Ultra-High-Strength Galvanized Wire and Cable for Offshore Applications

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A look at a collaborative program of work that has resulted in the commercial availability of the next generation in large-diameter, ultra-high-strength (1960 MPa grade) galvanized UHC-Si-Cr steel wire.

Large-diameter, high-strength, hot-dipped galvanized wire is utilized in a variety of 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. While the use of such high-strength wire is well established, there is a drive for enhancing the ultimate tensile strength of the wire, thereby 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 (ultimate tensile strength) of high-strength galvanized wire, as shown in **Table 1**.

Table 1. Strength Grades for 5.0 mm Galvanized Wire.

Grade	Min Tensile Strength	
	Kgf/mm^2	MPa
Normal Tensile (0.80%C)	160	1570
High Tensile (0.80%C-V)	180	1760
Super Tensile (0.90%C-V)	190	1860
Ultra Tensile (UHC-Si-Cr)	200	1960

A number of carefully controlled processing operations are utilized for the production of high-strength galvanized wire. 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 to 15mm diameter.

The rod coils are supplied to wire manufacturers, such as **Bridon International Limited**., who draw the rod down to wire, galvanize and produce 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 microstructure (pearlite), thus maximizing the tensile strength. This heat treatment, which is known as "patenting" consists of re-austenitising the rod followed by quenching into a molten lead bath to isothermally transform the austenite to a very fine pearlitic structure. Wire drawing takes place on multi-hole drawing machines with water-cooled dies and cooling blocks in order to control the wire temperature and minimize dynamic strain aging. The drawing reduction per pass and drawing speed are carefully selected for this reason. For long-life applications, the wire is first drawn uncoated (bright wire) and then hot-dip galvanized to provide a zinc coating to a specified thickness for corrosion protection. The resultant hot-dip galvanized wire can either be stranded into cables or supplied as coils of wire dependant on the application. A schematic of the production route is shown in **Figure 1**.

The properties of the finished wire are influenced by strain aging, which involves the diffusion of carbon atoms from the cementite to the ferrite laths of the pearlite both during drawing (dynamic) and galvanizing (static). This reaction is influenced by microstructure, temperature, drawing schedule, total drawing strain and time at temperature[1]. The aging response can be characterized by immersing as-drawn wire into a salt bath (at typical galvanizing temperatures) for a series of different times, and measuring the resultant strength and ductility. Typically, at short immersion times, the carbon atoms are locking dislocations, causing an increase in tensile strength and decrease in (torsional) ductility. At longer times, the pinning action is lost and the ductility recovers, with a corresponding decrease in strength as shown in **Figure 2**.

This article presents the culmination of an extensive collaboration between Corus and Bridon International Ltd., which has resulted in the development of a new ultra-high strength (with minimum UTS of 1960 MPa (200 Kgf/mm^2)) galvanized wire product.

Steel Development for 1960 MPa Applications

Composition. To develop a new ultra-high-strength galvanized wire, a detailed understanding of the metallurgy is required. Previous work had highlighted the potential of an ultra-high carbon steel with additions of silicon and chromium (0.90 wt%C-0.60wt%Si-0.20wt%Cr). Therefore, this steel chemistry was selected as the base composition, examining three levels of silicon, as shown (in wt%) in **Table 2**.

The high carbon content of the steel is essential to maximize the strength, as it refines the pearlite. Higher additions than 0.90 wt% would make the steel prone to proeutectoid cementite formation, which reduces the ductility/drawability. Chromium and manganese increase the steel's hardenability, i.e., reduces the temperature at which pearlite begins to transform from austenite, resulting in finer pearlite, which increases

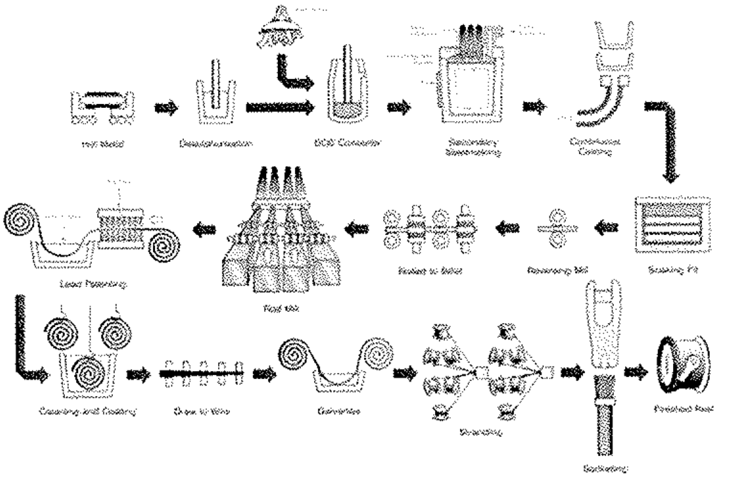

Fig. 1 — Production route for high-strength galvanized wire/cable.

the strength. Silicon improves the strength by solid solution strengthening the ferrite laths of the pearlite. Silicon is a ferrite stabilizer and is thought to influence the aging characteristics and hence the mechanical properties of the galvanized wire. Exactly 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 galvanizing[2,5]. 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.

Laboratory assessment of experimental melts. Small laboratory vacuum melts (60 kg) were produced, cast to ingots, forged to billet, rolled to bar and ground to 10 mm 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. The samples were then drawn to 4.43mm diameter wire (80% total reduction of area) on a laboratory single-hole draw bench. A salt bath was then utilized to simulate the galvanizing process. See **Table 3** for a summary.

The aging response was also examined, using a salt bath at both 450°C and 500°C, for different immersion times. These data are shown in **Figure 3** and **Figure 4**.

From the lab assessments, it was found that Steel 3 exhibited the best combination of strength and ductility. In addition, the aging response curves demonstrated that a high Silicon content (1.2 wt%) accelerated the recovery of the torsional ductility, with little/no loss in UTS during the ageing trials. Therefore, Steel 3 was selected for commercial processing to galvanized wire.

Commercial processing of experimental melts. In order to assess if the composition of Steel 3 was suitable for commercial production, a further two 60 kg 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 then flash-butt welded onto the back ends of two high-carbon billets and rolled to 12 mm rod coils. This resulted in two coils of high carbon material, with about 10 waps of experimental UHC-Si-Cr material on the back ends. The coils were delivered to Bridon for processing to galvanized wire under production conditions.

One coil was processed in the as-rolled condition (direct drawn) to 5.0 mm galvanized wire, aiming for a minimum UTS of 1770 MPa (83% reduction). The other coil was patented, using revised conditions derived from laboratory vacuum dilatometry work which demonstrated that the pearlite nose temperature was raised to ~610°C, as shown in **Figure 5**.

The patented material was drawn/galvanized to 5.4 mm wire (80% reduction), aiming for the ultra-high strength of 1960 MPa. Trial data are summarized in **Table 4**, **Table 5** and **Table 6**.

The target UTS for galvanized wire manufactured through the direct drawn and patented routes were 1770 N/mm^2 and 1960 N/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 utilized for the trial. It was noted that there was little loss in UTS after galvanizing.

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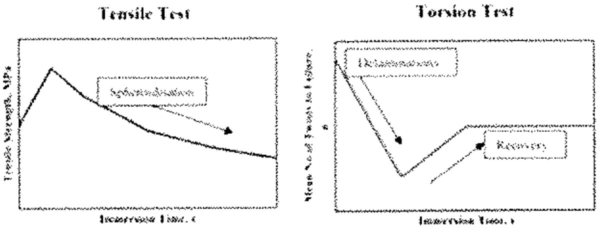

Fig. 2 — Schematic of aging response characteristics.

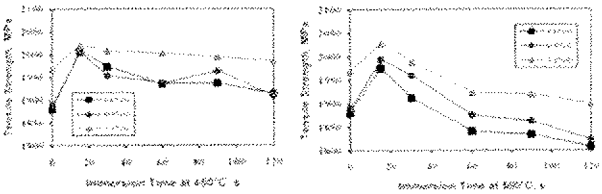

Fig. 3 — Aging response on tensile strength.

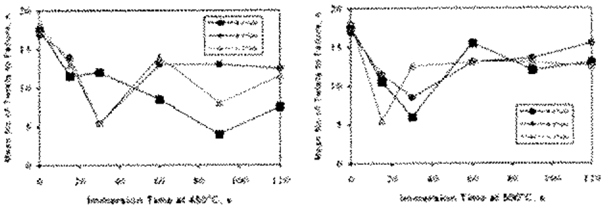

Fig. 4 — Aging response on torsional properties.

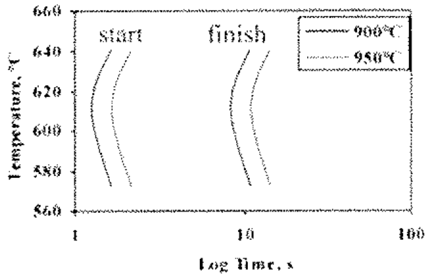

Fig. 5 — TTT curves for UHC-Si-Cr

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

Table 3. Summary of Experimental Steels Assessment.

Steel	No of Tests, n	Bright Wire Properties		Simulated Galvanized Wire Properties		
		Avg UTS, MPa (Red of Area, %)	Avg Torsion (50d), n (fracture type)	Avg UTS, MPa (R of A, %)	Avg Torsions (50d), n (fracture type)	Avg Reverse Bends, n
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

Table 4. 4.12 mm 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. Galvanized Wire Properties
*Zn Layer Included in Cross-Sectional Area.

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)

Assessment of Commercial Cast

A 300 t cast of the 0.90 wt%C-1.20 wt%Si-0.2 wt%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.

Rod production. A range of rod diameters (8 to 13.5 mm) were produced at Scunthorpe Rod Mill. A summary of the tensile strength data from the as-rolled UHC-Si-Cr rod (along with that of a Vanadium microalloyed steel) is given in **Figure 6**.

Patenting. The suitability of the revised patenting conditions (defined in earlier trials) was confirmed by the fully pearlitic microstructure, as shown in SEM micrograph in **Figure 7**. The patenting process was shown to increase the UTS of the rod by ~100 MPa over the as-rolled condition, resulting in a 12 mm diameter rod having a mean strength of ~1450 MPa and a tensile ductility of 30%.

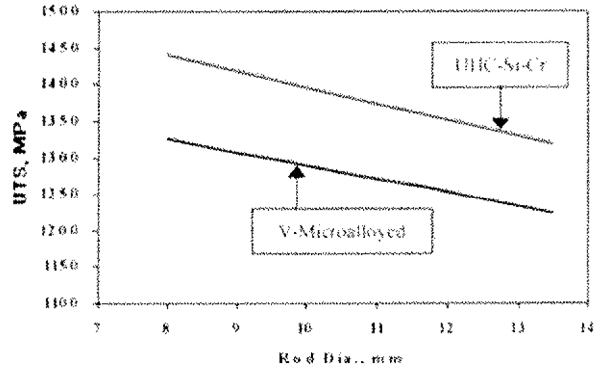

Fig. 6 — Comparison of as-rolled UTS of UHS-Si-Cr and V-Microalloyed steels.

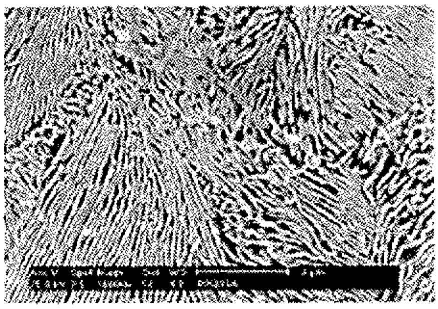

Fig. 7 — Fully pearlitic microstructure of UHC-Si-Cr steel.

Wire drawing and galvanizing. Various drawing trials examined the potential of this new grade for a number of applications. For the purposes of this article, the focus will be on the permanent mooring cable application. Typically, permanent mooring cables consist of a spiral strand construction comprising of a series of helically spun galvanized 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 under axial loading. 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 ultra-high-strength wire development was to improve the breaking load of the existing highest-strength cable available (Vanadium microalloyed steel) by 10%. Torsional ductility is not specified for such applications, but was recorded for information. The 12 mm patented rod feedstock (UTS of ~1450MPa) was drawn to 5.20 and 4.91mm wire (at 81% and 83%) at Bridon, and the resultant mechanical properties are detailed in **Table 7**.

The bright wire was hot-dip galvanized to provide corrosion protection. The mechanical properties of the galvanized wire are given in **Table 8**.

In order to assess the influence of galvanizing temperature on properties, a small coil of 4.91 mm wire was galvanized 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**.

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

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 guaranteed UTS (GUTS), i.e., 1960 MPa, with a series of different ranges/amplitudes. The data from the most severe tests are shown in **Table 10**.

Table 7. Bright Wire Properties.

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

Table 8. Galvanized 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

Table 9. Galvanized 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

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 demonstrated that the fatigue properties of single wires of the new grade were acceptable as failure did not occur. A full cable was also fatigue tested, as discussed in a later section.

Cable manufacture and testing. The target market for the ultra-high tensile UHC-Si-Cr steel wire was spirally stranded permanent mooring cables as shown in **Figure 8**.

A 102 mm diameter spiral strand, with an anticipated breaking load of 1145 metric tons, was produced incorporating the A class galvanized wire manufactured utilizing the trial cast of UHC-Si-Cr steel. The spiral strand was comprised of a five-layer sealed center manufactured utilizing small-diameter wires of standard grade, six layers of 5.0 mm diameter wire (UHC-Si-Cr) and a final layer of 5.3 mm diameter wire (UHC-Si-Cr), totalling 321 individual wires. It is important to note that a commercial product would comprise of UHC-Si-Cr wire throughout, hence