety of fastener designs.

Extensive component testing and analysis of service conditions enables efficient customer process routes to be designed, removing expensive and time consuming heat treatments. Eliminating process stages takes costs out, improves logistics and reduces product lead times.

There is a competitive advantage to be gained by utilising new steel products which improve in-house manufacturing efficiencies. Are the requirements within the standard acting as a barrier to adoption?

1 Introduction

The desire to produce higher strength steels with formability greater than those obtained in conventional controlled rolled high strength microalloyed grades has led to the development of microstructure strengthened steels. These include dual phase, retained austenite (or TRIP), complex phase and martensitic steels. Of the microstructure strengthened grades martensitic steels have the highest strength, often in excess of 1200MPa, with dual phase steels having the highest formability. The high formability of dual phase steels is due to low yield to tensile strength ratio with high work hardening rates, promoting uniform elongation. In addition to high ductility, dual phase steels also exhibit a strong bake hardening response and have excellent fatigue resistance.

Due to the exceptional strength, formability and associated properties of dual phase grades they have found numerous applications in the automotive sector, including safety critical products such as side impact bars and wheel rims [1-3]. Obviously, the combination of mechanical properties that has encouraged the development and adoption of these steels in the high strength strip market sector is also of relevance to wire rod customers. This is particularly the case where these grades could eliminate the requirement for subsequent downstream processing operations or where their use simplifies the production of complex components. For this reason Corus Construction & Industrial has been developing microstructure strengthened steels, with emphasis on steels for high strength cold headed applications.

The typical process route for the production of “standard” strength and “high” strength fasteners is illustrated in figure 1. The distinction between the two types is based on the requirement for quench and tempering (Q&T) treatments for high strength fasteners with property classes of 8.8 (800MPa tensile strength and minimum yield strength of 80% of this value) and above, as specified in BS EN ISO 898-1:1999 [4]. Improvements in composition control and processing, providing enhanced as-rolled ductility in conventional low carbon and boron treated grades, have already eliminated the need for spheroidisation annealing in many less demanding cold heading operations. However, with conventional steels it has not yet been possible to produce grades with tensile strength in excess of 800MPa that are sufficiently ductile to allow cold heading. Therefore, for the high strength property classes heading has been performed in a softened condition. The shaped components are subsequently hardened by a Q&T process. Standards such as BS EN ISO 898 have simply reflected this practice.

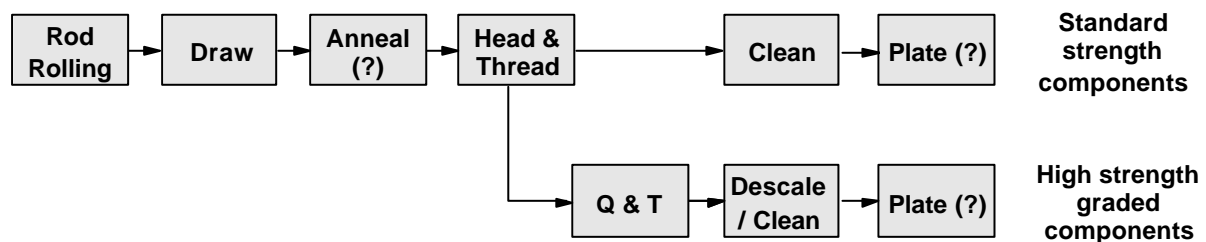


Figure 1. Typical process routes for standard and high strength mechanical fasteners.

This work describes the development of Dupla from Corus, dual phase rod which can be processed to meet the requirements for 8.8 properties, yet is sufficiently formable to allow cold heading. Dupla enables property class 8.8 cold headed components to be produced eliminating the need for expensive Q&T treatments. Although the cost of Q&T treatments vary based on whether they are performed in-

house or contracted out and also depend on the furnace atmospheres used, Q&T is usually the most costly processing stage in the production of high strength fasteners.

The paper describes the potential benefits of the Dupla cold heading steel and discusses the additional process understanding required and potential constraints on the use of this material.

1.1 Metallurgy of Dual Phase Steels

Dual phase steels are characterised by a matrix of fine ferrite containing small islands of martensite (figure 2). The hard martensite particles provide substantial strengthening while the ductile ferrite matrix gives good formability.

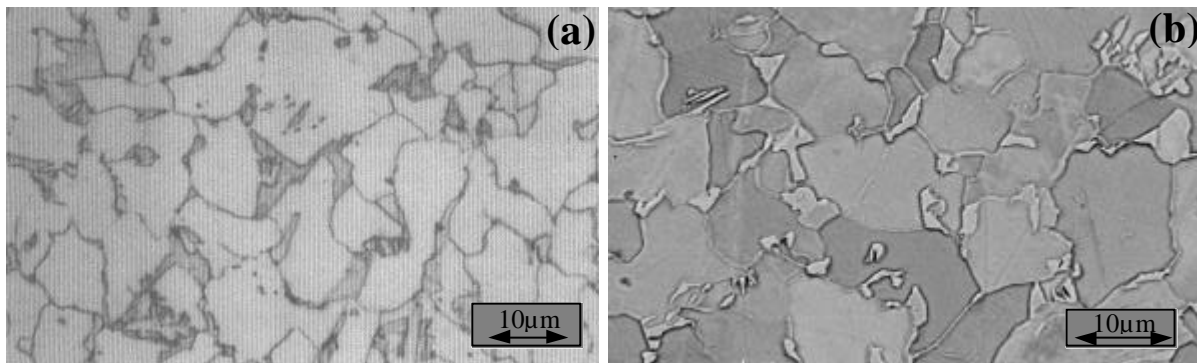


Figure 2. Optical (a) and back scattered electron (b) images of typical Dupla dual phase rod microstructures.

The martensite/ferrite dual phase mixture acts like a particle reinforced composite. The tensile strength of the composite can be approximated by a simple rule of mixtures [5],

$$\sigma_{DP} = V_F \sigma_F + V_M \sigma_M$$

where, V is the volume fraction of the phases and σ is tensile strength. The subscripts DP, F and M indicate the composite dual phase structure and the ferrite and martensite phases respectively.

As martensite is the stronger phase, increasing the volume fraction increases the strength of the dual phase material. Unfortunately increasing the martensite content reduces ductility and for this reason the volume fraction is usually restricted in the range 10 to 20%, where the martensite remains as discrete isolated islands in an interconnected ferrite matrix.

Further, to maintain high ductility in these steels it is desirable not only to limit the martensite fraction, but also to restrict the carbon content of this phase. At lower carbon contents (<0.4wt%) lath martensite forms, rather than high carbon twinned martensite. Lath martensite is desirable as it will deform to a limited degree and this helps to delay void formation at martensite/ferrite interfaces when the material is strained.

Therefore the carbon content of dual phase steels is usually limited to ~0.1wt% maximum. For these typical compositions, with martensite volume fraction of ~15%, dual phase steels give tensile strengths in the range 550 to 650MPa in the as-rolled condition.

To produce a dual phase microstructure, the equilibrium pearlite phase needs to be eliminated, with austenite being encouraged to form martensite by rapid cooling. The simplest method for producing dual phase microstructures is to anneal a ferrite/pearlite steel in the intercritical temperature range. The annealing temperature is controlled within the ferrite plus austenite two phase region, such that much of the room temperature ferrite phase remains. The pearlite reverts to carbon rich austenite. When the steel is then quenched from the annealing temperature the austenite proportion is sufficiently hardenable to transform to martensite. By controlling the steel chemistry and annealing temperature, both the phase fractions and the properties of martensite can be adjusted.

The need for a post rolling heat treatment adds significantly to costs and methods have subsequently been developed to produce dual phase microstructures by direct rolling and cooling. This has been achieved through a combination of process control and new alloy design. The new chemistries are low in carbon and rich in hardenability enhancing elements. The low carbon content encourages ferrite to form at temperatures above that necessary for pearlite formation. Other additions delay the pearlite transformation and therefore increase the potential to form martensite. The post rolling cooling process is controlled to allow the desired volume fraction of ferrite to form before rapid cooling. The later stage cooling rate must be sufficient to “quench” the remaining austenite to martensite.

Although the properties of the dual phase material depend on the volume fraction of the phases as indicated by equation 1, Thomas [6] has suggested that for a given composition this relationship does not strictly hold. The reason for this is that changing the amount of martensite will also affect its properties. In the two phase ferrite plus austenite region, prior to quenching, the carbon can be assumed to have partitioned almost entirely to the austenite phase (at equilibrium ferrite contains <0.02wt% carbon). The carbon enrichment in the austenite, which is quenched to martensite, depends on the austenite volume fraction. If there is a large amount of austenite present immediately before the quench it will be dilute in carbon. In the quench this will transform to a higher volume fraction of martensite, which is relatively low in carbon and hence lower in strength. Conversely if there is only a limited austenite fraction then this will be richer in carbon. This austenite will transform to a lower volume fraction of higher carbon, higher strength martensite on quenching. Within the 10-20% martensite volume fraction range the properties for a given composition dual phase steel are reasonably consistent and relatively insensitive to minor processing variations.

2 Dupla rod from Corus

The typical chemical composition of Dupla dual phase steel developed at Corus is shown in table 1. The steel is based on a C-Si-Mn compositions, with ~0.08-0.1% carbon, ~1% silicon and 1.7% manganese. The high silicon and manganese content increases the hardenability, thereby enabling martensite to be produced at relatively low cooling rates and promote the formation of martensite with lower carbon contents. These additions also provide a substantial solid solution hardening contribution. Dupla is BOS steel produced as continuously cast 750x355mm bloom. Low residual levels are typical of BOS steel and are essential to maintain adequate ductility.

	C	Si	Mn	P	S	Cr
Dupla	0.08	1.0	1.7	0.010	0.005	0.016

Table 1. Typical chemical composition of Dupla dual phase steel, in weight %.

2.1 Rod Rolling

Billets are rolled from $\sim 1200^{\circ}\text{C}$ through 21-25 passes, with finishing reductions carried out in 6-10 passes in a continuous no-twist mill. The rod emerges from the no twist mill at $\sim 35\text{-}65\text{m/s}$ and a temperature of $\sim 1000^{\circ}\text{C}$. On exit from the no twist mill the rod is rapidly cooled to a temperature at which it is “laid” onto a Stelmor forced air cooling line. Once on the Stelmor conveyor, slow cooling is maintained until the required proportion of ferrite has transformed, at which point the forced air-cooling rate is increased sufficiently to cause the remaining carbon enriched austenite to transform to martensite. The process route is designed to produce a fine grained dual phase microstructure in the hot rolled rod coil, without requiring any further heat treatments. Figure 3 shows a schematic CCT diagram illustrating the effect of carbon partitioning during ferrite formation on transformation behaviour.

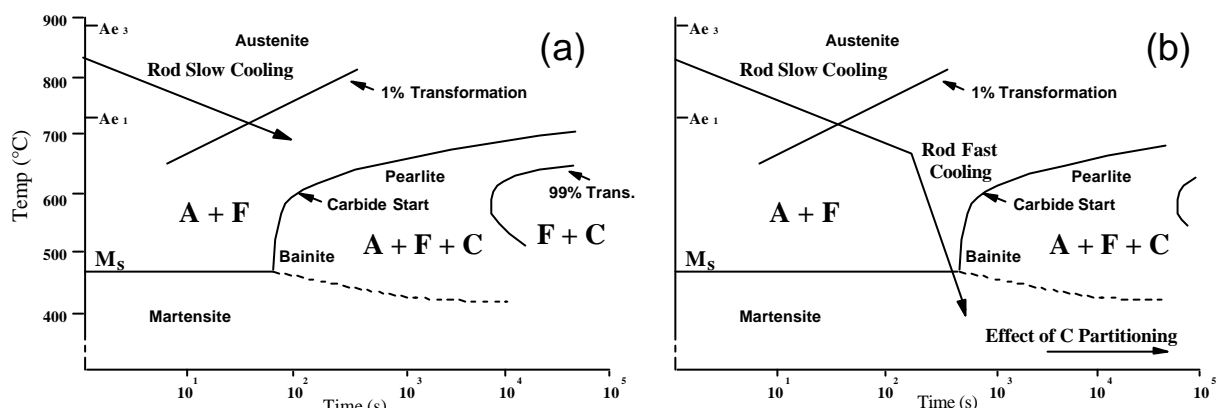


Figure 3. Schematic CCT diagrams for dual phase process route. (a) CCT diagram at the start of transformation. (b) Effect of carbon partitioning during transformation delaying the carbide start reaction and increases potential for forming martensite.

2.2 Microstructure and Mechanical Properties

Figure 2 showed typical microstructures of the as-rolled Dupla material, with table 2 summarising details of the typical structures seen in a range of rollings. It is clear that the product is not strictly dual phase as small amounts of pearlite and bainite are not uncommon. However, any pearlite present is in the form of small isolated patches and is often degenerate/globular in nature. The martensite content is successfully controlled to the desirable 10-20% range. The ferrite grain size is maintained at \sim ASTM 10 for the range of product sizes rolled.

Ferrite ASTM Grain Size No.	Microstructural Constituents (volume %)			
	Ferrite	Pearlite	Bainite	Martensite
8-10	70-75	<2	7-13	15-20

Table 2. Typical range of microstructures seen in Dupla rod rolled to a range of rod sizes.

Due to the configuration of Stelmor cooling with the rod laid into a helical coil, different parts of the rod experience different post rolling cooling. Where material is bunched together the cooling rate will be slower and although the air flow rates in these regions are increased there is the possibility that round ring properties could show variability. Figure 4 is the round ring tensile strength data showing

the very consistent product properties obtained from the Dupla material. The as-rolled tensile strength is in the range 575 to 675MPa. To achieve this value even with the high strength dual phase structure requires a significant solid solution hardening contribution at the aim carbon level, hence the high manganese and silicon contents. From simple structure property equation calculations, the combined effect of manganese and silicon on tensile strength is in excess of 100MPa [7].

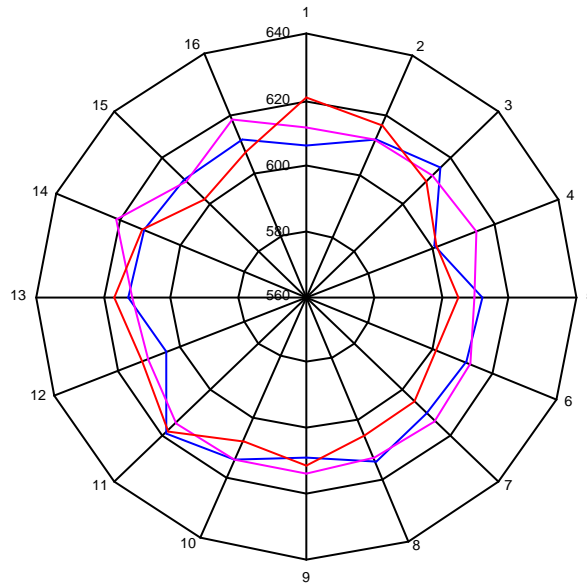


Figure 4. Round ring tensile strength properties for 5.5, 6.5 and 8.0mm as-rolled rod.
(Tensile strength values in MPa)

The consistency of properties shown in figure 4 is maintained across the range of rod diameters produced. Round ring as-rolled ductility levels, as measured by cross sectional reduction of area at failure, are similarly consistent in the range 60 to 70 %.

It is clear from the foregoing that although the as-rolled rod mechanical properties are consistent, the tensile strength is below 800MPa minimum required to meet the tensile strength specification for grade 8.8 components. However, it is the final component properties and not the rod properties which must meet the specified property requirements. The forming process from rod to component involves significant cold work, both in drawing the rod to correctly sized wire (to ensure correct die filling) and in the heading itself. Both these operations work harden the steel and increase tensile strength.

Although the heading operation produces significant work hardening, the deformation is non-uniform and the shank of a component often receives little or no cold work. Because the shank of a component not only transmits the load but also has the smallest cross section, it is the shank region in particular which must meet the minimum property levels. Therefore, it is necessary to achieve the property requirements in the drawn wire, which then relates directly to shank properties. Because of high work hardening rates the choice of rod size is an important consideration when employing dual phase type steels.

The Dupla grade has been developed with an aim as-rolled tensile strength of 575 to 675MPa, which when drawn ~25% reduction in area work hardens to >800MPa. Typical drawn wire mechanical

properties are given in table 3. Obviously, the ductility in the drawn wire condition is not as great as spheroidise annealed boron treated low carbon grades. However, the ductility is sufficient for the majority of heading operations particularly as martensite particles act to prevent crack propagation. Figure 5 shows a range of cold headed components produced from Dupla wire, all with a minimum tensile strength of 800MPa.

As-Rolled Rod		Wire – Drawn 27 % R of A	
Tensile Strength	R of A Ductility	Tensile Strength	R of A Ductility
610MPa	63%	810MPa	55%

Table 3. Typical mechanical properties of Dupla rod and drawn wire.



Figure 5. Typical cold headed components produced from >800MPa Dupla wire.

3. Dual Phase Benefits

The main incentive for adopting dual phase steels for high strength fastener manufacture is the significant reduction in processing costs that are possible. To understand these potential savings the process route should be mapped both in terms of direct costs but also in logistic and delay costs. The potential benefits will vary greatly from company to company depending on production methods and whether treatments are carried out in-house or contracted out. The three major direct cost savings are detailed below.

- **No spheroidisation anneal.** The controlled cooling regime employed on the Stelmor processing line produces a rod with the required dual phase microstructure and sufficient formability for cold heading. Subsequent annealing is not necessary and would in fact destroy the designed microstructure. No annealing requirement eliminates cost and reduces the raw material lead-time, as additional processing of the rod is not required.
- **No quench and temper treatment.** Q&T involves heating above the austenite transition temperature, followed by rapid cooling to produce martensite (~90% martensite in the core of the shank). The hard and brittle martensite produced is then tempered by holding at elevated temperature (>425°C for property class 8.8 [4]) to improve ductility at the expense of a slight drop in strength. The process requires controlled furnace atmospheres to prevent surface decarburisation and often uses oil or polymer media to provide controlled cooling rates during quenching. As previously stated Q&T is the major processing cost, often in excess of the raw material rod costs, for high strength fasteners.

- **No post Q&T descaling necessary.** Despite the use of controlled furnace atmospheres, adherent scale forms during Q&T heat treatment. This scale has to be removed before plating or for components which may need to be welded. Component descaling is usually carried out by acid pickling in a tumbling operation and is followed by protective oiling. For the dual phase process route no component descaling is necessary with cold heading machine lubrication oil providing short-term corrosion protection.

Obviously cost savings are possible by eliminating these processes but there are also implications for product quality. Fewer processing steps removes the potential for introducing “defects”, which means product quality can usually benefit. For example, it is possible that the quenching process may not be fully effective. If a martensitic structure is not produced during the quench then the final product properties will be below target. Although this is generally more of a problem with the highest strength graded products (10.9 and 12.9) regular component testing is required to ensure adequate heat treatment has been carried out. It is also necessary to carry out metallographic testing to ensure surface decarburisation has not taken place leading to poor properties in threaded regions.

With correct heat treatment conditions it is still possible to introduce significant component distortion, particularly for long components or ones with specific dimensional requirements, e.g. alternator bolts, U-bolts, etc. Removing the high temperature heat treatment means that products retain as-formed dimensions as controlled by the die geometry.

Having produced a correctly dimensioned component with the desired property levels, product quality can be compromised by further processing. For example, if it is necessary to acid descale heat-treated components this is usually carried out in a tumbling operation. The tumbling of components against each other can cause damage to “delicate” areas such as threads which are vital to component performance. Again eliminating the requirement for such operations will reduce the likelihood of causing component damage.

The focus of these arguments is cost savings and potential product quality benefits from dual phase steels. It should be remembered that additional alloying and production costs will mean higher rod prices. However, the through process production costs savings still make Dupla an attractive market proposition.

3.1 Practical Considerations

Having concluded that there is a benefit to be gained from dual phase steel, certain practicalities need to be considered. Unlike Q&T heat-treated components dual phase materials gain their strength through microstructure strengthening plus a contribution from work hardening. It is possible that during elevated temperature service conditions there could be degradation in properties due to recovery of the cold work. Therefore, service temperatures might need to be limited. To investigate the possibility of recovery, a series of elevated temperature ageing trials have been carried out. Samples of drawn wire were aged at a range of temperatures up to 400°C for times of up to 1000hrs.

The results of these ageing trials have been examined by interpreting the time at temperature by the Larsen-Miller parameter as used in creep testing,

$$LM \text{ parameter} = T (20 + \log(t)) / 1000$$

where, T is temperature in Kelvin and t is the time in hours.

The Larsen-Miller parameter allows the effects of extended times at lower temperatures to be simulated by shorter treatments at higher temperatures. Interpretation assumes that the mechanisms taking place do not change at higher temperatures. Figure 6 shows tensile strength of the aged samples plotted against the calculated Larsen-Miller parameter. The chart shows that tensile strength of the drawn wire actually increases with elevated temperature ageing up to 890MPa at an L-M parameter of ~12. This equates to 1000hrs at 250°C or 100,000hrs at 210°C. It is also clear from figure 6 that this increase in strength with ageing is accompanied by an increase in R of A ductility. The observed increase in strength is common in dual phase strip materials where a strong bake hardening response has been seen [1&3] and is attributed to the precipitation of fine carbides. Figure 6 shows that strength does not fall below 800MPa until the time at temperature gives a L-M parameter of >13. This equates to ~100 years at 225°C, i.e. service temperatures up to 225°C are acceptable for the Dupla material.

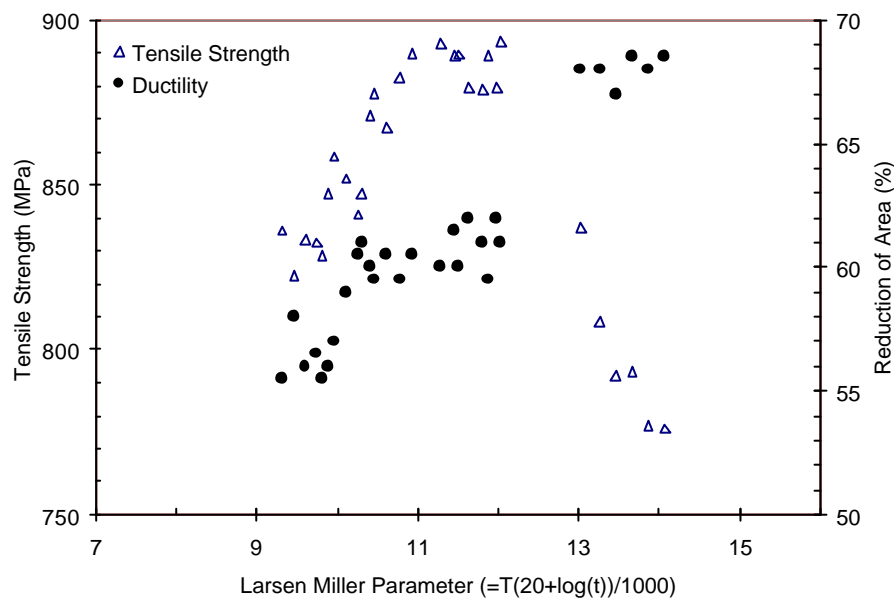


Figure 6. Effect of elevated temperature ageing on tensile strength and ductility of drawn wire.

Another potential difficulty with these grades is that the properties of the final component are not uniform throughout the cross section. As strength is obtained from a combination of microstructure and work hardening, the degree of cold work will affect the properties. The control of as-rolled properties and the drawing process gives a uniform feedstock for cold heading. However, the heading process can produce highly non-uniform deformation. The head region and in particular the head /shank interface can undergo significant cold work raising the tensile strength in these regions in excess of 1000MPa.

At these high strength levels there is a distinct possibility of hydrogen embrittlement if the component is to undergo subsequent electroplating. This has been seen to be the case during component testing with fracture at the head/shank interface and occasional splitting of the head in plated components (see figure 7). The effect of hydrogen embrittlement can however be mitigated by a post plating de-embrittlement treatment at ~200°C. An additional effect of the de-embrittlement treatment is that the

bake hardening reaction indicated takes place. The effect of de-embrittling for 6hrs at 220°C on the tensile strength of M8 weld bolts is given in table 4.

The extreme loading conditions produced by wedge tensile testing (carried out in accordance with BS EN ISO 898-1) can be used to promote brittle fracture at the head/shank interface when it might not be observed under normal tensile loading. Wedge tensile tests have been carried out on de-embrittled components to ensure that the treatment has been fully effective. The results showed no evidence of brittle failures. All de-embrittled components fractured in the threaded shank region and all achieved minimum tensile strengths of >800MPa.



Figure 7. Example of brittle fracture caused by hydrogen pick-up during plating.

As-formed	As-plated	De-embrittled (6hrs @ 220°C)
820 MPa	753 MPa	850 MPa

Table 4. Average tensile strength of Dupla M8 weld bolts in the as-formed, as-plated and de-embrittled components.

Probably the greatest obstacle to widespread commercialisation of dual phase grades for fasteners is not their technical suitability but the requirements of the finished component specifications. Dual phase materials are not Q&T'd and as such they do not match the international standards. Where these standards are specified by the customer dual phase components cannot be directly substituted, but require agreement with the end user and possible modification of specification documents. Where the standards have been adopted for internal use on proprietary products there is greater scope for substitution.

Conclusions

Dual phase steels are microstructure strengthened grades with excellent combinations of strength and ductility. They have a proven track record with numerous applications in the automotive strip sector. The current work has focussed on the development of a dual phase rod for applications in the cold heading industry. The following conclusions have been drawn from this development.

- Appropriate use of dual phase steels for fastener applications can provide substantial cost savings through the elimination of processing stages with associated logistic, environmental and product quality benefits.
- Dupla from Corus is suitable for service temperatures up to 225°C. At these temperatures the steel exhibits a strong bake hardening response, improving both strength and ductility.

- Potential service conditions, product performance and relevant specifications should be understood before attempting to substitute dual phase grades for standard heat treatable steels.
- Without a change in material specifications, such as BS EN ISO 898-1, it is unlikely that new steel grades will significantly penetrate the market for high strength fasteners.

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