VDM Metals

VDM® Alloy 601
Nicrofer 6023 H

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VDM® Alloy 601

Nicrofer 6023 H

VDM® Alloy 601 is a nickel-chromium-iron alloy with additions of aluminum and titanium. VDM® Alloy 601 is characterized by:

- Outstanding resistance to oxidation at high temperatures
- Good resistance to carburizing conditions
- Good resistance in oxidizing, sulfuric atmospheres
- Good mechanical properties at both room temperature and elevated temperatures
- Good resistance to stress-corrosion cracking

VDM® Alloy 601 is specifically recommended for service above 550 °C (1,022 °F) because of its higher creep-rupture properties resulting from its controlled carbon content and coarse grain size.

Designations and standards

Standardisation	Material designation
EN	2.4851 - NiCr23Fe
ISO	NiCr23Fe15Al
UNS	N06601
AFNOR	NC23FeA

Table 1a – Designations and standards

Designations and standards

Product form	DIN	DIN EN	ISO	ASTM	ASME	VdTüV	(SAE) AMS	SEW
Rod, bar	17742 17752	10095		B 166	SB 166			
Sheet, plate	17742 17750	10095	6208 9722	B 168	SB 168		5870	
Strip	17742 17750	10095		B 168	SB 168		5870	470
Wire	17742 17753	10095		B 166				

Table 1b – Designations and standards

Chemical composition

	Ni	Cr	Fe	C[1)]	Mn	Si	Co[2)]	Cu	Al	Ti	P	S	B
Min.	58	21		0.03					1				
Max.	63	25	18	0.1	1	0.5		0.5	1.7	0.5	0.02	0.015	0.006

[1)] C = 0.03-0.10 wt.-% (according to DIN EN 10095); C ≤ 0.10 wt.-% (according to DIN 17742 and UNS N06601)

[2)] A max. of 1.5 wt.-% Co, classified as Ni, is permitted. In ASTM, Co is not specified.

Table 2 – Chemical composition (wt.-%)

Physical Properties

Density	Melting range	Relative magnetic permeability at 20 °C (68 °F)	Curie temperature
8.05 g/cm³ (0.29 lb/in³)	1,330-1,370 °C (2,426-2,498 °F)	1.01 (Maximum)	-196 °C (Maximum) (-320.8 °F)

Temperature		Specific heat		Thermal conductivity		Electrical resistivity	Modulus of elasticity		Coefficient of thermal expansion		Thermal diffusivity
°C	°F	J / kg · K	Btu / lb · °F	W / m · K	Btu · in / sq. ft · h · °F	µΩ · cm	GPa	10³ ksi	10^{-6} / K	10^{-6} / °F	$10^{-6} \cdot m^2$ / s
20	68	472	0.113	11.3	78.3	122	207	30.0			2.97
100	212	484	0.116	12.5	86.7	124	201	29.2	14.46	8.03	3.24
200	392	498	0.119	14.2	98.5	126	196	28.4	14.59	8.11	3.57
300	572	512	0.122	15.8	109.5	128	191	27.7	14.77	8.21	3.9
400	762	526	0.123	17.5	121.3	131	186	27.0	15.04	8.34	4.22
500	932	540	0.129	19.2	133.1	132	180	26.1	15.3	8.5	4.51
600	1,112	554	0.132	20.6	142.8	132	171	24.8	15.57	8.65	4.76
700	1,292	569	0.134	22	152.5	132	161	23.4	15.69	8.72	4.95
800	1,472	588	0.140	23.2	160.9	132	150	21.8	16.34	9.01	5.09
900	1,652	609	0.145	24.4	169.2	133	138	20.0	16.83	9.35	5.21
1,000	1,832	651	0.155	26.6	184.4	133	124	17.0	17.38	9.66	5.34
1,100	2,012	668	0.160	28.2	195.5		110	16.0	18.05	10.03	5.58

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

Microstructural properties

VDM® Alloy 601 has a face-centered-cubic lattice. The good mechanical properties are determined by the precipitation of carbides below 1,150 °C (2,102 °F). Below 800 °C (1,472 °F), additional γ' precipitations may occur.

Mechanical properties

The following properties are applicable to VDM® Alloy 601 in the annealed condition and indicated size ranges.

Temperature		Yield strength $R_{p\ 0.2}$		Tensile strength R_m		Elongation A
°C	°F	MPa	ksi	MPa	ksi	%
20	68	270	39.2	620	89.9	30
100	212	260	37.7	610	88.5	45
200	392	220	31.9	610	88.5	45
300	572	200	29	570	82.7	45
400	762	180	26.1	530	76.9	45
500	932	175	25.4	510	74	45
600	1,112	165	23.9	470	68.2	45
700	1,292	130	18.9	420	60.9	50
800	1,472	110	16	270	39.2	55
900	1,652	75	10.9	120	17.4	65
1,000	1,832	60	8.7	80	11.6	65

Table 4 – Typical short-time properties of solution annealed VDM® Alloy 601 at room and elevated temperatures

Product form	Dimensions mm	Yield strength $R_{p\ 0.2}$ MPa	Tensile strength R_m MPa	Elongation A %	Brinell hardness HB
Strip	≤ 25	≥ 205	550	≥ 30	≤ 220
Sheet, plate	≤ 75	≥ 205	550	≥ 30	≤ 220
Rod, bar	≤ 160	≥ 205	550	≥ 30	≤ 220
Rolled wire	≤ 25		550		

Table 5 – Mechanical properties at room temperature according to DIN EN 10095

Temperature		Time yield limit[1)] $R_{p\ 1.0}/10^4$ h	$R_{p\ 1.0}/10^5$ h	Creep rupture strength[2)] $R_m/10^4$ h	$R_m/10^5$ h
°C	°F	MPa	MPa	MPa	MPa
600	1,112	151	116	205	156
650	1,202	112	70		
700	1,292	69	39	101	55
750	1,382	38	21,7		
800	1,472	22	11,8	31	17
850	1,562	12	6,2		
900	1,652	6,9	2,2	10	4.0
950	1,742	4	1,5		
1,000	1,832	2,3		4,6	2.0
1,100	2,012	1,6			

Table 6 –
1) 1.0 % creep limit of solution annealed VDM® Alloy 601
2) Middle values of creep rupture strength at elevated temperatures of solution annealed VDM® Alloy 601 according to DIN EN 10095

Corrosion resistance

According to DIN EN 10095 VDM® Alloy 601 is termed a heat resistant alloy on account of its excellent resistance above 550 °C (1,022 °F) against hot gases and combustion products, as well as against molten salt, while at the same time exhibiting good mechanical short-time and long-term properties.

Even under severe conditions, such as under cyclic heating and cooling, VDM® Alloy 601 retains a tightly adherent oxide layer which is very resistant to spalling.

According to DIN EN 10095, the maximum operating temperature in air is 1,200 °C (2,192 °F), while the loss of weight from scaling is not higher than 1 $g/m^2 \cdot h$ on average.

Resistance to carburization is good. VDM® Alloy 601 has also shown good resistance in (carbo) nitriding conditions, if a sufficiently high oxygen partial pressure is present.

Applications

VDM® Alloy 601 has found a wide variety of applications in high temperature areas in furnace construction, the chemical industry, in environmental protection facilities, in the automobile industry and in power plants. Typical application fields include:

- Trays, baskets and fixtures for heat treatment plants, e. g. in carburizing or carbonitriding environments
- Refractory anchors, strand-annealing and radiant heater tubes, high-velocity gas burners, wire mesh belts in industrial furnaces
- Isolating inserts in ammonia crackers and catalyst support grids in nitric acid production
- High temperature components in automotive parts, e. g. manifolds, glow plug tubes or sensor caps
- Combustion chambers in solid waste incinerators
- Tube supports and ash-handling components
- Components in exhaust gas systems
- Oxygen preheaters

Fabrication and heat treatment

VDM® Alloy 601 can readily be hot- and cold-worked and machined.

Heating

Workpieces must be clean and free of any contaminants before and during heat treatment. Sulfur, phosphor, lead and other low-melting-point metals can lead to damages when heat treating VDM® Alloy 601. Sources of such contaminants include marking and temperature-indicating paints and crayons, lubricating grease and fluids, and fuels. Heat treatments can be carried out in gas fired, oil fired or electric furnaces in air, under vacuum or inert gas atmosphere. Fuels should contain as little sulfur as possible. Natural gas should contain less than 0.1 wt.-% of sulfur. Heating oil with a sulfur content of maximum 0.5 wt.-% is also suitable with a slightly oxidizing atmosphere. Reducing or changing furnace atmosphere should be avoided, as well as direct flame impingement. The temperature should be precisely controlled.

Hot working

VDM® Alloy 601 may be hot-worked in the temperature range 1,200 to 900 °C (2,192 to 1,650 °F) with subsequent rapid cooling down in water or by using air. The workpieces should be placed in the furnace heated to hot working temperature in order to heat up.

Heat treatment after hot working is recommended in order to achieve optimum fabrication properties (cold forming, machinability, weldability) and creep resistance.

Cold working

Cold working should be carried out on annealed material. VDM® Alloy 601 has a higher work hardening rate than austenitic stainless steels. This must be taken into account during design and selection of forming tools and equipment and during the planning of the forming processes. Intermediate annealing may be necessary at high degrees of cold working deformation.

After cold working with more than 10 % deformation the material should be solution annealed in order to avoid recrystallization to a fine-grained microstructure with low creep resistance during operation. Scaled workpieces can also be cold-worked. The inside bending diameter should be at least 1.5 times the sheet/plate thickness.

Heat treatment

For any thermal treatment the material should be charged into the furnace at maximum annealing temperature observing the precautions concerning cleanliness mentioned earlier under 'Heating'. Solution annealing should be carried out in the temperature range 1,100 to 1,200 °C (2,010 to 2,190 °F). Optimum creep strength is achieved by a relatively coarse grained microstructure (≤ 5 according to ASTM E 112 or > 65 µm) using annealing temperatures between 1,140 and 1,160 °C (2,084 and 2,120 °F).

The retention time during annealing depends on the workpiece thickness and can be calculated as follows:

- For thicknesses d ≤ 10 mm (0.4 in) the retention time is t = d • 3 min/mm
- For thicknesses d = 10 to 20 mm (0.4 to 0.8 in) the retention time is t = 30 min + (d - 10 mm) • 2 min/mm
- For thicknesses d > 20 mm (0.8 in) the retention time is t = 50 min + (d - 20 mm) • 1 min/mm

The retention time starts when the annealing temperature is reached. Longer retention times are less critical than too short retention times.

Water quenching should be carried out rapidly if the material should be further fabricated after solution annealing. Workpieces of less than 3 mm (0.12 in) thickness can be cooled down using air nozzles. If the solution annealing is the last fabrication step, the material can be cooled down more slowly in order to avoid material distortion.

In components made of VDM® Alloy 601, stress relaxation cracks may occur during in continuous operation (> 100 h) in the temperature range between 600 and 650 °C (1,112 and 1,202 °F). The risk of cracking can significantly be reduced through a thermal treatment at 980 °C (1,796 °F) for ~ 3 h. Heating rates are not critical, but should not be too high in order to avoid material distortion.

Descaling and pickling

High-temperature alloys develop a protective oxide layer in service. Therefore the necessity of descaling should be checked during the order process. Oxides of VDM® Alloy 601 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.

Particular attention should be paid to short pickling times (to avoid intercrystalline attacks) and pickling temperatures. Before pickling in a nitric/hydrofluoric acid mixture, the surface oxide layer must be broken up by abrasive blasting or grinding or by pretreatment in a fused salt bath.

Machining

VDM® Alloy 601 should be machined in the solution annealed condition. As the alloy is prone to work-hardening, low cutting speeds and appropriate feed rates should be used and the tool should be engaged at all times. Sufficient chip depths are important to get below the work-hardened surface layer.

Due to the high temperature loads on the cutting edge during machining, large amounts of cooling lubricants should be used. Water-based emulsions, as they are also used for construction and stainless steels, are suitable for instance.

Welding

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

Workplace
A separately-located workplace, which is specifically separated from areas in which carbon steels are being processed, should be used. Maximum cleanliness is required, and draughts should be avoided during inert gas welding.

Auxiliary equipment and clothing
Clean fine leather gloves and clean working clothes should be used.

Tools and machines
Tools used for other materials must not be used for nickel-base alloys and stainless steels. Brushes should be made of stainless materials. Processing and machining equipment such as shears, punches or rollers must be fitted with means (felt, cardboard, films) in order to avoid material contamination with ferrous particles, which can be pressed into the surface of the material and thus lead to corrosion.

Welding edge preparation
Welding edge preparation should preferably be carried out using mechanical methods such as lathing, milling or planing. Abrasive waterjet cutting or plasma cutting is also suitable. In the latter case, however, the cut edge (seam flank) must be cleanly re-worked. Careful grinding without overheating is also acceptable.

Ignition
The arc may only be struck in the weld area, e.g. along the seam flanks or outlets, and should not be carried out on the workpiece surface. Arc striking areas are prone to corrosion.

Included angle
The different physical characteristics of nickel alloys and special stainless steels are generally expressed through lower thermal conductivity and higher thermal expansion in comparison with carbon steel. This should be allowed for by means of, among other things, wider root gaps or openings (1-3 mm; 0.04-1.2 in), while larger included angles (60-70°), as shown in Fig. 1, should be used for individual butt joints owing to the viscous nature of the molten weld metal and to counteract the pronounced shrinkage tendency.

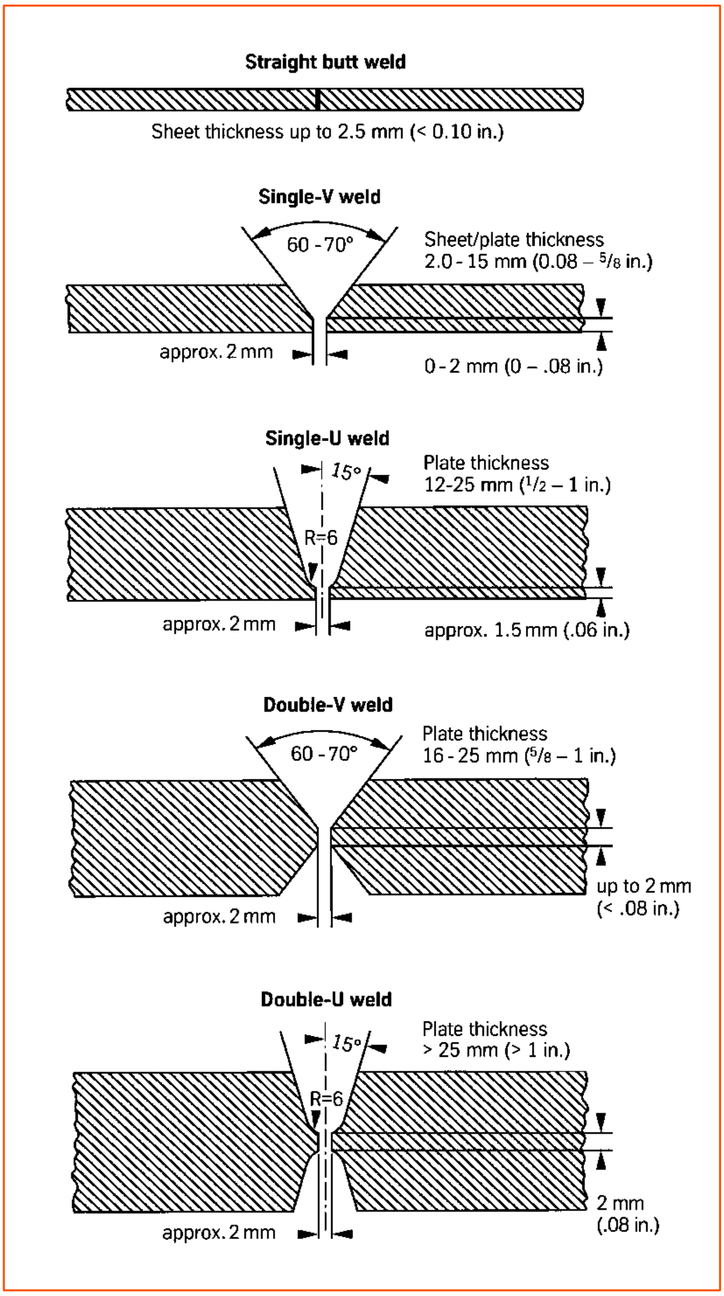

Figure 1 – Edge preparation for welding nickel alloys and special stainless steels

Cleaning

Cleaning of the base material in the seam area (both sides) and the filler material (e.g. welding rod) should be carried out using Acetone.

Welding process

For welding, VDM® Alloy 601 should be in the annealed condition and be free from scale, grease and markings. VDM® Alloy 601 can be welded using the following procedures: GTAW (TIG), GMAW (MIG/MAG), plasma, electron beam welding (EB) and SMAW (MMA).

For MAG welding the use of shielding gas ISO 14175 Z ArHeNC 10-5-0.05 is recommended, when VDM® FM 602 CA wire electrodes are used. For TIG and plasma welding with VDM® FM 602 CA as filler metal, an argon/nitrogen mixture (argon with 2 to 3 % nitrogen) should be used as a protective gas. However, when using VDM® FM 617 as filler metal, pure argon (Ar 4.6) should be used.

For submerged arc welding the material must be covered with two TIG welded cover passes due to the combustion of aluminum. When welding roots, sufficient protection of the root needs to be ensured with pure argon (Ar 4.6) so that the welding seam is free of oxides after welding. Root backing is also recommended for the first intermediate pass following the initial root pass and in some cases even for the second pass, depending on the weld set-up.

Any discoloration/heat tint should be removed preferably by brushing with a stainless steel wire brush while the weld metal is still hot.

Filler metal
The following filler materials are recommended:

Welding rods and wire electrodes

VDM® FM 602 CA (W.-Nr. 2.4649)
DIN EN ISO 18274: S Ni 6602 (NiCr25Fe10AlY)
UNS N06025
AWS A5.14: ERNiCrFe-12

or

VDM® FM 617 (W.-Nr. 2.4627)
DIN EN ISO 18274: S Ni 6617 (NiCr22Co12Mo)
UNS N06617
AWS A5.14: ERNiCrCoMo-1

Welding parameters and influences
Care should be taken that the work is performed with a deliberately chosen, low heat input as indicated in Table 6 by way of example. The stringer bead technique is recommended. The interpass temperature should not exceed 120 °C (248 °F). The welding parameters should be monitored as a matter of principle.

The heat input Q may be calculated as follows:

$$Q=\frac{U \cdot I \cdot 60}{v \cdot 1.000} \left(\frac{kJ}{cm}\right)$$

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

Post-weld treatment
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. Please also refer to the information on ‘Descaling and pickling’. Neither pre- nor postweld heat treatments are required. Preheating before welding is generally not necessary. Stabilizing annealing should be carried out on semi-finished products which were in use at temperatures between 600 and 650 °C (1,112 and 1,202 °F) before they are reused in this critical temperature range after repair welding.

Thickness	Welding technique	Filler material		Root pass[1)]		Intermediate and final passes		Welding speed	Shielding gas[2)]	
(mm)		Diameter (mm)	Speed (m/min)	I in (A)	U in (V)	I in (A)	U in (V)	(cm/min)	Type	Rate (l/min)
3	manual TIG	2		90	10	110-120	11	15	I1, N2 at max. 2% N2	8-10
6	manual TIG	2-2.4		100-110	10	120-140	12	14-16	I1, N2 at max. 2% N2	8-10
8	manual TIG	2.4		100-110	11	130-140	12	14-16	I1, N2 at max. 2% N2	8-10
10	manual TIG	2.4		100-110	11	130-140	12	14-16	I1, N2 at max. 2% N2	8-10
3	autom. TIG	1.2	1,2			150	11	25	I1, N2 at max. 2% N2	12-14
5	autom. TIG	1.2	1,4			180	12	25	I1, N2 at max. 2% N2	12-14
4	Plasma[3)]	1.2	1	180	25			30	I1, N2 at max. 2% N2	30
6	Plasma[3)]	1.2	1	200-220	26			26	I1, N2 at max. 2% N2	30
8	MIG/MAG[4)]	1	6-7			130-140	23-27	24-30		18
10	MIG/MAG[4)]	1.2	6-7			130-150	23-27	25-30		18

[1)] It must be ensured that there is sufficient root protection, for example using Ar 4.6, for all inert gas welding processes.

[2)] The listed shielding gases are to be used when welding with filler VDM® FM 602 CA. When welding with filler VDM® FM 617 only pure argon (Ar 4.6) or R1 with 3% H2 is to be used as a shielding gas.

[3)] Recommended plasma gas Ar 4.6 / rate 3.0 to 3.5 l/min

[4)] For MAG welding the use of multicomponent inert gases is recommended.

Section energy kJ/cm:
TIG, MIG/MAG max. 8; MMA max. 7; Plasma max. 10

Figures are for guidance only and are intended to facilitate setting of the welding machines.

Table 7 – Welding parameters

Availability

VDM® Alloy 601 is available in the following standard semi-finished product forms:

Rod and bar

Delivery conditions: forged, rolled, drawn, heat treated, oxidised, descaled resp. pickled, machined, peeled, ground or polished

Dimensions*	Outside diameter mm (in)	Length mm (in)
General dimensions	6-800 (0.24-31.5)	1,500-12,000 (59.06-472.44)
Material specific dimensions	12-300 (0.47-11.81)	1,500-12,000 (59.06-472.44)

* Further dimensions on request

Sheet and plate

Delivery conditions: hot or cold rolled, heat treated, descaled resp. pickled

Condition	Thickness mm (in)	Width mm (in)	Length mm (in)	Piece weight kg
Cold rolled	1-7 (0.04-0.28)	1,000-2,500 (39.37-98.43)	≤ 5,500 (216.54)	≤ 3,350
Hot rolled*	3-100 (0.12-3.94)	1,000-2,500 (39.37-98.43)	≤ 12,000 (472.44)	≤ 3,350

* 2 mm thickness on request

Strip

Delivery conditions: cold rolled, heat treated, pickled or bright annealed

Thickness mm (in)	Width mm (in)	Coil - inside diameter mm			
0.02-0.15 (0.0008-0.0059)	4-230 (0.16-9.06)	300	400	500	–
0.15-0.25 (0.0059-0.01)	4-720 (0.16-28.34)	300	400	500	–
0.25-0.6 (0.01-0.024)	6-750 (0.24-29.5)	–	400	500	600
0.6-1 (0.024-0.04)	8-750 (0.32-29.5)	–	400	500	600
1-2 (0.04-0.08)	15-750 (0.6-29.5)	–	400	500	600
2-3 (0.08-0.12)	25-750 (0.98-29.5)	–	400	500	600

Wire

Delivery conditions: bright drawn, ¼ hard to hard, bright annealed in rings, containers, on spools and spiders

Drawn mm (in)	Hot rolled mm (in)
0.16-10 (0.006-0.4)	5.5-19 (0.22-0.75)

Other shapes and dimensions such as circular blanks, rings, seamless or longitudinal-welded tubes and pipes or forgings are subject to special enquiry.

Technical publications

U. Brill: "Korrosion und Korrosionsschutz – Nickel, Cobalt und Nickel und Cobalt-Basislegierungen", in Egon Kunze (Hrsg.), Sonderdruck aus Band 2: "Korrosion der verschiedenen Werkstoffe", WILEY-VCH Verlag, Weinheim, 1992.

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