Working and machining of austenitic special stainless steels and nickel-base alloys.







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Introduction
This brochure discusses, with the exception of joining methods, the most important fabrication processes employed in the manufacture of process equipment and piping and their special characteristics for working of high-alloyed austenitic stainless steels and nickel-base alloys. An overview of the materials discussed in these guidelines is given in Tables 1, 2 and 3.

Materials which by virtue of their chemical composition and the manufacturing process are resistant to corrosion and/or high temperatures are naturally required to exhibit these properties also in the finished component. That means, they should correspond to the as-delivered condition of the respective mill product such as sheet and plate, rod and bar as well as tube and pipe.

Material Designation				Typical Analysis in wt.-%				
CRONIFER®	Alloy	UNS	W.-Nr.	Ni	Cr	Mo	Fe	Others
1925 hMo	926	N 08926	1.4529	25	21	6.5	Balance	Cu 0.9; N 0.19
NICROFER®	Alloy	UNS	W.-Nr.	Ni	Cr	Mo	Fe	Others
3033	33	R 20033	1.4591	31	33	1.6	Balance	Cu 0.6; N 0.4
3127 LC	28	N 08028	1.4563	31	27	3.5	Balance	Cu 1.3
3127 hMo	31	N 08031	1.4562	31	27	6.5	Balance	Cu 1.3; N 0.2
3620 Cb	20	N 08020	2.4660	38	20	2.4	Balance	Cu 3.4; Cb 0.2
4221	825	N 08825	2.4858	39	23	3.2	Balance	Cu 2.2; Ti 0.8
4823 hMo	G-3	N 06985	2.4619	48	23	7	19	Cu 2; Cb 0.3
6020 hMo	625	N 06625	2.4856	63	22	9	2	Cb 3.4
6616 hMo	C-4	N 06455	2.4610	66	16	16		Ti 0.3
5716 hMoW	C-276	N 10276	2.4819	57	16	16	6	W 3.5; V 0.2
5923 hMo	59	N 06059	2.4605	59	23	16		

Table 1 – Corrosion-resistant Cr-Ni stainless steels and Ni-Cr-Mo-(Fe) alloys

Material Designation				Typical Analysis in wt.-%					
VDM Designation	Alloy	UNS	W.-Nr.	Ni	Cr	Fe	Cu	Mo	Others
VDM Ni 99.2	200	N 02200	2.4066	99.2					
VDM LC-Nickel 99.2	201	N 02201	2.4068	99.2					
Nicorros®	400	N 04400	2.4360	64		1.8	32		Mn 1
Nicorros® Al	K-500	N 05500	2.4375	64		1.0	30		Al 2.8; Mn 0.6; Ti 0.5
Cunifer® 30	CuNi 70/30	C 71500	2.0882	31		0.6	67		Mn 0.7
Cunifer® 10	CuNi 90/10	C 70600	2.0872	10		1.6	87		Mn 0.8
Nimofer® 6928	B-2	N 10665	2.4617	69	0.8	1.7		28	

Table 2 – Nickel, Ni-Cu, Cu-Ni, and Ni-Mo alloys

The alloying constituents of the materials listed in these tables exhibit mechanical properties which are generally markedly higher than that of standard Cr-Ni stainless steels, e.g., AISI 316 (UNS S31600 – German material no. 1.4571). This is true both at room temperature and at elevated temperatures at which hot working is carried out.

High-alloyed austenitic stainless steels and nickel-base alloys can readily be worked and machined by all conventional processes. However, extremely exacting demands are made on tools and fixtures. The working processes are nowadays easily controllable, but they are often more cost-intensive than in the case with conventional structural steels, and this should appropriately be taken into account in cost calculations.

Material Designation				Typical Analysis in wt.-%				
NICROFER®	Alloy	UNS	W.-Nr.	Ni	Cr	Mo	Fe	Others
3220 H	800 H	N 08810	1.4876 1.4958	31	20		Balance	Si 0.4; Al 0.3; Ti 0.3
3220 HP	800 HP	N 08811	1.4959	31	20		Balance	Si 0.4; Al 0.4; Ti 0.4
3718	(330)	(N 08330)	1.4864	36	16		Balance	Si 1.5
45 TM	45 TM	N 06045	2.4889	45	28		24	Si 2.7; R.E. 0.08
4626 MoW	333	N 06333	2.4608	46	25	3	Balance	W 3; Co 3; Mn 1.6
4722 Co	X	N 06002	2.4665	Balance	22	9	18	Co 1.5; W 0.6
5520 Co	617	N 06617	2.4663	54	22	9	1	Co 12; Al 1; Ti 0.4
6023 H	601 H	N 06601	2.4851	60	23		14	Al 1.4
6025 HT	602 CA	N 06025	2.4633	60	25		9	Al 2.1; Y 0.1
7216 H	600 H	N 06600	2.4816	73	16		9	

Table 3 – High-temperature and heat-resistant nickel-base alloys

Forming

In the manufacture of vessels and process equipment, hot and cold working is an indispensable part of fabrication. Hot working is generally carried out at temperatures above or near the recrystallization temperature, while cold working is used when the forming process is carried out at room temperature or at well below the recrystallization temperature. During hot working the resistance to deformation is much lower than during cold working when materials work harden which increases the resistance to deformation.

Hot working

Hot working is carried out in a temperature range between the recrystallization temperature and the solution-annealing temperature. As a result, the resistance to deformation is greatly reduced and the forces required to work the material are correspondingly lower.

If, as the temperature falls, the forces required for forming are no longer adequate due to the increasing resistance to deformation, hot working should be terminated and the workpiece reheated or rapidly cooled to below approximately 100 °C (212 °F).

Table 4 shows, by way of example, the hot-working and thermal-treatment temperatures for a number of special stainless steels and nickel-base alloys.

During hot working, care should be taken that deformation proceeds as uniformly as possible so as to prevent the formation of an inhomogeneous grain structure. In addition, for low amounts of deformation (≤ 30 % approx.), the forming temperature should be as close as possible to the lower limit in order to prevent a duplex microstructure of coarse and fine-grained areas. For higher amounts of deformation (> 30 % approx.), the higher temperatures might appropriately be applied.

After every hot-working operation, a thermal treatment should be carried out in accordance with the mill product manufacturer's recommendation. Details with regard to heat control are described under **Thermal Treatment**. Applicable thermal-treatment temperatures are listed in the respective material data sheets available from Krupp VDM GmbH.

VDM designation	Alloy	UNS	W.-Nr.	Hot-working temperature, °C	Solution heat-treatment temperature, °C	Soft-annealing temperature, °C
Cronifer® 1925 hMo	926	N 08926	1.4529	1200 - 900	1150 - 1180	-
Nicrofer® 3033	33	R 20033	1.4591	1200 - 1000	1100 - 1150	-
Nicrofer® 3127 hMo	31	N 08031	1.4562	1200 - 1050	1150 - 1180	-
Nicrofer® 5716 hMoW	C-276	N 10276	2.4819	1200 - 950	1100 - 1160	-
Nicrofer® 5923 hMo	59	N 06059	2.4605	1180 - 950	1100 - 1180	-
Nircrofer® 6020 hMo	625	N 06625	2.4856	1150 - 900	-	950 - 1050
Nicrofer® 3220 H	800 H	N 08810	1.4876	1200 - 900	1150	-
Nicrofer® 45 TM	45 TM	N 06045	2.4889	1180 - 900	1160 - 1200	-
Nicrofer® 4626 MoW	333	N 06333	2.4608	1180 - 950	1150 - 1180	-
Nicrofer® 6023 (H)	601 (H)	N 06601	2.4851	1200 - 900	(1100 - 1180)	920 - 980
Nicrofer® 6025 HT	602 CA	N 06025	2.4633	1200 - 900	1180 - 1220	-
Nicrofer® 7216 (H)	600 (H)	N 06600	2.4816	1200 - 900	(1080 - 1150)	920 - 1000

Table 4 – Hot-working and thermal-treatment temperature ranges for selected special stainless steels and nickel-base alloys

Cold working

Among the processes of cold working, only the ones that are most important in manufacturing of process equipment are considered here, i.e., bending - folding - rounding.

Austenitic stainless steels and nickel-base alloys in the thermally treated condition can be readily cold worked. The specific material properties, such as the yield strength and the rate of work hardening resulting in a decrease in elongation should, however, be taken into account.

Figure 1 shows how the degree of cold deformation during the relatively simple operation of bending a sheet, which approximates uniaxial stress conditions, can be determined. According to the given formula, a bending radius (r = inner radius) of 3x the sheet thickness results in a cold deformation of approximately 14 %.

Thus a bending radius of 3x the sheet thickness generally allows the component to be put into service without a subsequent thermal treatment, as described below.

Cold working alters the mechanical properties of metallic materials, as exemplified in Figure 2 with reference to stainless steel AISI 316 and nickel-base alloy Nicrofer 6020 hMo - alloy 625. As typically seen in this figure, stainless steels and nickel-base alloys are prone to appreciable work hardening accompanied by a noticeable decrease in the elongation which quickly results in necking with subsequent fracture in tensile testing.

German rules for pressure vessel constructions therefore stipulate that in the case of austenitic stainless steels cold working with 15 % deformation or more must as a rule be followed by a thermal treatment (see AD-Merkblatt HP 7/3).

Conditions under which a thermal treatment is not required after such cold working, e.g., after forming of dished heads, are also specified in this AD-Merkblatt.

Some materials, especially those containing Mo, are prone to precipitation of intermetallic phases, if, following extensive cold working, welding is carried out in the area of deformation. As a result, these areas may become sensitized, i.e., their corrosion resistance may be impaired.

For most Krupp VDM materials cold working, up to 15 % deformation, is permitted without subsequent thermal treatment. In individual cases, though, depending on the material and the proposed application, a thermal treatment may be necessary, even if the amount of cold deformation is less than 15 %. This may be the case when solution heat-treated high-temperature alloys are used. In other cases, higher amounts of deformation may be permitted without a thermal treatment, especially if no welding is carried out in the area of deformation.

As thermal treatment with the necessary follow-up operations such as pickling and straightening

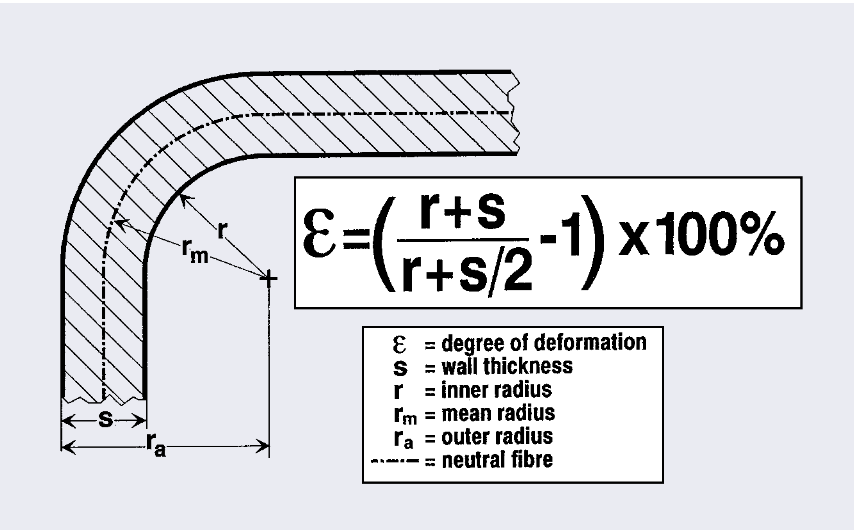


Fig. 1 – Calculation of the degree of cold deformation in bending

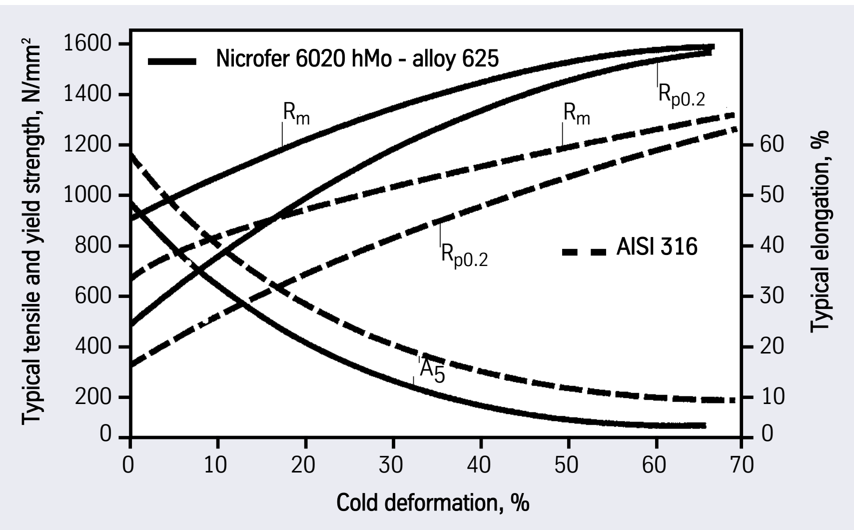


Fig. 2 – Effect of cold deformation on mechanical properties

is very cost-intensive, it is advisable initially, at the design stage, to provide, for example, for the largest possible bending radii to be employed and to enter into discussions with the fabricator, the enduser and material supplier regarding the proposed design and fabrication details at an early stage. This is especially true for critical applications.

Cold working with 15 % deformation typically results in an increase of the 0.2 % yield strength to double the original value. Some high-alloyed special stainless steels and nickel-base alloys exhibit relatively high strength values even in the as-delivered condition; this significantly increases the force required to form these materials, as schematically indicated in Figure 3.

Therefore, bending rollers and folding presses may not be able to apply sufficient pressing or plunging force to obtain the desired final shape of the component. In order to overcome this, the workpiece may be preheated to within a temperature range at which the strength of the material falls below the value at room temperature thereby greatly reducing the resistance to forming.

Forming of austenitic chrome-nickel stainless steels and nickel-base alloys is often carried out with tools, fixtures and machines that are used to also form mild steel. Extraneous ferrite particles on the surface of these tools resulting from processing mild steel may in the presence of moisture cause corrosive attack during later service. Under such conditions ferrite particles can destroy the component's passive layer, which in turn leads locally to a decrease in the corrosion resistance and eventually to corrosion. Care should therefore be taken that all tools and equipment used during mild steel fabrication are always thoroughly cleaned so that no loose particles of mild steel are carried onto the surface of high-alloyed workpieces.

Surfaces of finished components, which will be exposed to moisture or corrosive media during actual service should therefore be checked to insure that no ferrite particles remain on the surface. This can be done, for example, by the 'Ferroxyl Test for Free Iron' as described in ASTM specification A380. If ferrite particles are found to be still present the finished component may have to be submitted to a further cleaning operation, such as pickling followed by passivation, before it can be delivered and put into service.

Factor 1.0 1.5 2.0

Material	UNS	Alloy	Strength min R_m, N/mm²
Boiler plate H II			420
NIROSTA 4571	S 31600	316	520
Cronifer® 1925 LC	N 08904	904 L	520
Nicrofer® 45 TM	N 06045	45 TM	620
Cronifer® 1925 hMo	N 08926	926	650
Nicrofer® 3127 hMo	N 08031	31	650
Nicrofer® 6025 HT	N 06025	602 CA	675
Nicrofer® 5923 hMo	N 06059	59	690
Nicrofer® 5520 Co	N 06617	617	750
Nimofer® 6928	N 10665	B-2	760
Nicrofer® 6020 hMo	N 06625	625	830

Fig. 3 – Comparison of forces required for cold working of various alloys

Thermal Treatment

Hot and/or cold working carried out in the fabricator's workshop alters the mechanical properties and the corrosion behaviour associated with the material in the as-delivered condition. These properties can only be re-established by means of specific, controlled thermal treatments. The thermal treatment causes the microstructure to form anew, generally through recrystallization, and thereby eliminates the changes in the material's properties, which were brought about by the forming operation. Thermal treatments, though, are expensive and often cannot easily be performed on a component.

After hot working, the component should undergo a thermal treatment. After cold working, a thermal treatment may not be necessary. The question of whether a finished component should be thermally-treated or not depends, for example, on the amount of cold deformation performed as discussed under **Cold working** and should be agreed upon with the client in each specific case, unless applicable codes and specifications make a thermal treatment mandatory.

Prior to any thermal treatment, contaminants such as grease, oil, marking paints and similar substances must be removed from the surface of the workpiece usually with chlorine-free solvents such as acetone or isopropanol. Trichlorethylene (TRI), perchlorethylene (PER) and carbon tetrachloride (TETRA) must, however, not be used. Among other things, these contaminants may also contain sulfur, phosphorus and low-melting point metals, which with nickel may form low-melting phases, which in turn may have a deleterious effect on the material during service. Fuels must therefore be as low in sulfur as possible. Natural gas should contain less than 0.1 wt.-% sulfur. Fuel oil with a sulfur content not exceeding 0.5 wt.-% is considered suitable.

Though electric furnaces are preferred due to their close control of temperature and freedom from contamination, gas-fired furnaces are acceptable if contaminants are kept at low levels.

The furnace atmosphere should be neutral to slightly oxidizing and must not fluctuate between oxidizing and reducing. Direct flame impingement on the metal must be avoided.

Generally recommended thermal treatment temperatures are stated in the relevant material data sheets. For selected special stainless steels and nickel alloys they are summarized in Table 4.

Workpieces made from materials with a high alloying content of molybdenum should be heated up rapidly. Such materials include the 6%-Mo stainless steels Cronifer 1925 hMo - alloy 926 and Nicrofer 3127 hMo – alloy 31, and the nickel-base alloys Nicrofer 6020 hMo – alloy 625, Nicrofer 6616 hMo – alloy C-4, Nicrofer 5716 hMoW – alloy C-276 and Nicrofer 5923 hMo – alloy 59. For heating, they should therefore be placed in a furnace, which has already been heated up to the desired temperature. After the workpiece has reached the desired temperature, holding times according to Table 5 are generally recommended and given as a guide.

Cooling of high-molybdenum austenitic stainless steels and nickel-base alloys should be carried out rapidly so as to prevent precipitation of undesirable phases. Delayed cooling, e.g. in the furnace, should thus be avoided at all costs, as this leads to formation of precipitates, chiefly along and close to grain boundaries. Such precipitates usually have an adverse effect both on the corrosion resistance and the toughness properties of the material.

Satisfactory results are obtained with a cooling rate of ≥ 150 °C/min. (300 °F/min.) from the material-specific thermal treatment temperature down to below approx. 500 °C (932 °F).

Workpiece thickness	Holding time
≤ 10 mm	3 min./mm thickness
> 10 mm to ≤ 20 mm	30 min. + 2 min./mm thickness > 10 mm
> 20 mm	50 min. + 1 min./mm thickness > 20 mm

Table 5 – Holding times at temperature during heating for various workpiece thicknesses

Abrasive Treatment
It is usually necessary to remove the oxides, formed during a thermal treatment in air, from components for wet corrosive service made of stainless steels and nickel-base alloys. For components intended for high-temperature service, there is in many cases no need for abrasive blasting as descaled material will again form an oxide layer as soon as it enters service. In many cases, the material is in fact deliberately preoxidized to obtain better high temperature service performance as a result of a protective oxide scale. Agreement regarding the surface condition of as-delivered material for high temperature service should therefore specifically be reached with the client before the order is processed.

As oxides adhere very strongly in the case of high-nickel containing materials, it is advisable to blast clean the components with a suitable grit or with glass beads or to grind them with, for instance, 80 grit mop wheels prior to pickling. If the material is pickled after abrasive blasting the use of carbon steel shot is cost-effective and will suffice.

Pickling
Pickling to remove surface oxides is best carried out by immersion in a pickling bath consisting of approx. 15 to 22 % nitric acid and approx. 2 to 3 % hydrofluoric acid. Alternatively, commercially available pickling sprays or pastes can be used. This method is particularly applicable for large fabricated components or sections, which cannot be treated in conventional pickling tanks.

Typical immersion times at room temperature for various alloy groups can be seen in Table 6.

Actual immersion time depends on the material, the oxide thickness and the temperature of the pickling bath. If in doubt, tests should be carried out at the start on the component to establish optimum pickling parameters.

If the technical requirements, e.g., fume extraction, are met, it is recommended to increase the temperature of the bath to approx. 40 °C. This shortens the pickling time considerably.

However, high-temperature materials with fairly high C-content as well as Ni-Mo and Ni-Cu alloys with low Cr-content are particularly sensitive to over-pickling!

After pickling, the component must be carefully rinsed with plenty of water and brushed down.

Any oxide still adhering after pickling should be removed with a stainless steel wire brush. The pickling operation should be repeated, if necessary.

When using pickling agents, such as sprays and pastes, a separate passivating treatment is not required, as this takes place simultaneously during the pickling operation.

In all cases, applicable environmental-friendly effluent management regulations are to be followed to insure that effluents, such as rinse water, are properly neutralised prior to disposal. Pickling by specialist firms, who also take care of the effluent disposal, is often a cost-effective alternative.

Depending on the shape and size of the component, mechanical descaling by grinding or with buffing or mop wheels may also be appropriate, finishing with a fine grit (80 or finer). If necessary the required surface condition of the finished component should be established in consultation with the enduser before commencing with the finishing operation.

To impart optimum corrosion resistance to components, it is generally advantageous, after grinding, to pickle and passivate surfaces, which come in contact with chemical process fluids.

Alloy group	Typical pickling time
Cr-Ni stainless steels	2 - 8 hrs
Ni-Cr-Mo-(Fe) alloys	8 - 24 hrs
Nickel and Ni-Cu alloys	10 - 15 min.
Ni-Mo alloys	8 - 10 min.

Table 6 – Typical pickling times for various alloy groups

Machining

A high work-hardening rate and toughness together with poor thermal conductivity are characteristic for austenitic stainless steels and nickel-base alloys. In machining, allowance must therefore be made to these aspects by the following measures:

- Only use well-ground, sharp tools with smooth surfaces;
- Ensure maximum stability of machine tools and secure work clamping in order to produce a clean cut;
- Apply plenty of coolant and lubricant;
- The tool should be constantly engaged, and with a relatively low cutting speed, a higher rather than lower rate of feed should be used in order to limit work hardening of the material to a minimum;
- If vibrations occur, the cause should immediately be established and remedied, because vibrations always lead to destruction of the cutting edge.

Of the various machining processes, essentially only turning, milling and drilling are dealt with here. Most of the other working processes, such as planing, sawing and the like, follow rules similar to those applicable to turning.

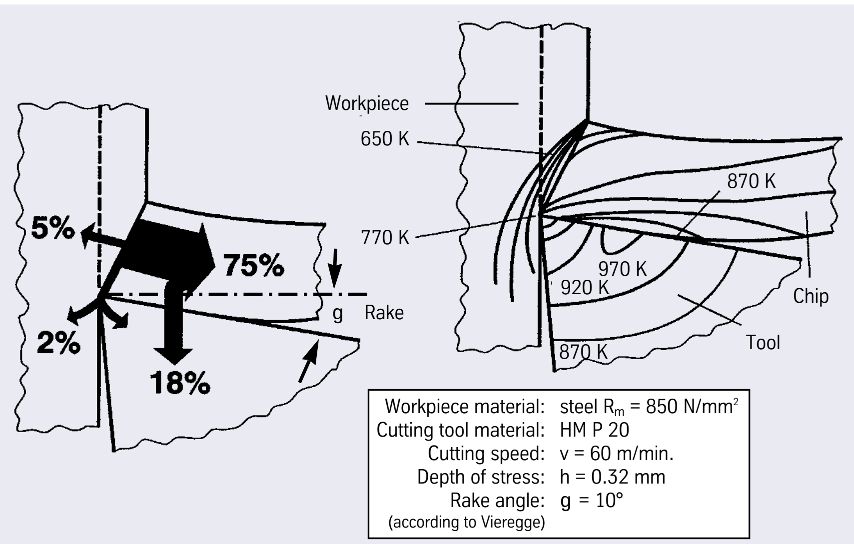


Fig. 4 – Heat distribution in the workpiece, chip and tool during machining of steel according to Kronenberg

Turning

Nowadays, metallic materials are predominantly machined using tools with indexable carbide inserts. These tools produce the highest cutting rates and are recommended for most turning operations involving uninterrupted cuts.

To determine the cutting speed and the rate of feed, it is necessary to consider the stress and wear on the tool.

Tool wear is influenced by the following factors:

- Removal of metal due to excessive mechanical stress, e.g., chipping in the event of vibration;
- Abrasion;
- Shearing-off of pressure-welded points;
- Formation of deposits;
- Oxidation.

Removal of metal due to excessive thermal stress should be seen in relation to the respective properties of the material being machined and the tool. With toughened tools, the cutting edge undergoes plastic deformation. This also happens if high temperature at the cutting edge leads to softening of the tool. This may especially occur with those materials, which have rather poor thermal conductivity. Whereas thermal conductivity for Cr-Ni stainless steels and nickel-base alloys is approx. 8 to 15 W/m·K, the value for carbon steel lies in comparison with approx. 58 W/m·K by a factor of 4 to 7 times higher.

The heat and temperature distribution in the contact zone ‘workpiece-tool-chip’ is illustrated in Figure 4 for machining of steel. The severe thermal stress on the cutting edge is clearly shown in the diagram. Therefore, it is particularly important when machining austenitic stainless steels and nickel-base alloys to ensure adequate heat removal by cooling.

Coolants, either the chemical type or the oil emulsion type, should be used for all roughing operations and finish cuts with carbide tools. Water-base coolants are preferred for use in high-speed operations such as turning and milling, because of their greater cooling effect. These may be soluble oils or proprietary chemical mixtures.

Any work done with high-speed steel tools can be improved by the use of sulfurized, chlorinated cutting oil. For slower operations such as drilling and boring, for example, heavy lubricants and very rich mixtures of chemical coolants are desirable.

Spray mist coolant is adequate for simple turning operations on all stainless steels and nickel-base alloys.

Tools should chiefly be manufactured from carbides of the ISO application groups P 10 to P 50 and K 10 to K 40.

Tests in a neutral atmosphere have proven that oxidation of carbide cutting edges accelerates wear.

Table 7 shows guide values for machining with uncoated indexable carbide inserts, resulting in acceptable and economic service life; there is, however, no ISO standard available for these as yet. The coating counteracts the tendency towards metal pick-up. If coated inserts are used, the cutting speed can be increased by up to 20 %.

Milling

Conventional milling is recommended. Cutting guide values suggested for use in milling operations are given in Table 8.

For end and cylindrical milling cutters, HSS-E steels are used, which can be reground. Milling heads with indexable inserts of the ISO groups P 10 - P 30, e.g., SPUN 120308 P 30, are also used.

Drilling

Drilling is one of the most difficult machining operations, especially in the case of austenitic stainless steels and nickel-base alloys. Problems which may be encountered generally stem from

Material categories	Cutting data							
	Chip cross-section: rigid and/or continuous				Chip cross-section Non-rigid and/or discontinuous			
	Depth of cut a_a mm	Rate of feed f mm/rev.	Cutting speed v_c m/min.	ISO application group	Depth of cut a_a mm	Rate of feed f mm/rev.	Cutting speed v_c m/min.	ISO application group
Stainless steels Special stainless steels	1 - 10	0.1 - 1.5	100 - 60	P10 - P30	1 - 6	0.1 - 1.0	80 - 40	P20 - P50
Ni-Cu alloys, soft annealed Nickel	1 - 10	0.1 - 1.5	80 - 40	P20 - P30 K10 - K20	1 - 6	0.1 - 1.0	60 - 30	P20 - P50 K10 - K40
Ni-Cu alloys, age-hardened Nickel-base alloys Ni-Cr-Mo-(Fe) with Mo ≤ 10 %	1 - 10	0.1 - 1.5	60 - 20	K10 - K20	1 - 6	0.1 - 1.0	50 - 20	K20 - K40
Nickel-base alloys Ni-Cr-Mo-(Fe) with Mo > 10 % and/or Ti > 2 % Cb > 5 % Co > 10 %	1 - 10	0.1 - 1.5	30 - 10	K10 - K20	1 - 6	0.1 - 1.0	20 - 8	K20 - K40

Table 7 – Guide values for turning with uncoated, indexable carbide inserts

the properties of the materials, which were highlighted under **Turning**, and from the complex drilling operation, involving extrusion of metal by the chisel edge in the center of the drill and shear cutting by the lips of the tool. Because of high strength and work-hardening tendencies, drilling of high nickel-base alloys can be a difficult operation if good drilling practice is not adhered to.

The use of short drills (according to DIN 1897) with a large web thickness made of high-speed steel (HSS) alloyed with molybdenum and cobalt is suggested. It has been found that drills made of this material are, on account of its higher elasticity, superior to carbide tools.

Surface treatment of the drills by nitriding or coating with TiN is advisable.

To obtain favourable cutting conditions at the drill tip, a tip angle of 120° to 130° and thinning of the drill by undercutting, e.g., in accordance with DIN 1414 shape A, is recommended.

To optimize chip removal, a tool side rake angle of 25 to 30° (30 to 35° for pure nickel) should be used.

On examining the metal-cutting operation during drilling, one notes the variation in the cutting speed, which steadily decreases to v = 0 m/min. from the outside diameter of the drill towards its tip. This alone may cause considerable work hardening.

Work hardening may even occur during centering. Pyramidal centering punches and light centering facilitate the first cut.

When applying the drill, it is vital to ensure that the cutting edge begins to cut immediately without rubbing for a while over the surface to be cut. In this way work hardening can be avoided.

Material categories	Cutting data			
	Depth of cut a_a mm	Rate of feed f mm/min.	Cutting speed v_c m/min.	ISO application group
Stainless steels Special stainless steels	3 - 6	30 - 50	20 - 30	P10 - P30
Ni-Cu alloys, soft annealed Nickel	3 - 6	30 - 50	25 - 15	P10 - P30
Ni-Cu alloys, age-hardened Nickel-base alloys Ni-Cr-Mo-(Fe) with Mo ≤ 10 %	3 - 6	30 - 50	18 - 10	P10 - P30
Nickel-base alloys Ni-Cr-Mo-(Fe) with Mo > 10 % and/or Ti > 2 % Cb > 5 % Co > 10 %	3 - 6	30 - 50	12 - 8	P10 - P30
Ni-Fe alloys with 36 % Ni	3 - 6	30 - 50	120 - 80	P20 - P30

Table 8 – Guide values for milling with HSS-E steel end and cylindrical milling cutters

Manual feeding should be avoided as far as possible. If automatic feeding at a steady feed rate cannot be used, even pressure should be applied during manual feeding, so that the drill cuts steadily and continuously. If the drill slips, work-hardening occurs, and it is difficult to resume cutting. In fact, the drill may break when it does take hold again after restarting cutting.

For holes over 20 mm in diameter, pilot drilling is recommended.

With deeper hole depths, it is essential to raise and if necessary clean the drill on reaching a hole depth of approx. 4 times the drill diameter and again after every 0.7 times the drill diameter by which the hole is further deepened.

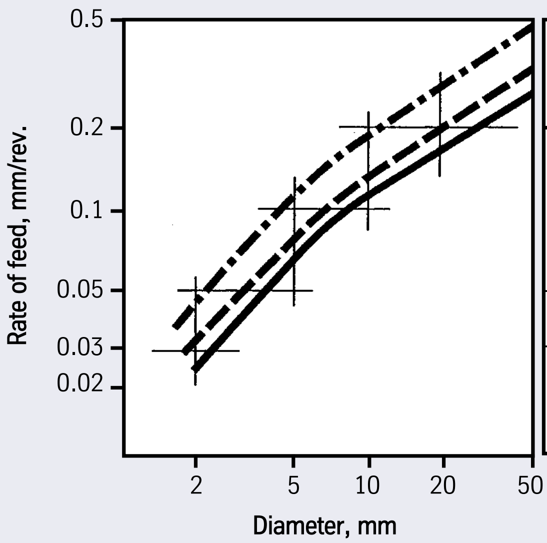
Special care should be taken to apply sufficient coolant and lubricant. 10:1 emulsions as well as heavy and extra-heavy cutting fluids are used as coolants. The use of special cutting fluids suitable for Cr-Ni stainless steels is recommended.

The cutting speeds recommended for drilling are given in Table 9.

Cutting speeds and feed rates in relation to diameter suggested for drilling of various alloy groups are shown in Figure 5.

Countersinking and counterboring
Countersinking and counterboring should be carried out with single- or three-edged tools. In all other respects the instructions apply as given under **Drilling**.

Tapping
Taps made of bright, nitrided or TiN-coated HSS steel may be used for tapping. It is advantageous to use stable taps with discontinuous cutting edges. Core holes should be drilled as large as



Materials	Cutting speed v_c m/min.	Rate of feed mm/rev.
Ni-Cr-Mo-(Fe) alloys, Ni-Cu alloys (age-hardened)	approx. 6	
Cr-Ni stainless steels	approx. 8	
Nickel, Ni-Cu alloys	approx. 25	

Fig. 5 – Guide values for cutting speeds and rates of feed in relation to tool diameter for drilling with HSS tools

Alloy group	Approx. cutting speed
Cr-Ni stainless steels	6 - 10 m/min.
Ni-Cr-Mo-(Fe) alloys	4 - 8 m/min.
Ni-Cu alloys (age-hardened)	4 - 8 m/min.
Ni-Mo alloys	3 - 7 m/min.
Nickel and Ni-Cu alloys	25 m/min.

Table 9 – Recommended cutting speeds for drilling

possible. Maximum applicable diameters are according to DIN 13.

The same cutting speeds as recommended under **Drilling** should be used. The cutting fluids used for drilling are often unsuitable here, as they evaporate. Drilling pastes should be used instead.

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Drilling: Günther & Co.
Eschborner Landstrasse 112
D-60489 Frankfurt
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78 90 21 09

Any suggestions or recommendations for changes to be incorporated into future editions are always gratefully received.

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