Nicrofer® 6616 hMo – alloy C-4

Material Data Sheet No. 4024
February 2003 Edition

Corrosion-resistant alloy

A company of ThyssenKrupp Stainless

ThyssenKrupp VDM

ThyssenKrupp

Nicrofer® 6616hMo – alloy C-4

Nicrofer 6616 hMo is an austenitic low-carbon nickel-molybdenum alloy.

The main difference between Nicrofer 6616 hMo and other alloys of similar composition developed earlier, is its reduced carbon, silicon, iron and tungsten contents. This composition shows greater stability during extended exposure to temperatures in the range 650 – 1040 °C (1200 –1900 °F). As a result, resistance to intergranular corrosion is improved.

Susceptibility to knife line corrosion and weld decay in the heat-affected zone is avoided under proper manufacturing conditions.

Nicrofer 6616 hMo is characterized by:

- Very good resistance to a wide range of corrosive media, particularly under reducing conditions
- Excellent resistance to localized corrosion in halide media.

Designations and standards

Country National standards	Material designation	Specification							
		Chemical composition	Tube and pipe		Sheet and plate	Rod and bar	Strip	Forgings	Fittings
			seamless	welded					
D DIN VdTÜV	**W.-Nr. 2.4610** NiMo16Cr16Ti	17744 424	17751 424		17750 424	17752 424	17750 424	424	
F AFNOR									
UK BS									
USA ASTM ASME	UNS N06455		B 622 SB 622	B 619/626 B 619/626	B 575 SB 575	B 574* SB 574*	B 575 SB 575		B 366 SB 366
ISO	NiMo16Cr16Ti								
*rod only									

Table 1 - Designations and standards.

Chemical composition

	Ni	Cr	Fe	C	Mn	Si	Mo	Co	Ti	P	S
min.	bal.	14.5					10.0				
max.		17.5	3.0	0.009	1.0	0.05	17.0	2.0	0.7	0.020	0.010
Some compositional limits of other specifications may vary slightly.											

Table 2 – Chemical composition (wt.-%) according to VdTÜV 424.

Physical properties

Density	8.7 g/cm³	0.314 lb/in.³
Melting range	1335–1380 °C	2435–2515 °F
Permeability at 20°C/68°F (RT)	< 1.01	

Temperature (T)		Specific heat		Thermal conductivity		Electrical resistivity		Modulus of elasticity		Coefficient of thermal expansion between room temperature and T	
°C	°F	J / kg K	Btu / lb °F	W / mK	Btu in. / ft² h °F	µ Ω cm	Ω circ mil / ft	kN / mm²	10³ ksi	10⁻⁶ / K	10⁻⁶ / °F
0	32	406	0.097								
20	**68**	408	0.097	10.1	70	124	75	211	30.8		
93	**200**		0.101		79		75		30.2		6.0
100	212	426		11.4		125		207		10.9	
200	392	448		13.2		126		202		11.9	
204	**400**		0.107		92		76		29.3		6.6
300	572	465		15.0		127		195		12.5	
316	**600**		0.111		106		76		28.3		7.0
400	752	477		16.7		128		188		12.9	
427	**800**		0.115		119		77		27.3		7.2
500	932	490		18.4		129		181		13.2	
538	**1000**		0.118		133		78		26.2		7.4
600	1112	502		20.5		132		175		13.6	
649	**1200**		0.121		149		80		25.0		7.7
700	1292	512		22.6		135		168		14.0	
760	**1400**		0.124		152		82		23.7		8.0
800	1472	522		24.8		138		158		14.5	
871	**1600**								22.2		8.3
900	1652							149		15.1	
982	**1800**								20.6		8.7
1000	1832							138		15.9	

Table 3 – Typical physical properties at room and elevated temperatures.

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Mechanical properties

The following properties are applicable to Nicrofer 6616 hMo in the solution-annealed condition and indicated size ranges. Specified properties of materials outside these size ranges are subject to special enquiry. All minimum values are valid for longitudinal and transverse specimens.

Product	Dimensions thickness/diameter		Tensile strength R_m		Yield strength $R_{p0.2}$		Yield strength $R_{p1.0}$		Elongation A_5	Brinell hardness
	mm	inches	N/mm²	ksi	N/mm²	ksi	N/mm2	ksi	%	HB
Strip, sheet & plate	≤ 5	≤ 0.2	700	100	305	44	340	49	40	≤320 (For information only)
	> 5 to ≤ 20	> 0.2 to ≤ 0.8			300	43	330	48		
	> 20 to ≤ 65	> 0.8 to ≤ 2 1/2								
Forgings	≤ 160	≤ 6 1/4								
Rod & bar	≤ 250	≤ 10			280	41	315	46		
Seamless tube	s ≤ 5 / 75 dia.	s ≤ 0.20 / 3 dia.								

Table 4 – Minimum mechanical properties at room temperature according to VdTÜV data sheet 424.

Product	Dimensions thickness/diameter	Yield strength, $R_{p0.2}$				Yield strength, $R_{p1.0}$			
	mm	N/mm²				N/mm²			
Temperature, °C		100	200	300	400	100	200	300	400
Strip, Sheet & plate	≤ 5	285	255	245	225	315	285	270	260
	> 5 to ≤ 20	270	245	220	205	305	280	255	240
	> 20 to ≤ 65	260	235	215	205	295	275	255	240
Forgings	≤ 160								
Rod & bar	≤ 250								
Seamless tube	s ≤ 5 / 75 dia.								
	inches	ksi				ksi			
Temperature, °F		200	400	600	800	200	400	600	800
Strip, Sheet & plate	≤ 0.20	41.6	36.9	35.1	31.9	46.1	41.3	39.0	37.4
	> 0.20 to ≤ 0.80	39.6	35.5	31.5	29.4	44.7	40.6	36.5	34.2
	> 0.80 to ≤ 2 1/2	38.0	34.0	30.9	29.4	43.1	39.9	36.5	34.2
Forgings	≤ 6 1/4								
Rod & bar	≤ 10								
Seamless tube	s ≤ 0.20 / 3.0 dia.								

Table 5 – Minimum mechanical properties at elevated temperatures according to VdTÜV data sheet 424.

ISO V-notch impact toughness

Average values at room temperature: ≥ 120 J/cm²
at -196 °C (-320 °F): ≥ 120 J/cm²

Metallurgical structure
Nicrofer 6616 hMo has a face-centered-cubic structure. Its balanced chemical composition gives this alloy good metallurgical stability and high resistance to sensitization.

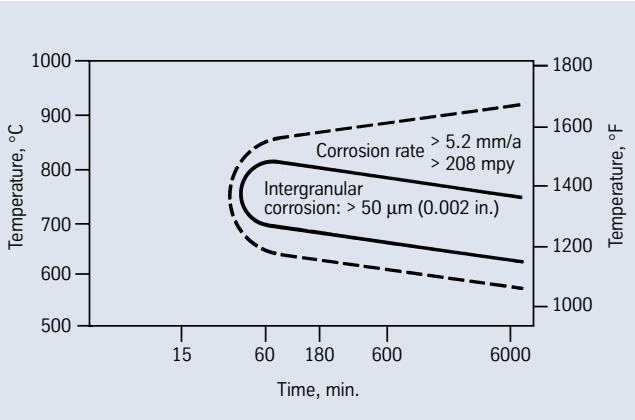

Fig. 1 – Time-temperature-sensitization (TTS) diagram for Nicrofer 6616 hMo with 0.008% C according to the Streicher test (ASTM G-28, Method A). Corrosion rate in the initial solution-annealed condition: 3 mm/a (120 mpy)

Corrosion resistance
Its high chromium and molybdenum contents make Nicrofer 6616 hMo exceptionally resistant to a variety of chemical media, including reducing contaminated mineral acids such as phosphoric, hydrochloric and sulphuric acids, chlorides and organic and inorganic chloride-contaminated media. Due to its high nickel content, Nicrofer 6616 hMo is virtually immune to chloride-induced stress-corrosion cracking, even in hot chloride solutions.

Applications
Nicrofer 6616 hMo finds application in the chemical industry in a wide range of chemical process environments at ambient and higher temperatures.

Typical applications are:
- flue gas desulphurisation equipment
- pickling baths and acid regeneration
- acetic acid production and agrochemicals production
- titanium dioxide production (chloride route)
- electrolytic galvanizing rolls

Fabrication and heat treatment
Nicrofer 6616 hMo can readily be hot- and cold worked and machined.

Heating
Workpieces must be clean and free from all kinds of contaminants before and during any heat treatment.

Nicrofer 6616 hMo may become embrittled if heated in the presence of contaminants such as sulphur, phosphorus, lead and other low-melting-point metals. Sources of such contaminants include marking and temperature-indicating paints and crayons, lubricating grease, fluids and fuels.

Fuels must be as low in sulphur as possible. Natural gas should contain less than 0.1 wt.-% sulphur. Fuel oils with a sulphur content not exceeding 0.5 wt.-% are suitable.

Due to their close control of temperature and freedom from contamination, thermal treatments in electric furnaces under vacuum or an inert gas atmosphere are to be preferred. Treatments in an air atmosphere and alternatively in gas-fired furnaces are acceptable though, if contaminants are at low levels so that a neutral or slightly oxidizing furnace atmosphere is attained. A furnace atmosphere fluctuating between oxidizing and reducing must be avoided as well as direct flame impingement on the metal.

Hot working
Nicrofer 6616 hMo may be hot worked in the temperature range 1080 to 900 °C (1980 to 1650 °F), followed by water quenching or rapid air cooling.

For heating up, workpieces may be charged into the furnace at maximum working temperature. When the furnace has returned to temperature, the workpieces should be soaked for 60 minutes per 100 mm (4 in.) of thickness. At the end of this period it should be withdraw immediately and worked within the above temperature range. If the metal temperature falls below the minimum hot working temperature, it must be reheated.

Heat treatment after hot working is required in order to achieve optimum properties and to ensure maximum corrosion resistance.

Cold working
For cold working the material should be in the annealed condition. Nicrofer 6616 hMo has a higher work-hardening rate than austenitic stainless steels. This should be taken into account when selecting forming equipment.

Interstage annealing may be necessary with high degrees of cold forming. After cold working with more than 15 % deformation solution annealing is required before use.

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Heat treatment
Solution heat treatment should be carried out in the temperature range 1050 to 1100 °C (1920 to 2010 °F). Water quenching or rapid air cooling is recommended for thicknesses above 1.5 mm (0.06 in.) and is essential for maximum corrosion resistance.

For any thermal treatment the material should be charged into the furnace at maximum working temperature. Also for any thermal treatment operation the precautions concerning cleanliness mentioned earlier under **'Heating'** must be observed.

Descaling and pickling
Oxides of Nicrofer 6616 hMo and discoloration adjacent to welds are more adherent than on stainless steels. Grinding with very fine abrasive belts or discs is recommended. Care should be taken to prevent tarnishing.

Before pickling which may be performed in a nitric/hydroflouric acid mixture with proper control of pickling time and temperature, the surface oxide layer must be broken up by abrasive blasting or by carefully performed grinding or by pretreatment in a fused salt bath.

Machining
Nicrofer 6616 hMo should be machined in the solution-treated condition. As the alloy exhibits a high work-hardening rate only low cutting speeds should be used compared with low-alloyed standard austenitic stainless steels. Tools should be engaged at all times. An adequate depth of cut is important in order to cut below the previously formed work-hardened zone.

Welding
When welding nickel-base alloys and high-alloyed special stainless steels, the following instructions should be adhered to:

Workplace
The workplace should be in a separate location, well away from the areas where carbon steel fabrication takes place. Maximum cleanliness and avoidance of draughts are paramount.

Auxiliaries, clothing
Clean fine leather gloves and clean working clothes should be used.

Tools and machinery
Tools used for nickel-base alloys and stainless steels must not be used for other materials. Brushes should be made of stainless material. Fabricating and working machinery such as shears, presses or rollers should be fitted with means (felt, cardboard, plastic sheet) of avoiding contamination of the metal with ferrous particles, which can be pressed into the surface and thus lead to corrosion.

Cleaning
Cleaning of the base metal in the weld area (both sides) and of the filler metal (e. g. welding rod) should be carried out with acetone.

Trichlorethylene (TRI), perchlorethylene (PER), and carbon tetrachloride (TETRA) must not be used.

Edge preparation
This should preferably be done by mechanical means, i. e. turning, milling or planing; abrasive water jet or plasma cutting is also possible. However, in the latter case the cut edge (the face to be welded) must be finished off cleanly. Careful grinding without overheating is permissible.

Included angle
The different physical characteristics of nickel-base alloys and special stainless steels compared with carbon steel generally manifest themselves in a lower thermal conductivity and a higher rate of thermal expansion. This should be allowed for by means of, among other things, wider root gaps or openings (1 – 3 mm), while larger included angles (60 – 70°), as shown in Fig. 2, should be used for individual butt joints owing to the viscous nature of the molten weld metal and to counteract the pronounced shrinkage tendency.

Striking the arc
The arc should only be struck in the weld area, i. e. on the faces to be welded or on a run-out piece. Striking marks lead to corrosion.

Welding process

Nicrofer 6616 hMo can be joined to itself and to many other metals by conventional welding processes. These include GTAW (TIG), plasma arc, GMAW (MIG/MAG and MAG-Tandem) and SMAW (MMA). Pulsed arc welding is the preferred technique. For the MAG processes the use of a multi-component shielding gas (Ar+He+H_2+CO_2) is recommended.

For welding, Nicrofer 6616 hMo should be in the annealed condition and be free from scale, grease and markings. When welding the root, care should be taken to achieve best-quality root backing (argon 99.99), so that the weld is free from oxides after welding the root. Any heat tint should be removed preferably by brushing with a stainless steel wire brush while the weld metal is still hot.

Filler metal

For the gas-shielded welding processes, filler metal with the same composition as the base metal is recommended:

Bare electrodes:	Nicrofer S 6616 – FM C-4 W.-Nr. 2.4611 SG-NiMo16Cr16Ti AWS A5.14: ERNiCrMo-7 BS 2901 Part 5: NA 45
Covered electrodes:	W.-Nr. 2.4612 EL-NiMo15Cr15Ti AWS A5.11: ENiCrMo-7

For overlay welding by the electro-slag method (RES):

Weld strip:	Nicrofer B 6616 – WS C-4 W.-Nr. 2.4611 UP-NiMo16Cr16Ti AWS A5.14: ERNiCrMo-7

Welding parameters and influences (heat input)

Care should be taken that the work is performed with a deliberately chosen, low heat input as indicated in Table 7 by way of example. Use of the stringer bead technique should be aimed at. Interpass temperature should be kept below 100 °C (212 °F).

The welding parameters should be monitored as a matter of principle.

The heat input Q may be calculated as follows:

$$Q = \frac{U \times I \times 60}{v \times 1000} \text{ (kJ/cm)}$$

U = arc voltage, volts
I = welding current, amps
v = welding speed, cm/min.

Consultation with ThyssenKrupp VDM's Welding Laboratory is recommended.

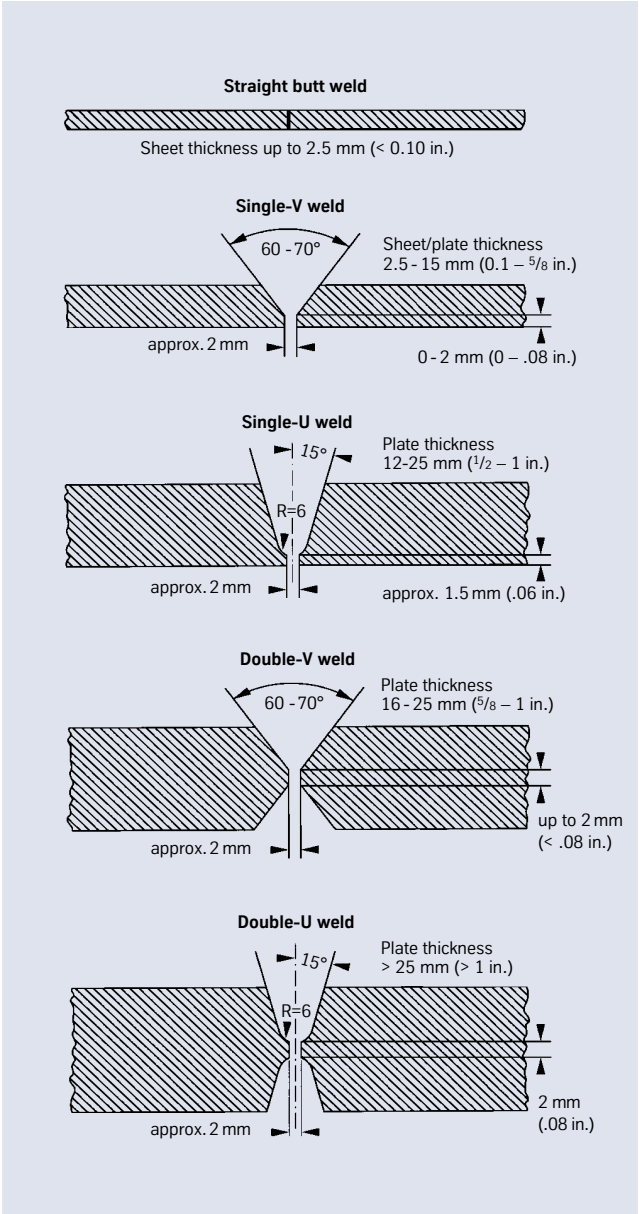

Fig. 2 – Edge preparation for welding of nickel-base alloys and special stainless steels.

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Sheet/ plate thick-ness mm	Welding process	Filler metal Diameter mm	Speed m/min.	Welding parameters Root pass A	V	Intermediate and final passes A	V	Welding speed cm/min.	Flux/ shielding gas rate l/min.	Plasma-gas rate l/min.	Plasma-nozzle diameter mm
3.0	Manual GTAW	2.0		90	10	110 – 120	11	10 – 15	Ar W3[1] 8 – 10		
6.0	Manual GTAW	2.0 – 2.4		100 – 110	10	120 – 130	12	10 – 15	Ar W3[1] 8 – 10		
8.0	Manual GTAW	2.4		110 – 120	11	130 – 140	12	10 – 15	Ar W3[1] 8 – 10		
10.0	Manual GTAW	2.4		110 – 120	11	130 – 140	12	10 – 15	Ar W3[1] 8 – 10		
3.0	Autom. GTAW	1.2	0.5	manual		150	10	25	Ar W3[1] 15 – 20		
5.0	Autom. GTAW	1.2	0.5	manual		150	10	25	Ar W3[1] 15 – 20		
2.0	Hot wire GTAW	1.0	0.3			180	10	80	Ar W3[1] 15 – 20		
10.0	Hot wire GTAW	1.2	0.45	manual		250	12	40	Ar W3[1] 15 – 20		
4.0	Plasma arc	1.2	0.5	165	25			25	Ar W3[1] 30	Ar W3[1] 3.0	3.2
6.0	Plasma arc	1.2	0.5	190 – 200	25			25	Ar W3[1] 30	Ar W3[1] 3.5	3.2
8.0	MIG/MAG GMAW	1.0	approx. 8	GTAW		130 – 140	23 – 27	24 – 30	MAG[2] MIG: argon 18 – 20		
10.0	MIG/MAG GMAW	1.2	approx. 5	GTAW		130 – 150	23 – 27	20 – 26	MAG[2] MIG: argon 18 – 20		
6.0	SMAW	2.5		40 – 70	approx. 21	40 – 70	approx. 21				
8.0	SMAW	2.5–3.25		40 – 70	approx. 21	70 – 100	aprrox. 22				
16.0	SMAW	4.0				90 – 130	approx. 22				

[1] Argon or argon + max. 3 % hydrogen
[2] For MAG welding use of the shielding gas Cronigon He30S or Argomag-Ni, for example, is recommended.
In all gas-shielded welding operations, ensure adequate back shielding.
These figures are only a guide and are intended to facilitate setting of the welding machines.

Table 6 – Welding parameters (guide values).

Welding process	Heat input per unit length kJ/cm	Welding process	Heat input per unit length kJ/cm
GTAW, manual, fully mechanised	max. 8	GMAW, MIG/MAG, manual, fully mechanised	max. 11
Hot wire GTAW	max. 6	SMAW, manual metal arc (MMA)	max. 7
Plasma arc	max. 10		

Table 7 – Heat input per unit length (guide values).

Postweld treatment
(brushing, pickling and thermal treatments)

Brushing with a stainless steel wire brush immediately after welding, i.e. while the metal is still hot generally results in removal of heat tint and produces the desired surface condition without additional pickling.

Pickling, if required or prescribed, however, would generally be the last operation performed on the weldment. Also refer to the information on **'Descaling and pickling'**.

Neither pre- nor postweld thermal treatments are required.

Availability
Nicrofer 6616 hMo is available in the following standard product forms:

Sheet & plate
(for cut-to-length availability, refer to strip)

Conditions:
hot or cold rolled (hr, cr),
thermally treated and pickled

Thickness mm	hr / cr	Width[1] mm	Length[1] mm
1.10 – < 1.50	cr	2000	8000
1.50 – < 3.00	cr	2500	8000
3.00 – < 7.50	cr / hr	2500	8000
7.50 – ≤ 25.00	hr	2500	8000[2]
> 25.00[1]	hr	2500[2]	8000[2]

inches		inches	inches
0.043 – < 0.060	cr	80	320
0.060 – < 0.120	cr	100	320
0.120 – < 0.300	cr / hr	100	320
0.300 – ≤ 1.000	hr	100	320[2]
> 1.000[1]	hr	100[2]	320[2]

[1] other sizes subject to special enquiry
[2] depending on piece weight

Discs and rings
Conditions:
hot rolled or forged,
thermally treated,
pickled or machined

Product	Weight kg	Thickness mm	o. d.[1] mm	i. d.[1] mm
Disc	≤ 10000	≤ 300	≤ 3000	
Ring	≤ 3000	≤ 200	≤ 2500	on request

	lbs	inches	inches	inches
Disc	≤ 22000	≤ 12	≤ 120	
Ring	≤ 6600	≤ 8	≤ 100	on request

[1] other sizes subject to special enquiry

Rod & bar
Conditions:
forged, rolled, drawn,
thermally treated,
pickled, machined, peeled or ground

Product	Forged[1] mm	Rolled[1] mm	Drawn[1] mm
Rod (o. d.)	≤ 600	8 – 60	12 – 50
Bar, square (a)	40 – 600	15 – 280	not standard
Bar, flat (a x b)	(40 – 80) x (200 – 600)	(5 – 20) x (120 – 600)	(10 – 20) x (30 – 80)
Bar, hexagonal (s)	40 – 80	13 – 41	≤ 50

	inches	inches	inches
Rod (o. d.)	≤ 24	$^{5}/_{16}$ – 2 $^{3}/_{8}$	$^{1}/_{2}$ – 2
Bar, square (a)	$1^{5}/_{8}$ – 24	$^{10}/_{16}$ – 11	not standard
Bar, flat (a x b)	($1^{5}/_{8}$ – $3^{1}/_{8}$) x (8 – 24)	($^{3}/_{16}$ – $^{3}/_{4}$) x ($4^{3}/_{4}$ – 24)	($^{3}/_{8}$ – $^{3}/_{4}$) x ($1^{1}/_{4}$ – $3^{1}/_{8}$)
Bar, hexagonal (s)	$1^{5}/_{8}$ – $3^{1}/_{8}$	$^{1}/_{2}$ – $1^{5}/_{8}$	≤ 2

[1] other sizes and conditions subject to special enquiry

Forgings
Shapes other than discs, rings, rod and bar are subject to special enquiry. Flanges and hollow shafts may be available up to a piece weight of 10 t.

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Strip[1)]
Conditions:
cold rolled,
thermally treated and pickled or bright annealed

Thickness mm	Width[3)] mm	Coil i. d. mm			
0.02 – ≤ 0.10	4 – 200[4)]	300	400		
> 0.10 – ≤ 0.20	4 – 350[4)]	300	400	500	
> 0.20 – ≤ 0.25	4 – 750		400	500	600
> 0.25 – ≤ 0.60	6 – 750		400	500	600
> 0.60 – ≤ 1.0	8 – 750		400	500	600
> 1.0 – ≤ 2.0	15 – 750		400	500	600
> 2.0 – ≤ 3.0 (≤ 3.5)[2)]	25 – 750		400	500	600

inches	nches	inches			
0.0008 – ≤ 0.004	0.16 – 8[4)]	12	16		
> 0.004 – ≤ 0.008	0.16 – 14[4)]	12	16	20	
> 0.008 – ≤ 0.010	0.16 – 30		16	20	24
> 0.010 – ≤ 0.024	0.24 – 30		16	20	24
> 0.024 – ≤ 0.040	0.32 – 30		16	20	24
> 0.040 – ≤ 0.080	0.60 – 30		16	20	24
> 0.080 – ≤ 0.120 (≤ 0.140)[2)]	1.0 – 30		16	20	24

[1)] Cut-to-length available in lengths from 250 to 4000 mm (10 to 158 in.)
[2)] Maximum thickness: bright annealed – 3 mm (0.120 in.);
cold rolled only – 3.5 mm (0.140 in.)
[3)] Wider widths subject to special enquiry
[4)] Wider widths up to 730 mm (29 in.) subject to special enquiry

Wire
Conditions:
bright drawn, $^{1}/_{4}$ hard to hard,
bright annealed

Dimensions:
0.01 – 12.0 mm (0.0004 – 0.47 in.) diameter,
in coils, pay-off packs, on spools and spiders

Welding filler metals
Suitable welding rods, wire, strip electrodes and electrode core wire are available in all standard sizes.

Seamless tube and pipe
Using ThyssenKrupp VDM cast materials seamless tubes and pipes are produced and available from DMV STAINLESS SAS, Tour Neptune, F-92086 Paris, La Défense Cedex
(Fax: +33-1-4796 8141; Tel.: +33-1-4796 8140;
E-mail: dmv-hq@dmv-stainless.com).

Welded tube and pipe
Welded tubes and pipes are obtainable from qualified manufacturers using ThyssenKrupp VDM semi-fabricated products.

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Nicrofer

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