THE DEVELOPMENT OF ULTRAHIGH STRENGTH WIRE

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ABSTRACT

This paper details the collaborative development of a new grade of steel, designed for the production of large diameter ultrahigh strength hot-dip galvanised wire, with a minimum tensile strength of 1960 MPa. The new grade is an ultrahigh carbon steel (0.90wt%), alloyed with silicon and chromium. The silicon has been shown to be beneficial as it minimises the loss in tensile strength during galvanising [1-4], which usually occurs due to a strain ageing reaction. Details of the development programme are given, from small-scale laboratory experiments assessing potential compositions, culminating with a full scale production cast produced by Corus, which was processed to wire for spiral strand by Bridon.

This work has led to 1960 MPa grade 'ultrahigh tensile' galvanised wire being made commercially available. The benefits from this new grade are numerous across a diverse range of galvanised wire products. One major product area is for permanent mooring systems for floating production vessels used by the offshore oil industry, where the stronger wires enable higher strength, lighter cables to be manufactured, supporting exploration and production in more demanding deep water oil fields. The manufacture of such a system utilising the new steel grade has recently been completed and is due to be installed in the Gulf of Mexico during summer 2005.

KEYWORDS

Ultrahigh Strength, Rod, Wire, Silicon, Chromium, Galvanising, Ageing, Cable.

INTRODUCTION

Large diameter, high strength hot-dipped galvanised wire is utilised in a number of diverse applications, such as mooring cables and anchor lines for the offshore oil industry, the main cables of suspension bridges, structural stay cables in civil engineering projects and roof bolts for the mining sector. Whilst the use of such high strength wire is well established, there is a continuous customer drive for enhancing the ultimate tensile strength of the wire, and thus improving the strength to weight ratio of the cables. Over the past 25 years the development of microalloyed steels along with advances in steelmaking and wire drawing practice has resulted in a number of incremental improvements in the UTS of commercially available galvanised wire, shown in table 1.

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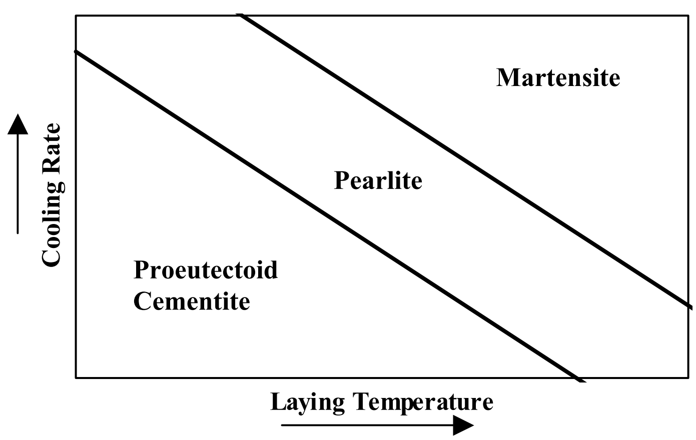
Table 1 Commercially Available Grades of 5.0mm Galvanised Wire

Grade	Min Tensile Strength	
	Kgf/mm²	MPa
Normal Tensile	160	1570
High Tensile	180	1760
Super Tensile	190	1860

Various processing operations are utilised for the production of high strength galvanised wire, all of which require careful control to ensure the demanding specifications are met. At Corus, the BOS plant produces the liquid steel, which is continuously cast to blooms. These blooms are converted to billet and supplied to the rod mill, where the billets are reheated and rolled down to rod (ranging from 5.0 – 13.5mm dia.) into approximately 2 tonne coils. At the end of the rolling stage the coils are laid out onto a cooling conveyor and a series of fans supply a controlled air blast to cool the rod at the required rate, in order to produce a pearlitic microstructure suitable for drawing. In order to achieve high strength and ductility, a fine pearlitic microstructure is essential. This consists of continuous laths of ferrite and cementite, which re-orientate and deform during the drawing process, whilst work hardening to very high strengths. If the cooling conditions are not optimised, then other detrimental phases such as proeutectoid cementite, bainite or martensite may also be formed. These phases cause problems during drawing, and are influenced by the rod processing conditions, as shown schematically in figure 1.

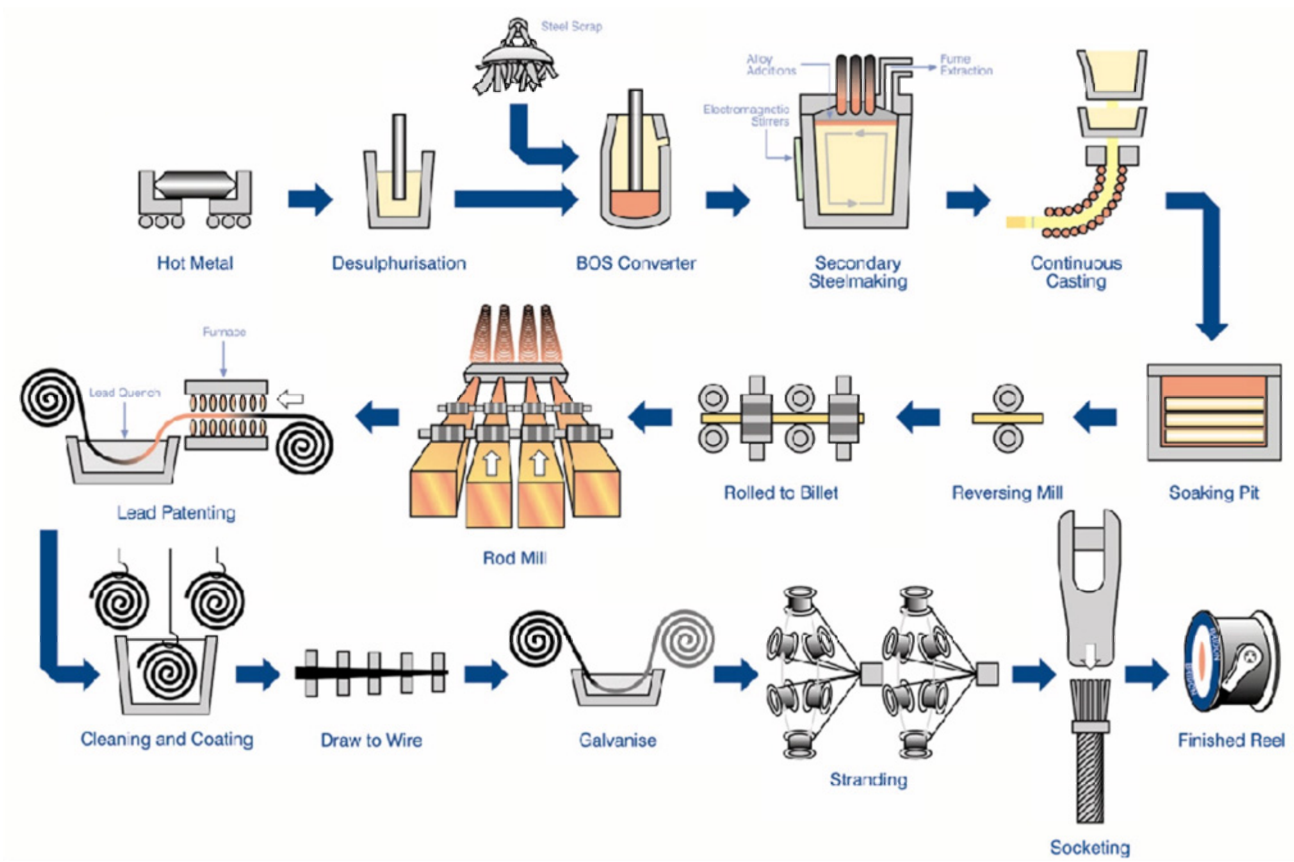
Fig. 1 Influence of Cooling Rate and Laying Temperature on Rod Microstructure



The coils of rod are supplied to the wire drawers, such as Bridon International Ltd, who draw the rod to wire, galvanise and manufacture the high strength rope and strand. The rod feedstock can either be directly drawn to wire or heat treated prior to drawing to refine the pearlite further, thus maximising the tensile strength. This heat treatment, which is known as 'patenting' consists of re-austenitising the rod in a gas-fired furnace followed by quenching into a lead bath set at the optimum temperature to isothermally transform the austenite to a very fine pearlitic microstructure, i.e. force the pearlite transformation to take place just above the pearlite 'nose' of the TTT curve. This produces a very fine pearlite, much finer than can be attained by continuously cooling the rod, as at the rod mill.

Prior to drawing, the rod is acid cleaned to remove the scale and then phosphate coated in readiness for the drawing operation. Wire drawing takes place on multi-hole drawing machines with water-cooled dies and cooling blocks, in order to control the wire temperature and minimise strain ageing. The drawing reduction per pass and drawing speed are carefully selected for this reason. Typically for longer life applications, the wire is first drawn uncoated (known as bright wire), and then hot-dip galvanised to provide a zinc coating to a specified thickness for corrosion protection. The resultant hot dip galvanised wire can either be stranded into cables or supplied as coils of wire dependant on the required application. A schematic of the production route for high strength galvanised wire and cable is shown in figure 2.

Fig. 2 Production Route for High Strength Galvanised Wire / Cable



The provision of higher strength, smaller diameter wire and rope facilitates solutions to a number of challenges occurring over a range of market sectors. For example, floating oilfield developments in deeper water locations require longer, lighter mooring cables and smaller diameter ropes enable the use of either existing or smaller more energy efficient handling winches while achieving more extreme specifications. Higher strength bridge wires can support longer span bridges and reduce the size and cost of other bridge structure components. Furthermore, the use of a higher strength grade of steel in the direct drawn condition may replace a lower strength grade in the patented condition, enabling the most efficient manufacturing routes to be utilised.

The detailed property requirements for high strength galvanised wire depend on the final application and are usually specified by the customer. Typically, for fatigue sensitive applications the ductility of the wire is important and may be measured by tensile ductility (reduction of area measurement

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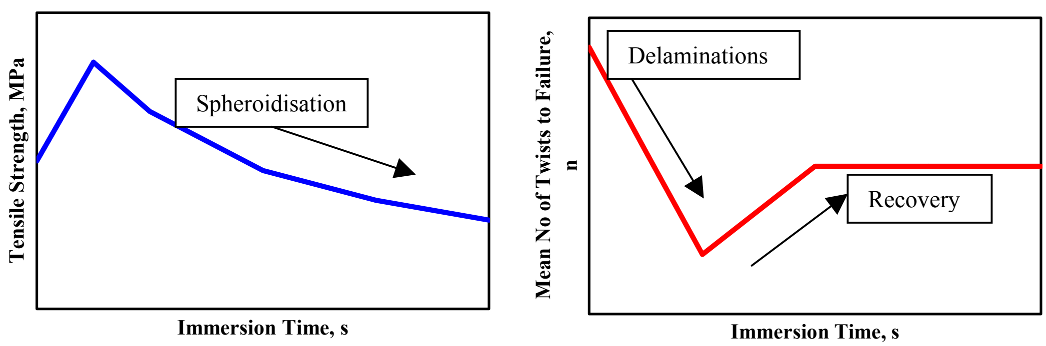
following tensile testing), reverse bend testing and torsional ductility (twisting the wire). For torsional testing, both the number of twists to fracture and the fracture type are important. The desired fracture type is a flat 90° break, perpendicular to the central axis of the wire (type A). Stepped fracture surfaces (type B) and ragged or delaminated breaks (type C) are an indication of reduced ductility and can result in the wire being rejected by the customer.

The strain ageing response of the steel during drawing (dynamic) and galvanising (static) is known to significantly influence the strength and ductility of the finished wire. It is thought that carbon atoms migrating from the cementite into the ferrite laths are responsible for this process, with a number of controlling factors, i.e. rod microstructure, wire temperature during drawing, drawing schedule, total drawing strain and time at temperature during galvanising [5]. This ageing response can be characterised by immersing as-drawn wire into a salt-bath (at typical galvanising temperatures) for a series of different times, and measuring the resultant properties (usually tensile strength and torsional ductility). Typically, at short immersion times, the carbon atoms are locking dislocations, causing an increase in tensile strength and decease in torsional properties. As the carbon atoms cluster and grow, they become too large to pin the dislocations and the ductility begins to recover (type A fractures), usually with a corresponding decrease in strength. During this time, the cementite laths of the pearlite begin to spheroidise. Typical ageing response curves are shown in figure 3.

Fig. 3 Schematic of Ageing Response Characteristics



The tensile strength of the galvanised wire can be increased by a number of methods. One option is to increase the drawing reduction, i.e. utilise a larger diameter rod feedstock. The disadvantage to this being that as the drawing strain is increased, the ductility of the finished wire is reduced and strain ageing may be more severe. This could lead to a large loss in tensile strength during hot dip galvanising along with poor ductility in the finished wire. A better approach is to increase the strength of the rod feedstock, via optimising the composition of the steel, i.e. designing a new steel to suit the processing conditions.

This paper presents the culmination of an extensive collaborative development programme between Corus plc and Bridon International ltd to develop a new grade of steel, capable of being processed to an even higher level of tensile strength than currently available, i.e. to develop an 'ultrahigh tensile' strength (min UTS of 1960MPa (200Kgf/mm²)) galvanised wire product. Such collaboration was essential for this development, in order to understand the processing requirements throughout the complex production route employed for this demanding product.

1. DEVELOPMENT PROGRAMME

1.1 Composition

In order to develop a new 'ultrahigh strength' grade of galvanised wire, a detailed understanding of the metallurgy is required. Previous collaborative work had highlighted the potential of an ultrahigh carbon steel with additions of silicon and chromium (0.90wt%C-0.60wt%Si-0.20wt%Cr). Therefore, this steel chemistry was selected as the base composition for a detailed examination, initially examining three levels of silicon, as shown in table 2 (in wt.%).

Table 2 Compositions of Experimental Steels

Steel	C	Si	Mn	Cr
1	0.90	0.60	0.50	0.20
2	0.90	0.90	0.50	0.20
3	0.90	1.20	0.50	0.20

The high carbon content of the steel is essential to maximise the strength, as it refines the pearlite spacing. Additions much higher than the 0.9wt% indicated would make the steel prone to proeutectoid cementite formation, which occurs around the grain boundaries and reduces the ductility/drawability significantly. Such a high carbon content requires excellent control over segregation during casting and precise control of the rolling/cooling conditions at the rod mill. Chromium and manganese increase the steel's hardenability, i.e. reduce the temperature at which pearlite begins to transform from austenite, resulting in finer pearlite, which increases the strength. Silicon improves the strength by solid solution strengthening the ferrite laths of the pearlite. Silicon is a ferrite stabiliser and is thought to influence the ageing characteristics and hence the mechanical properties of the galvanised wire. The precise mechanism of how this occurs is not clear, but it has been reported that silicon atoms partition to the ferrite laths and thus influence the kinetics of carbon atom migration during drawing and galvanising [1-4]. The three silicon levels were selected in this work in order to gain a better understanding of the metallurgy of this experimental grade and select the optimum chemistry for commercial processing.

1.2 Laboratory Assessment

In order to examine the influence of silicon content, it was necessary to carry out a laboratory scale assessment of the three compositions. Small (60kg) laboratory vacuum melts were produced, which were cast to ingots, forged to billet, rolled to bar and ground to 10mm rod samples. This provided the material feedstock to carry out a full simulation at Corus' RD&T research laboratories of the commercial production route described earlier.

Samples from each steel type were subjected to a simulated patenting treatment using a small tube furnace to re-austenitise the steels followed by a salt bath quench to isothermally transform to pearlite. It was found that the quench rates were slower than that of lead (as used commercially), and so the resultant tensile strengths were lower than would be attained via commercial lead patenting. The patented samples were then drawn to 4.43mm diameter wire (80% total reduction of area) on a laboratory draw bench (single hole passes). The laboratory salt bath was then utilised to heat treat the wire, using an identical immersion time and temperature as in commercial galvanising. A summary of the findings is given in table 3.

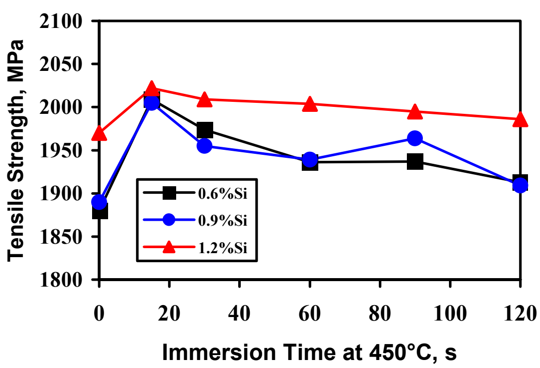
Table 3 Summary of Experimental Steels Assessment

Steel	No of Tests, n	Bright Wire Properties		Simulated Galvanised Wire Properties		
		Avg UTS, MPa (Red of Area, %)	Avg Torsions (50d), n (fracture type)	Avg UTS, MPa (Red of Area, %)	Avg Torsions (50d), n (fracture type)	Avg Reverse Bends
1	2	1880 (50)	18 (A)	1835 (39)	9 (C)	11
2		1890 (56)	17 (A)	1840 (40)	13 (A)	11
3		1970 (51)	18 (A)	1905 (45)	14 (A)	13

Torsional gauge length = 50 x wire dia.

The effect of different immersion times during galvanising were also examined using the salt bath at both 450°C and 500°C, in order to gain an appreciation of the ageing response, as measured by tensile strength and torsional ductility. These data are shown in figures 4 and 5.

Fig. 4 Ageing Response on Tensile Strength



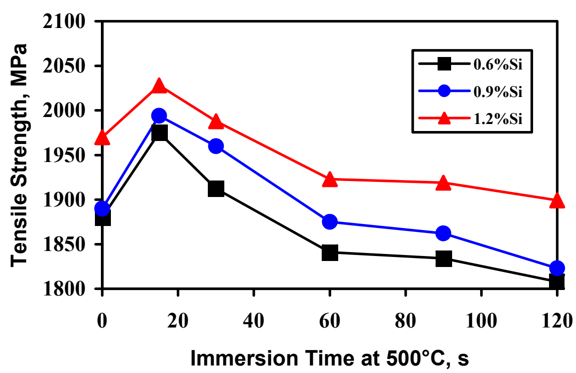
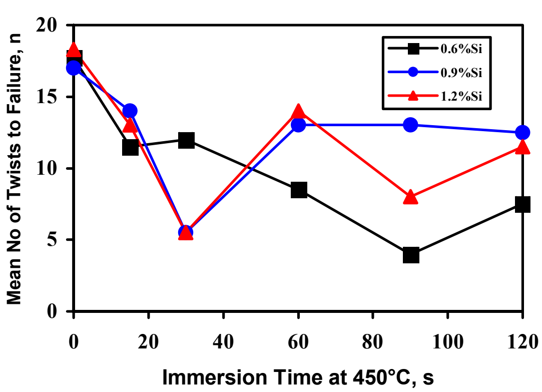
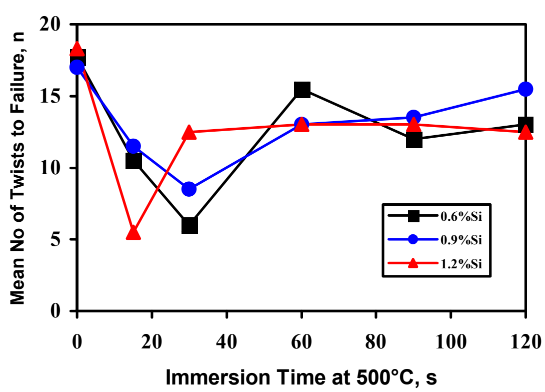


Fig. 5 Ageing Response on Torsional Properties





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Examination of the ageing response curves showed that Steel 3 did not lose tensile strength with immersion time as rapidly as the other two compositions for both temperatures examined. The torsional properties of Steel 3 were also shown to recover to type A fractures faster than the alternative compositions. These results indicated that the high silicon level of 1.2wt% was accelerating the ageing response during galvanising, but with minimal loss in tensile strength thus Steel 3 provided the best opportunity of attaining the required properties when processed commercially to galvanised wire.

In order to produce a fully pearlitic steel at the rod mill, it was necessary to determine the optimum laying temperature and cooling conditions for a range of rod diameters. This was carried out in the laboratory by re-austenitising short lengths of rod and using forced-air cooling to determine the critical cooling rates required to avoid martensite and cementite formation. This work provided the required processing information for the rod mill to successfully roll this new steel.

Once the optimum composition and initial processing temperatures had been established experimentally, the next stage of the development programme was to produce suitable material to roll to rod and draw to wire for a small scale processing trial under commercial production conditions

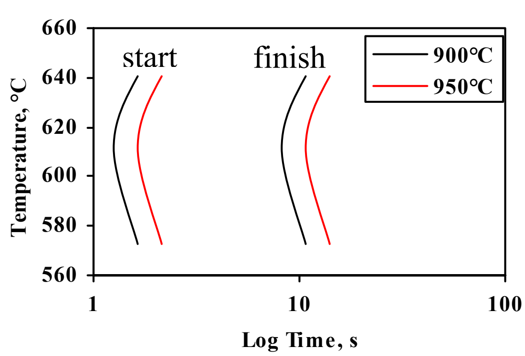
A number of other issues also required resolving during the processing trials, such as the rolling loads required, the descalability (as high silicon steels can form fayalite, a 'sticky scale' which is difficult to remove), the patenting conditions (as silicon will raise the pearlite nose) and the drawing performance of this new steel on a fast multi-hole modern drawing machine.

1.3 PROCESSING TRIALS

In order to assess if the composition of Steel 3 was suitable for commercial production, a further two 60kg vacuum melts were produced. These were forged and ground to match the cross-section of the billets rolled at Scunthorpe Rod Mill. The experimental melts were flash-butt welded onto the back-ends of two high carbon billets and rolled to 12mm rod coils, using the optimised laying temperature and cooling rate determined previously. This resulted in two full coils (2 tonnes each) of high carbon material, with approximately 10 waps of experimental UHC-Si-Cr material on the back ends. No practical problems were encountered during rolling with mill loads or the resultant microstructure. The coils were delivered to Bridon for processing to galvanised wire.

One coil was processed in the as-rolled condition (direct drawn) to 5.0mm galvanised wire, aiming for a UTS of 1770MPa (83% reduction). The other coil was first patented under a set of revised conditions for the new composition. These conditions were derived from laboratory vacuum dilatometry work which demonstrated that the pearlite nose temperature was raised to ~610°C, as shown in figure 6.

Fig. 6 TTT Curves for UHC-Si-Cr Steel



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The patented material was then drawn and galvanised to 5.4mm wire, aiming for the ultrahigh strength of 1960MPa (80% reduction). The data from these trials are summarised in tables 4-6.

Table 4 12mm Rod Properties

Coil No	No of Tests, n	Rod Condition	UTS, MPa	Tensile Ductility, %	Resolvable Pearlite, %
1	2	As-Rolled	1325	32	10
2	3	Patented	1445	30	2

Table 5 Bright Wire Properties

Coil No	No of Tests, n	Drawing Redn, %	UTS, MPa	Tensile Ductility, %	Reverse Bends, n	Torsions (50d), n (fracture type)
1	3	83	1930	52	13	18 (mixed)
2	3	80	2030	56	18	16 (A)

Table 6 Galvanised Wire Properties

Coil No	No of Tests, n	UTS*, MPa	Tensile Ductility, %	Reverse Bends, n	Torsions (50d), n (fracture type)
1	3 (6 torsions)	1950	40	11	4 (C)
2	3 (12 torsions)	1975	49	12	13 (A)

* Zn layer included in cross-sectional area.

The target UTS for galvanised wire manufactured through the direct drawn and patented routes were 1770N/mm^2 and 1960N/mm^2 respectively. These objectives were seen to be achieved. The tensile and reverse bend ductility was high through both routes and good torsional properties were recorded for the patented coil. The poor torsional ductility of the direct drawn coil was thought to be as a consequence of the high drawing strain utilised for the trial. It was noted that there was little loss in UTS after galvanising, even after allowing for the increased cross-sectional area from the zinc layer in the calculation (~100MPa reduction).

Throughout the small scale trial the physical property targets and microstructure analysis were as predicted. Furthermore, no practical problems were encountered during any stage of the manufacturing process. Therefore it was anticipated that commercial production of an ultrahigh strength galvanised wire was feasible. It was recommended to proceed to a full-scale commercial trial involving a 300t cast, which is detailed in the next section.

2. PRODUCT ASSESSMENT

A full cast of the 0.90wt%C-1.20wt%Si-0.2wt%Cr steel was made at Scunthorpe works. This was cast to bloom, rolled to billet and supplied to the rod mill for rolling to rod.

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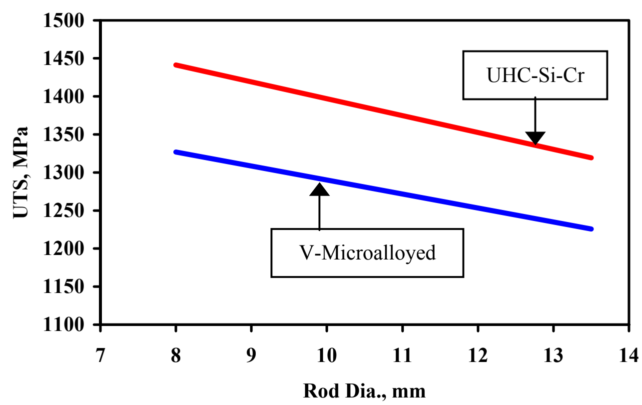
2.1 Rod Production

A range of rod diameters (8 – 13.5mm dia.) were produced at Scunthorpe Rod Mill. The previous laboratory work enabled the wide range of rod diameters to be produced with the desired fully pearlitic microstructures, devoid of any cementite/martensite. A summary of the tensile strength data from the as-rolled UHC-Si-Cr rod, (along with that of the previous highest strength rod produced at Scunthorpe, namely a vanadium microalloyed steel) is given in figure 7.

Fig. 7 Comparison of As-Rolled UTS of UHC-Si-Cr and V-Microalloyed Steels



No problems were encountered during the production of this grade, at either the steelmaking plant or the rod mill. Various diameters of UHC-Si-Cr rod were supplied to Bridon for a full evaluation via a number of drawing trials for different applications.

2.2 Patenting

The high silicon content of this grade caused an increase in the pearlite nose temperature of the TTT curve compared to plain carbon steels. The implications of this alteration to the isothermal transformation characteristics were that standard patenting conditions, as used for plain carbon steel, would not be suitable for this new grade. This is illustrated in figure 8(a-b), which shows the microstructure of a sample of UHC-Si-Cr material, patented to the standard conditions for plain carbon steel, (showing acicular ferrite, bainite and pearlite) and under the revised patenting conditions (which was fully pearlitic).

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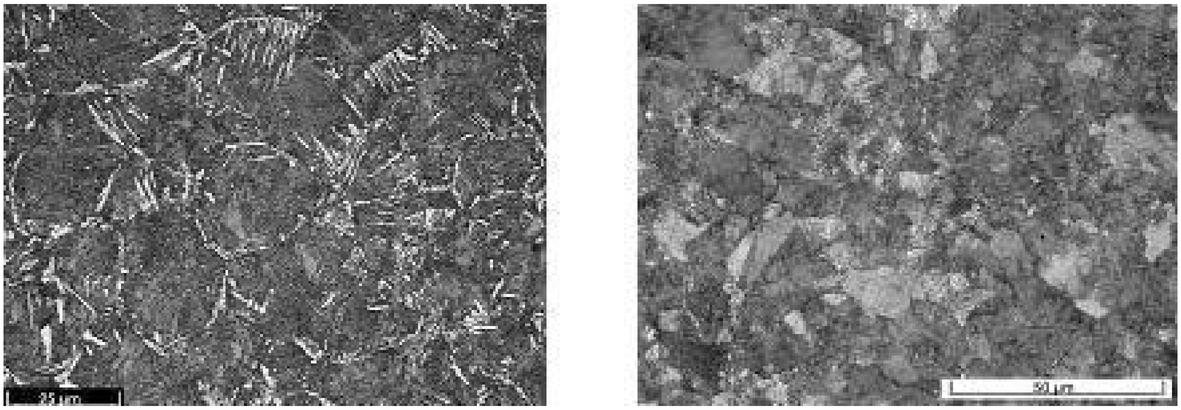
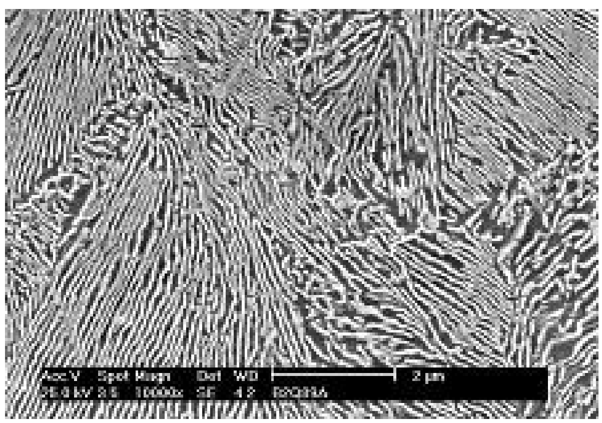
Fig. 8 Patented Microstructures of UHC-Si-Cr Steel

(a) Standard Patenting **(b) Optimised Patenting**



An SEM examination confirmed the microstructure of the steel patented under the revised conditions was fully pearlitic, ideal for drawing, as shown in figure 9.

Fig. 9 Fully Pearlitic Microstructure of UHC-Si-Cr Steel



Patenting was shown to increase the UTS of the rod by ~100MPa over the as rolled condition, resulting in 12mm diameter rod having a mean strength of ~1450MPa and a tensile ductility of 30%.

2.3 Wire Drawing and Galvanising

Various drawing trials have taken place to assess the potential of this new grade for a number of applications. For the purposes of this paper the focus will be on the permanent mooring cable application, as this was the source of the largest quantity of data for the new steel grade. Typically, permanent mooring cables consist of a spiral strand construction comprising of a series of helically spun galvanised wires applied in layers over a central wire or seale core. Generally, each layer is applied in the alternate direction to the layer below resulting in a balanced construction, which does not rotate or generate torque when an axial load is applied. This is a quasi static application, it is not a working rope travelling over rollers or sheaves, the load case is based on a relatively high mean axial load with the environmental conditions (tides, currents, wind etc.) exerting varying magnitude fluctuating loads at varying frequency. A typical system can be in position in excess of 20 years; hence long-term fatigue performance is critical.

The objective of the ultrahigh strength wire development was to improve the breaking load of the existing highest strength cable available (made from a vanadium microalloyed steel) by 10%, thus enabling 10% lighter cables to be utilised while attaining the required breaking load. Torsional ductility is not specified for such applications but was recorded for information.

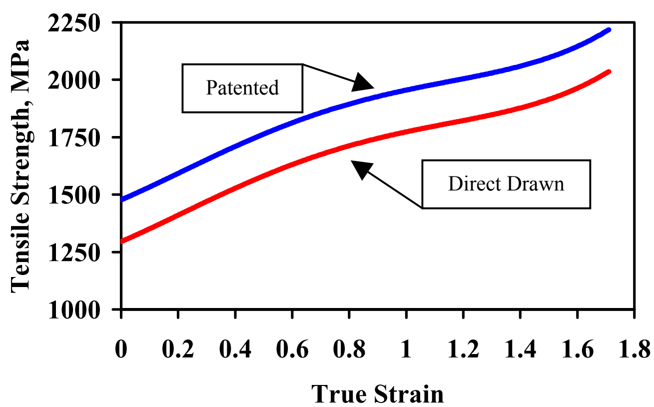
12mm patented rod feedstock (UTS of ~1450MPa) was drawn to 5.20 and 4.91mm wire (81 and 83%) at Bridon. The resultant mechanical properties are detailed in table 7.

Table 7 Bright Wire Properties

Wire Dia, mm	Mean UTS, MPa	Torsions (100d), n
5.20	2095	33A
4.91	2100	29A

During this trial, the work hardening curves were determined for this new grade. This data is shown in figure 10.

Fig. 10 Work Hardening Rates



The bright wire was then hot-dip galvanised to provide adequate corrosion protection. The mechanical properties of the galvanised wire are given in table 8.

Table 8 Galvanised Wire Properties

Wire Dia, mm	Mean UTS, MPa	Mean Torsions (100d), n	Mean Reverse Bends, n	Mean Elongation to Fracture, %
5.30	2040	11 (mixed)	not done	8.1
5.00	2070	8 C	10	8.3

In order to assess the influence of galvanising temperature on properties, a small coil of 4.91mm wire was galvanised at a slightly higher temperature than normal practice. This resulted in a reduction in tensile strength and reverse bend performance, but an improvement in elongation to fracture and torsional ductility, as shown in table 9.

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Table 9 Galvanised Properties (increased temperature)

Wire Dia,mm	Mean UTS, MPa	Mean Torsions (100d), n	Mean Reverse Bends, n	Mean Elongation to Fracture, %
5.00	2025	13A	9	10.0

Therefore, it was demonstrated that an excellent combination of properties was attainable, providing the wire was carefully processed. The wire produced under standard galvanising conditions, as detailed in Table 8, was utilised for the subsequent cable manufacturing stage.

2.4 Fatigue Testing of Single Wire

The fatigue properties of a cable are very important, as together with corrosion resistance, they govern the lifespan of mooring cable systems. Therefore, in order to assess the fatigue performance of this new grade against that of existing grades, single wire fatigue tests were carried out. This was carried out using a load of 45% of the GUTS (guaranteed UTS, i.e. 1960MPa), with a series of different ranges / amplitudes. The data from the most severe tests are shown in table 10.

Table 10 Fatigue Performance of Single Wire Tests

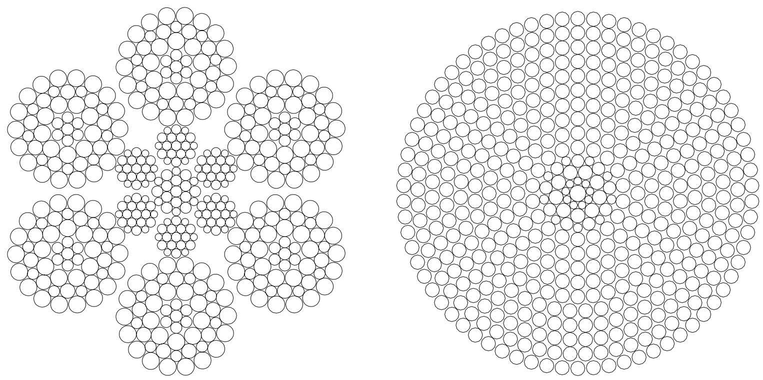
Wire Dia, mm	Min Load, kN	Mid Load, kN	Max Load, kN	Frequency, MHz	Endurance Level, %	Cycles, n	Comments
5.3	10.8	15.2	19.5	68	20.1	5600000	intact – terminated
5.0	8.1	12.7	17.3	76	23.9	26000000	intact - terminated

The findings from this work showed that the fatigue properties of single wires of the new grade were acceptable, as failure did not occur. However, for spiral strands in service, a 'fretting' fatigue mechanism is active, due to the nature of the construction of the cable with wires laid over each other in opposite directions, with the cross-over contact points becoming the initiation point for fatigue failure. This fretting action potentially reduces the fatigue properties compared with a single wire, and so a full cable was fatigue tested, as discussed in a later section.

2.5 Cable Manufacture and Testing

The initial target market for the ultra high tensile UHC-Si-Cr steel wire was permanent mooring cables for floating offshore oil production vessels. Typically these utilise a spiral strand construction rather than the more commonly known six-strand wire rope (figure 11), the selection being driven by corrosion and fatigue lifetime performance of the cables matching the anticipated field life.

Fig.11 Six Strand Wire Rope (left) and Spiral Strand (right) constructions



A 102mm diameter spiral strand, with an anticipated breaking load of 1145 tonnes, was produced incorporating the A class galvanised wire manufactured utilising the UHC-Si-Cr full cast trials. The spiral strand comprised of a 5 layer seale centre manufactured utilising small diameter wires of standard grade, 6 layers of 5.0mm diameter wire and a final layer of 5.3mm diameter wire. The 5.0mm and 5.3mm diameter wires were of the UHC-SI-Cr grade material. The outer 7 layers were added a layer at a time, typically each spun in the alternate direction to the layer beneath. The total construction comprised of 321 individual wires. It is important to note that a commercial product would comprise of UHC-Si-Cr wire throughout, hence the anticipated breaking load of the trial was slightly reduced from full commercial manufacture.

Individual wire tests suggested that the tensile strength and fatigue endurance would be suitable to achieve the target cable minimum breaking load and fatigue performance. However, full scale testing was essential to quantify the impact of cross fretting of the wires within the construction of the strand and ensure these losses were within acceptable levels. Tensile breaking load, apparent modulus and tension-tension fatigue tests were completed.

The strand was tensile tested, and achieved a 12% increase in breaking load over the stated minimum breaking load of an 1860 grade microalloyed strand. Subsequent testing of further commercial sizes has supported this breaking strength increase. The revised cable breaking loads are represented by the graph in figure 12, which shows the improvement over that of conventional, high strength and super high strength microalloyed grades for different strand diameters. The conventional strength strand, based on the 1570N/mm^2 grade material is equivalent to the currently published industry standard within DNV CN 2.5 (1995) [6].

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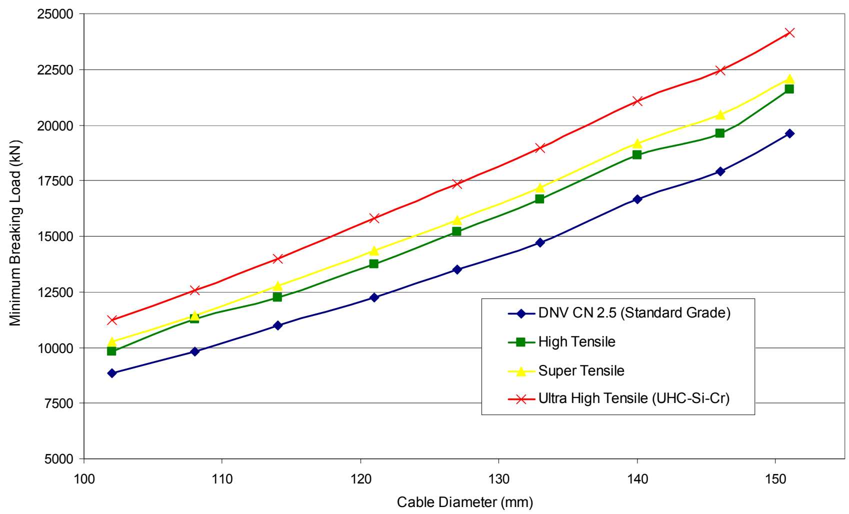
Fig. 12 Minimum Breaking Loads of High Strength Cables



The apparent modulus of a cable is governed by its geometry, rather than the material. This assumption was confirmed from the testing, the expected modulus not being adversely affected by the fretting of the increased tensile strength of the wires. However, for a given cable breaking load, the axial stiffness is reduced by approximately 10%, proportional to the reduction in steel area, due to a smaller cable being required.

It was anticipated that, due to the inter-wire fretting of the ultrahigh tensile wires, tension fatigue performance of the spiral strand would be the property most adversely affected. To test this assumption two full- scale fatigue tests were completed utilising two different mean load conditions (20% & 30% of the cable MBL) with a fluctuating load of +/-10% MBL. The results were then compared with the industry standard benchmark for assessing long term fatigue performance of different mooring components, API RP 2SK (1996) [7].

The initial test (30% mean load) was stopped after 384,650 cycles following failure of 104 wires, however this strand was still able at this time to support the applied loads. The second test (20% mean load) was stopped after 808,279 cycles when the strand failed to support the applied loads i.e. catastrophic failure. Under these loading conditions conventional grade spiral strand would expect 562,2200 and 1,239,595 cycles respectively, six-strand wire rope would be expected to achieve 166,878 and 316,418 respectively.

The mode of failure was exactly as anticipated, the failure point being initiated by wire on wire fretting as demonstrated by the micrographs in figure 13.

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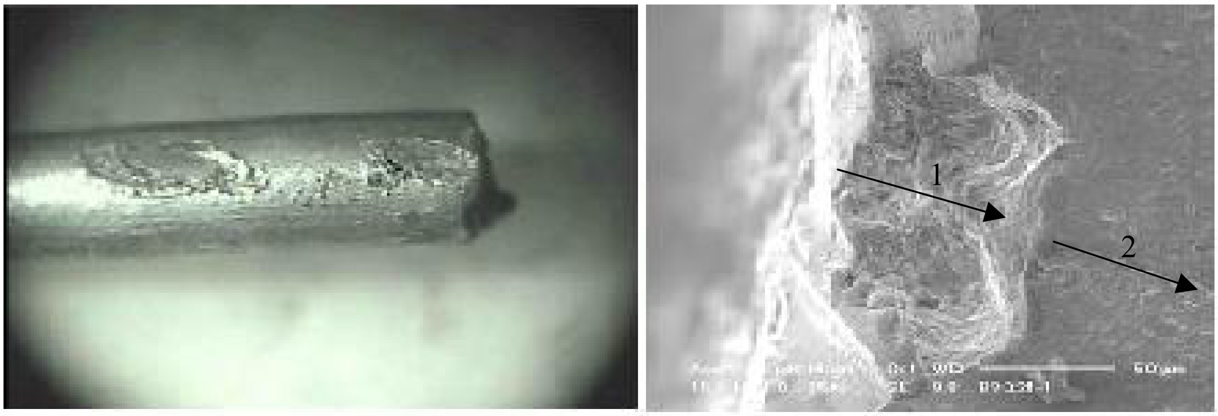
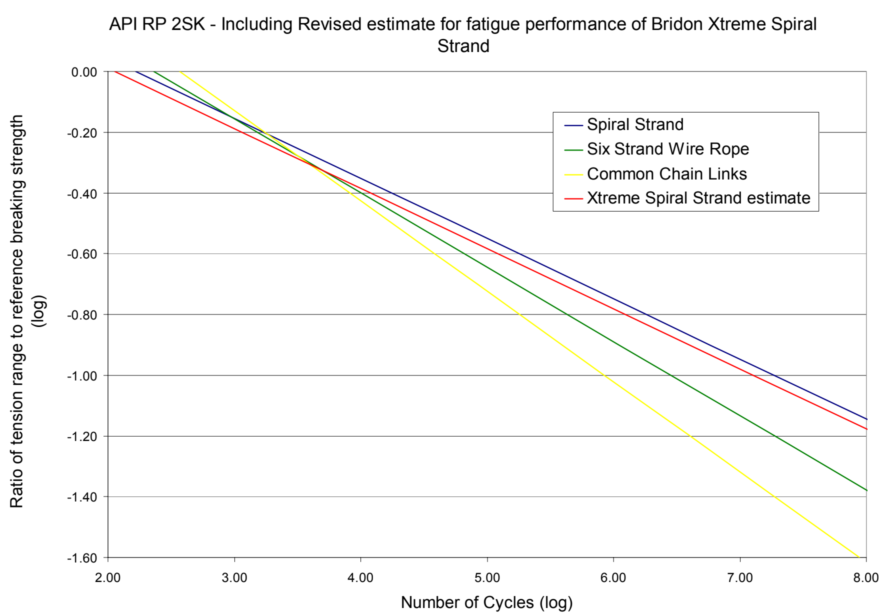
Fig. 13 Fretting Fatigue Damage on Wire Surface (left) and SEM Micrograph Showing (1) Fretted / Notched Initiation Site and (2) Smooth Fatigued Fractured Surface (right)



From the full-scale fatigue testing data, an estimate of the performance of the UHC-Si-Cr grade spiral strand could be added to the API RP 2SK information. This placed the performance of the new grade slightly lower than the standard grade spiral strand, but still in excess of the six-strand wire rope curve, as shown in figure 14.

In the assessment of a complete permanent mooring cable assembly, the spiral strand is assessed against its own curve and the cable terminations are assessed as a chain component. The results for the UHC-Si-Cr spiral strand still ensured that the assessment of the termination is the critical factor within the overall assembly, which allows the conclusion that the ultra high tensile spiral strands are suitable for use within this application.

Fig. 14 Fatigue Testing of Cable



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Expanding this information to a practical example the revised performance figures were applied to a lifetime fatigue spectrum anticipated for a typical Gulf of Mexico spar mooring system, the anticipated fatigue life as assessed by the API RP 2SK criteria of each component type is detailed in the table 11.

Table 11 Anticipated Fatigue Life

	Conventional Grade Spiral Strand	UHC-Si-Cr Grade Spiral Strand	Six Strand Wire Rope	Fittings / Common Chain
Life Span	1.8×10^6 yrs	1.2×10^6 yrs	2.2×10^5 yrs	9.45×10^4 yrs

3. COMMERCIAL APPLICATION

The objectives for the initial target market, offshore floating production mooring cables, have effectively been achieved and are now well accepted within the customer base. The increase in strength enables lighter weight mooring cables and reduced system loads, hence facilitating economical solutions in deepwater locations.

Bridon is currently manufacturing the third full scale system utilising the UHC-Si-Cr grade material. The first, supplied to a facility located offshore Brazil, was installed in August 2004. Kerr McGee's Constitution Spar is due for installation in the Gulf of Mexico during September 2005. Bridon is currently producing spiral strand for the mooring cables for the Spar destined for Murphy's Kikeh field offshore East Malaysia. It is clear that the benefits from the UHS-Si-Cr steel are being seen in a truly worldwide market.

Having now processed close to 2500 tonnes of the A class galvanised UHC-Si-Cr wire for spiral strand a large amount of data are now available for this product. Through the development focusing on mooring cables further commercial applications have been identified. Major structural projects utilise A-class galvanised wire both in factory fabricated cable assemblies and in on-site aerial spun bridge wire for suspension bridge main cables. Additional testing of the UHC-Si-Cr wire was necessary to confirm fracture toughness performance to aid in the promotion of the new material for these applications and positive results have allowed confidence to be built within this market.

The development of UHC-Si-Cr wire can potentially inform a wide range of products and applications with further application specific investigation. Wire & wire rope applications are continually subject to increasing economic and technical demands from optimisation of winch design to reducing the number of roof bolts to provide the necessary structural support. Furthermore, the next phase of refinement of the steel chemistry is being planned to further improve attainable tensile grades. The successes already seen within the offshore mooring market can be considered to be the just the beginning of an exceptional commercial opportunity utilising such special steels.

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