



## **Boiler Grade DMV 347 HFG**



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# 1 Introduction



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## 1.1 Salzgitter Mannesmann Stainless Tubes

Salzgitter Mannesmann Stainless Tubes is one of the leading manufacturers of seamless stainless steel and nickel alloy tubes and pipes. Our company has one of the largest product portfolios in this sector.

Our top quality products and efficient service contribute to the long-term success of our customers. Our top priority is to establish and maintain positive long-term relationships with our business partners.

In order to support you in the stockist and project business, with good quality, innovative materials and modern production technologies, our experts are constantly working to

keep up with all the latest trends.

As a company operating successfully on an international level, we unite many nationalities and cultures under one banner. Our network collaborates closely in all aspects of procurement, sales, production and logistics. Since our foundation as a joint venture, we hold our position in the top league of companies in this sector.

We are a member of the powerful Salzgitter Group and our stainless steel and nickel base products are an important addition to the Group's overall product range. Thanks to our impressive product portfolio, we can open up attractive growth prospects.

## 1.2 DMV 347 HFG

Our tubes and pipes are primarily used for boilers in thermal power plants and the energy sector. The same field of application (reheaters and superheaters) is also found in environmental technologies and waste incineration plants. Austenitic boiler steels are normally used in solution-annealed and quenched condition. Coarse grain structures are formed, due to the necessary solution-annealing at high temperature. A coarse grain structure is beneficial for creep strength, but has an adverse effect on oxidation resistance. An adherent protective  $\text{Cr}_2\text{O}_3$  layer at the surface is required for high oxidation resistance. At temperatures around  $600^\circ\text{C}$ , the diffusion rates in austenitic steels are rather low. However, diffusion along the grain boundary is faster. Fine-grained materials offer higher grain boundary area and thus promote grain boundary diffusion. Therefore an austenitic fine grain structure is beneficial in forming a protective chromium oxide layer under modern service conditions. The fine-grained austenitic stainless steel DMV 347 HFG which exhibits high steam-side oxidation resistance represents a modification of the well-known niobium-stabilised steel DMV 347 H.

## 1.3 Trend

Efficiency is a major criterion in defining the performance of boilers. Increasing the efficiency essentially results in a reduction of the fuel consumption and thus  $\text{CO}_2$  emissions, which is a big challenge at the present

time. Higher efficiency of such equipment is reached by higher steam temperatures and pressures. Target service conditions are currently steam temperatures above  $600^\circ\text{C}$  or  $1110^\circ\text{F}$  and pressures of more than 300 bar or 4,350 psi. The materials must withstand these conditions throughout the whole service life of the component. This results in higher demands on creep resistance, elevated temperature strength and high temperature corrosion resistance. An increased metal temperature will lead to increased corrosion and creep deformation of the steel tubes. The thickness of the oxide layer inside the tubes may increase. Thick oxide scales are more susceptible to spalling, which can cause blockages in the superheater tubes. Furthermore, higher steam temperatures will lead to higher material temperatures, resulting in a higher creep strength demand.

DMV 347 HFG is an austenitic stainless steel grade with fine grain structure. It is considered to be among the grades with the highest potential for use in super critical boilers, especially because of its high steam-side oxidation resistance.

In the future, steel development will continue to follow the new demands and challenges of the boiler applications. It is widely expected that new power plants will run at even higher temperatures and pressures. Different steels and nickel based alloys indicate already the development for this future application, such as DMV 310N (for

# 1 Introduction

design temperatures up to 670 °C), DMV 617 and DMV 263 (for design temperatures up to 770 °C). All of these alloys contain higher nickel and chromium contents in order to meet the requirements for higher service temperatures.

## 1.4 Specifications (Standards)

DMV 347 HFG fulfils the requirements of the following specifications:

- 1.4908 (X8CrNi 19 11) according to EN 10216-5, European Standard
- TP347HFG according to ASME SA-213/SA-213M, US Standard
- ASME Code Case 2159-2 (05.2003), United States
- VdTÜV material data sheet 547 (03.2007), Federal Republic of Germany

## 1.5 Available Sizes

DMV 347 HFG austenitic stainless steel is used to manufacture seamless austenitic reheater and superheater boiler tubes. This grade is suitable for all commonly used austenitic reheater and superheater boiler tube sizes and also in the most advanced coal fired power stations using steam temperatures up to approximately 640 °C (1185 °F) in supercritical and ultra supercritical boiler designs.

Following VdTÜV material data sheet 547 (03.2007), a maximum outside diameter of 65 mm and a maximum wall thickness of 12.5 mm is available (standard size range

according to EN-ISO 1127 as well as other sizes upon request).

## 1.6 Special Features

### · Production route of DMV 347 HFG:

- The material is first subjected to a hot forming process (hot extrusion). During this process, the material undergoes softening at a temperature of approx. 1230 °C to 1300 °C (2250 °F to 2375 °F), which is at least 50 °C (90 °F) above the final solution-annealing temperature. Subsequently, cold finishing is carried out on the material, followed by solution annealing at 1180 °C to 1250 °C (2160 °F to 2285 °F). During solution annealing, some of the niobium dissolved during hot forming is precipitated as NbC. These precipitates pin the grain boundaries to avoid grain coarsening.
- The resulting microstructure of this austenitic stainless steel is a **fine-grained structure** of No. 7 - 10 according to ASTM E112 with small and uniformly distributed NbC precipitates.
  - This material, with its ability to maintain a fine grain structure even at high temperatures, provides very high steam-side high-temperature corrosion resistance by enhancing chromium diffusion to the surface along the grain boundaries to form a protective Cr<sub>2</sub>O<sub>3</sub> layer at higher service temperatures.
  - In addition, high creep resistance is provided at temperatures in the range of 580 °C to 640 °C (1075 to 1185 °F).



## 2 Material Properties

### 2.1 Microstructure

The steel grade DMV 347 HFG is a 18Cr-8Ni austenitic stainless steel stabilised by niobium (content in the range of 8 x C up to 1.0 wt.-%). Differences in the material properties and especially in steam-side corrosion resistance compared to the coarser grained steel DMV 347 H are mainly achieved by changing the heat treatment conditions. In this way, the amount, size and distribution of the niobium carbonitride precipitates are changed, resulting in a fine-grained microstructure. Furthermore, the material properties are also influenced by additional precipitation of niobium carbonitrides during service, as a residual amount of niobium remains dissolved in the austenitic matrix after the final heat treatment.

As previously mentioned, the production of boiler tubes is divided into three main processing steps which are responsible for the development of the microstructure. A first thermal treatment is performed during the hot extrusion of the material. This is followed by cold deformation to produce the final dimensions of the tube (cold pilgering or cold drawing). A final heat treatment is carried out at the end of the process. The process to produce a fine-grained material is mainly characterised by the fact that the first heat treatment temperature is at least 50 °C (90 °F) higher than that of the final heat treatment. During the first heat treatment, the so-called “softening”, dissolution of the niobium carbonitrides, takes place. The microstructure is

retained by quenching. During cold deformation, dislocations and twin boundaries are formed which can act as nucleation sites for precipitation during the final heat treatment. This last processing step is commonly known as “solution annealing”. Due to the higher solubility of niobium at the first heat treatment temperature, a certain amount of NbC will precipitate during “solution annealing”. The precipitation of niobium carbonitrides takes place at the numerous nucleation sites created in the material by cold deformation. Thus, small (diameter less than 0.1 µm according to [1]) and uniformly distributed precipitates are formed. These precipitates restrict the grain size during recrystallisation to between No. 7 to 10 according to ASTM E112. In the conventional treatment without “softening”, an austenite grain size of about 3 or 4 after thermal treatment is formed at the same final treatment temperature [1]. Although nearly the same volume fraction of niobium carbonitrides is present, the different size and distribution of these precipitates significantly influence the microstructure.

The fully austenitic microstructure of DMV 347 HFG in as-delivered condition is shown in Figure 1 in two different magnifications.

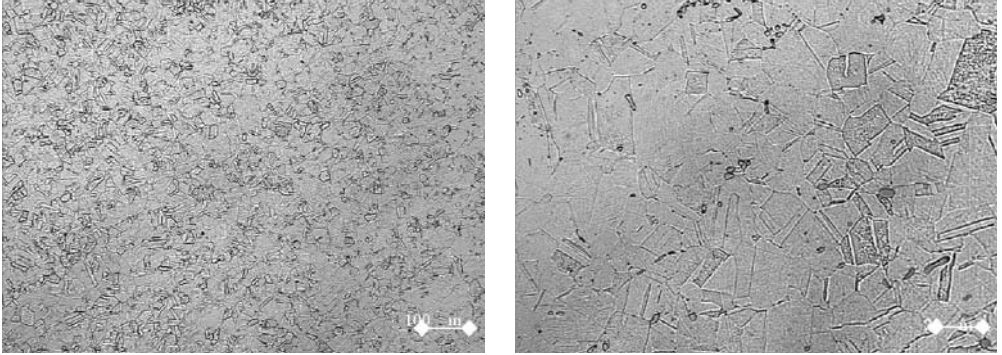


Figure 1: Microstructure of DMV 347 HFG in solution-annealed condition.

The niobium carbonitride precipitates also influence the material properties during service, besides causing a finer grain size of the resulting material. The grain size mainly influences the corrosion resistance as discussed in chapter 2.4. Fine secondary precipitation during service improves the creep resistance. This is the reason for the niobium alloying in the original material DMV 347 H. During service at significantly lower temperatures than the heat treatment temperatures during manufacture, no increase in the amount or size of the primary coarser precipitates is detected (aging at 700 °C up to 70,000 h) [2]. This is attributed to the fact that the distance between the primary precipitates is too large and the diffusion is too slow (kinetic restriction). The volume fraction of the secondary precipitates increases significantly and rapidly during the initial stages of service as the matrix is supersaturated

with niobium at the service temperature. During further aging when the supersaturation is reduced, the volume fraction remains constant. An increase in the size of these secondary precipitates is detected during the whole aging process (e.g. from 20 to 40 nm) which results from the so-called Ostwald ripening process, quantitatively described by Lifshitz, Slyozow and Wagner [2]. The coarsening of the secondary precipitates is influenced by the solubility of niobium, carbon and nitrogen in the austenitic matrix material. Especially the ratio of Nb:C must be optimised to reach a high amount of precipitates on the one hand and to reduce the coarsening of the precipitates on the other hand. A high amount of precipitates is important to reduce the grain size during processing and to improve the creep resistance during service. A coarsening of the precipitates reduces these effects.

## 2 Material Properties

### 2.2 Material properties according to ASME

The material meets the applicable requirements of ASME SA-213/SA-213M specifications. The required material properties are further described in the ASME Code Case 2159-2: Austenitic Stainless Steel Tubes TP347HFG (18Cr-10Ni-Cb).

#### 2.2.1 Chemical composition

The requirements with regard to the chemical composition are summarised in Table 1. The composition given in the ASME Code Case is the same as that given for the heat analysis in the VdTÜV material data sheet 547 (03.2007).

[wt-%]	C	Si	Mn	P	S	Cr	Ni	Nb + Ta
<b>min.</b>	0.06	-	-	-	-	17.0	9.0	8 x C
<b>max.</b>	0.10	0.75	2.00	0.04	0.03	20.0	13.0	1.00

Table 1: Chemical composition of DMV 347 HFG.

	ksi	MPa <sup>1)</sup>	%
<b>Minimum yield strength</b>	30	205	-
<b>Minimum tensile strength</b>	80	550	-
<b>Minimum elongation in 2 inch</b>	-	-	35

<sup>1)</sup> calculated values

Table 2: Mechanical property requirements in solution-annealed condition according to ASME Code Case 2159-2.

A three-step process is required to adjust the fine-grained microstructure (grain size 7 to 10 according to ASTM E112) and to guarantee adequate creep rupture strength:

1. Initial solution treatment at a temperature of at least 90 °F (50 °C) higher than the final solution treatment temperature
2. Cold deformation
3. Final solution treatment at a temperature of at least 2150 °F (1176 °C).

#### 2.2.2 Mechanical properties

Tensile properties at room temperature in the solution-annealed condition according to ASME are given in Table 2. Additionally, the hardness shall not exceed 192 HB (90 HRB).

In the ASME Code Case 2159-2, the maximum allowable stress values at different temperatures are given (see Table 3, Figure 2). They are based on the revised criterion of tensile strength at temperature divided by 3.5, where applicable. In the second column, higher values are given for cases in which slightly greater deformation (1 %) is acceptable. These values exceed

66.67 %, but do not exceed 90 % of the yield strength at temperature. The use of these stress values may result in dimensional changes due to permanent strain. Therefore, these stress values are not recommended for the flanges of gasketed joints or other applications where slight amounts of distortion can cause leakage or malfunction.

Temperature		Maximum allowable stresses		Maximum allowable stresses <sup>2)</sup>	
°F	°C <sup>1)</sup>	ksi	MPa <sup>1)</sup>	ksi <sup>2)</sup>	MPa <sup>1)</sup>
-20 to 100	-29 to 38	20	137.9	-	-
200	93	18.1	124.8	20	137.9
300	149	16.9	116.5	20	137.9
400	204	15.9	109.6	19.9	137.2
500	260	15.2	104.8	19.3	133.1
600	316	14.6	100.7	19.1	131.7
650	343	14.4	99.3	19.0	131.0
700	371	14.1	97.2	18.9	130.3
750	399	13.9	95.8	18.8	129.6
800	427	13.8	95.1	18.6	128.2
850	454	13.6	93.8	18.3	126.2
900	482	13.4	92.4	18.1	124.8
950	510	13.3	91.7	17.9	123.4
1000	538	13.1	90.3	17.7	122
1050	566	13.0	89.6	17.5	120.7
1100	593	12.8	88.3	16.6	114.5
1150	621	12.6	86.9	12.8	88.3
1200	649	9.7	66.9	9.7	66.9
1250	677	7.3	50.3	7.3	50.3
1300	704	5.4	37.2	5.4	37.2
1350	732	4.0	27.6	4.0	27.6

<sup>1)</sup> calculated values

<sup>2)</sup> slightly greater deformation acceptable

Table 3: Maximum allowable stresses at elevated temperatures according to ASME Code Case 2159-2.

## 2 Material Properties

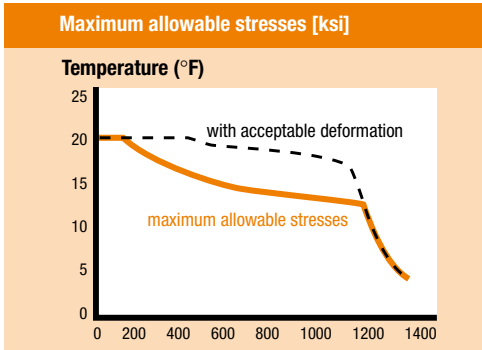


Figure 2: Maximum allowable stresses according to ASME Code Case 2159-2.

### 2.3 Material properties according to VdTÜV

In the following, material properties as given in the VdTÜV material data sheet 547 (03.2007) are summarised.

	[wt-%]	C	Si	Mn	P	S	Cr	Ni	Nb + Ta
Heat analysis	min.	0.06	-	-	-	-	17.0	9.0	8 x C
	max.	0.10	0.75	2.00	0.040	0.030	20.0	13.0	1.00
Product analysis	min.	0.05	-	-	-	-	16.8	8.9	8 x C
	max.	0.11	0.80	2.04	0.045	0.035	20.2	13.1	1.05

Table 4: Chemical composition of DMV 347 HFG.

### 2.3.1 Chemical composition

The requirements with regard to chemical composition are given in Table 4. The composition given in the VdTÜV material data sheet for the heat analysis is the same as that given in the ASME Code Case 2159-2. According to standard practice in Europe, the requirements for the product analysis are slightly extended.

The VdTÜV material data sheet specifies that the final thermal treatment temperature should be at least 50 °C (90 °F) lower than the initial thermal treatment temperature prior to cold deformation. The final thermal treatment temperature is in the range of 1180 to 1250 °C (2155 to 2280 °F). Adequate cooling by water, air or inert gas must be performed.

### 2.3.2 Tensile properties

Tensile properties at room temperature are given in Table 5. The values for proof strength are minimum values and are valid irrespective of location and position of the sample.

Tensile properties at elevated temperatures are presented in Table 6 and Figure 3. The 0.2 % and 1 % proof strength and the tensile strength are summarised. The samples are

taken in longitudinal direction. The given values are valid irrespective of location and position of the sample. The data for tensile strength at elevated temperature are guidelines. In principle, the fine-grained DMV 347 HFG has higher elevated temperature strength than the coarse-grained 347 H grades. Besides the grain size, the fine NbC precipitates can improve the strength at elevated temperatures.

	MPa	ksi <sup>1)</sup>	%
<b>0.2 % proof strength, min.</b>	205	29.7	-
<b>1% proof strength, min.</b>	240	34.8	-
<b>Tensile strength</b>	550-750	78.8-109	-
<b>Elongation at fracture</b>	-	-	35

<sup>1)</sup> calculated values

Table 5: Tensile properties at room temperature according to the VdTÜV material data sheet 547 (03.2007).

Temperature		0.2 % proof strength		1 % proof strength		Tensile strength	
°C	°F <sup>1)</sup>	MPa	ksi <sup>1)</sup>	MPa	ksi <sup>1)</sup>	MPa	ksi <sup>1)</sup>
100	212	182	26.4	217	31.5	475	68.9
200	392	163	23.6	198	28.7	430	62.4
300	572	152	22.0	187	27.1	420	60.9
350	662	148	21.5	173	25.1	420	60.9
400	752	143	20.7	173	25.1	420	60.9
450	842	139	20.2	164	23.8	410	59.5
500	932	136	19.7	161	23.3	400	58.0
550	1022	134	19.4	159	23.1	390	56.6
600	1112	131	19.0	156	22.6	380	55.1
650	1202	126	18.3	151	21.9	325	47.1
700	1292	122	17.7	147	21.3	310	45.0
750	1382	117	17.0	142	20.6	270	39.2

<sup>1)</sup> calculated values

Table 6: Minimum proof strength and tensile strength at elevated temperatures according to the VdTÜV material data sheet 547 (03.2007).

## 2 Material Properties

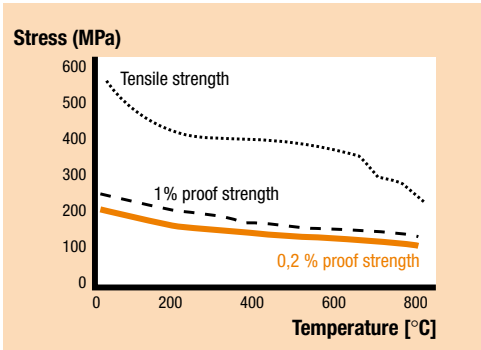


Figure 3: Minimum proof strength and tensile strength at elevated temperatures according to the VdTÜV material data sheet 547 (03.2007).

### 2.3.3 Creep strength

Precipitation hardening is one possible mechanism to increase the creep strength of austenitic steels. Niobium is a common alloying element used for this mechanism through the fine intergranular precipitation of niobium carbonitrides. Grain boundary sliding at high temperature is reduced by the pinning effect of precipitates at grain boundaries. To achieve this effect, not only the carbonitrides precipitated in the dislocations prior to service are used. In addition, fine secondary carbonitride precipitates form during service and lead to further improvement of the creep resistance [3].

The stability of these fine precipitates, as well as a delayed intergranular precipitation of brittle intermetallic phases such as  $\sigma$ - and  $\chi$ -phases, determines the long-term creep strength of such stabilised steels. An optimisation of both effects is possible by adjust-

ing the alloy composition. No significant difference between the creep strength of the coarse-grained 347 H and the fine-grained 347 HFG steels was detected [1]. In both cases, fine and homogeneously dispersed carbonitrides were found after creep rupture tests. The effects of precipitation and delay in formation of intermetallic phases have a higher influence on the creep strength than the grain size.

The creep rupture elongation is influenced by the formation of fine niobium carbonitride precipitates on dislocations. It decreases during their precipitation. The maximum resistance to dislocation movement appears to be present as long as the matrix remains supersaturated with niobium and further precipitation of niobium carbonitrides is possible. The ductility may increase again when the precipitates coarsen and the supersaturation disappears [4]. The delay in the formation of brittle intermetallic phases is also important for sustaining the creep ductility for longer periods.

Creep strength values for 10,000 h and 100,000 h are summarised in Table 7. The datasets consist of currently available long term test results. They are the average values of the existing scatter band. These datasets are reviewed and may be corrected from time to time in the VdTÜV material data sheet. It can be assumed, that the lower limit of the scatter band is about 20 % below the given average.

Temperature		10,000 h		100,000 h	
°C	°F <sup>1)</sup>	MPa	ksi <sup>1)</sup>	MPa	ksi <sup>1)</sup>
600	1112	215	31.2	159	23.1
610	1130	197	28.6	145	21.0
620	1148	182	26.4	134	19.4
630	1166	168	24.4	120	17.4
640	1184	155	22.5	109	15.8
650	1202	142	20.6	100	14.5
660	1220	130	18.9	90	13.1
670	1238	119	17.3	81	11.7
680	1256	108	15.7	72	10.4
690	1274	99	14.4	65	9.4
700	1292	90	13.1	58	8.4
710	1310	81	11.7	51	7.4
720	1328	74	10.7	46	6.7
730	1346	66	9.6	40	5.8
740	1364	59	8.6	34	4.9
750	1382	53	7.7	30	4.4

<sup>1)</sup>calculated values

Table 7: Average creep strength values for 10,000 h and 100,000 h according to the VdTÜV material data sheet 547 (03.2007).

In Figure 4, the average values of creep strength for 10,000 and 100,000 h are displayed together with the minimum values of 0.2 % proof strength of DMV 347 HFG showing the typical intersection of these values.

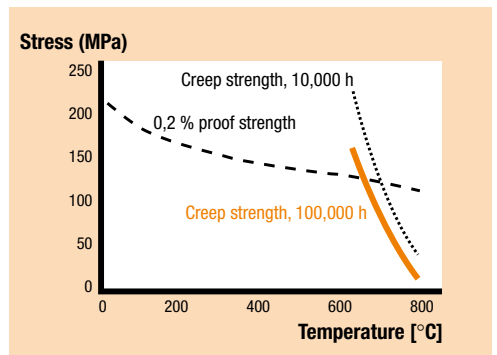


Figure 4: Creep strength for 10,000 and 100,000 h in comparison to 0.2 % proof strength at elevated temperatures.

## 2 Material Properties

### 2.3.4 Impact resistance

According to the VdTÜV material data sheet 547 (03.2007), the average impact energy in longitudinal direction should be at least 85 J at room temperature. This value is the average of 3 specimens. Only one of the 3 results is permitted to fall below the required level, by a maximum of 30 %. During service, the impact values drop significantly within a fairly short time (less than  $10^3$  hours) then remain constant up to  $10^4$  hours. No influence of the grain size on impact resistance is found [1]. In the VdTÜV material data sheet 547 (03.2007) it is stated that the typically decreased impact value should be considered during downtimes, hydrostatic pressure tests etc. For instance, fast start-up cycles should be avoided.

### 2.3.5 Physical properties

In Table 8 and Figure 5, the dynamic modulus of elasticity is given. The summarised values are guidelines.

Temperature		Modulus of elasticity	
°C	°F <sup>1)</sup>	10 <sup>3</sup> MPa	10 <sup>3</sup> ksi <sup>1)</sup>
20	68	200	29.0
100	212	190	27.6
200	392	185	26.8
300	572	175	25.4
400	752	170	24.7
500	932	160	23.2
600	1112	155	22.5
700	1292	145	21.0
750	1382	140	20.3

<sup>1)</sup> calculated values

Table 8: Modulus of elasticity according to the VdTÜV material data sheet 547 (03.2007).

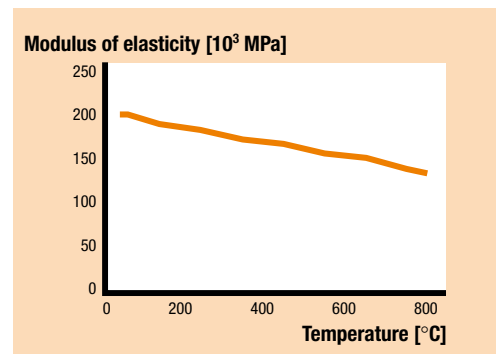


Figure 5: Modulus of elasticity according to the VdTÜV material data sheet 547 (03.2007).

The coefficient of thermal expansion is given in Table 9 and Figure 6. The reference temperature is 20 °C. The given values are guidelines.

Temperature: between 20 °C and ...		Coefficient of thermal expansion	
°C	°F <sup>1)</sup>	10 <sup>-6</sup> / K	10 <sup>-6</sup> / °F <sup>1)</sup>
100	212	16.3	9.1
200	392	16.9	9.4
300	572	17.3	9.6
400	752	17.8	9.9
500	932	18.2	10.1
600	1112	18.5	10.3
700	1292	18.7	10.4
750	1382	18.8	10.4

<sup>1)</sup>calculated values

Table 9: Coefficient of thermal expansion (reference temperature 20 °C (68 °F)) according to the VdTÜV material data sheet 547 (03.2007).

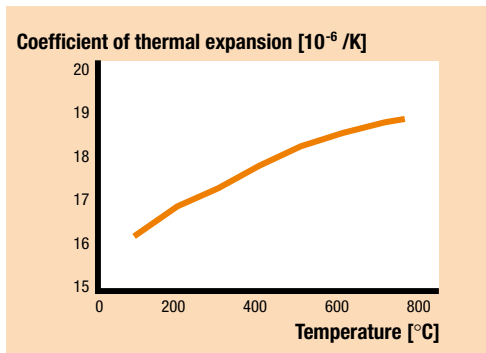


Figure 6: Coefficient of thermal expansion (reference temperature 20 °C (68 °F)) according to the VdTÜV material data sheet 547 (03.2007).

In Table 10 and Figure 7, the values of the thermal conductivity are summarised. Here again, the given values are guidelines.

Temperature		Thermal conductivity	
°C	°F <sup>1)</sup>	W / (m·K)	Btu / (ft·h·°F) <sup>1)</sup>
20	68	14.1	8.47
100	212	15.4	8.90
200	392	16.9	9.77
300	572	18.3	10.5
400	752	19.7	11.4
500	932	21.2	12.3
600	1112	22.6	13.1
700	1292	23.8	13.8
750	1382	24.6	14.2

<sup>1)</sup>calculated values

Table 10: Thermal conductivity according to the VdTÜV material data sheet 547 (03.2007).

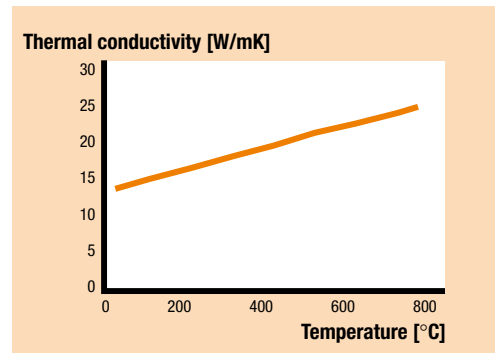


Figure 7: Thermal conductivity according to the VdTÜV material data sheet 547 (03.2007).

## 2 Material Properties

### 2.4 Corrosion resistance

The efficiency of conventional boiler-steam turbine fossil fuel power plants depends to a large degree on steam temperature and pressure. During the last 30 years, steam temperatures have increased by about 60 °C (110 °F) and a further increase of up to 100 °C (180 °F) in the next 30 years is expected. The sensitivity of the material to oxidation on the steam-side is one of the major limiting factors [5], and is of greater interest than the high-temperature corrosion, as the oxidation rate in steam is markedly greater than in air. As temperature increases, the oxide scale is generally formed more quickly and with a greater thickness. The higher wall loss leads to an increase in stress, causing creep rupture. This can be compensated to a certain extent by a thicker tube wall. In addition, the insulation of the tube material by the oxide scale from the cooling fluid leads to an increase in the metal temperature, which again may accelerate corrosion and creep rates on the flue gas side. Moreover, spalling of the thicker oxide scales can occur during service. The build up of these scales may cause blockages at the tube bends. The resulting decrease in steam flow can create local overheating and may lead to failure [1]. It is also possible that the scale might be transported further by the steam and enter the turbine, where severe erosion damage could occur. There is also a risk of erosion on valve seats and turbine blades due to the

exfoliated oxides during unit start up. The development of new or advanced materials is therefore an important task.

DMV 347 HFG is designed for service temperatures between 580 °C (1175 °F) and 640 °C (1185 °F). The major advantage of this material is its high steam-side corrosion resistance in modern boilers due to the reduced grain size compared to grade DMV 347 H [6, 7]. Methods such as shot peening of the tube bore can also be used to further enhance diffusion in order to create protective oxide scales [8].

In the following, the mechanisms and the formation of oxide layers under steam-side oxidation conditions are explained depending on different influencing parameters.

#### 2.4.1 Effect of grain refinement

DMV 347 HFG is proven to have high steam-side corrosion resistance by generating an adherent uniform chromium-rich oxide layer between the scale and the base material. In the fine-grained DMV 347 HFG material, protective  $\text{Cr}_2\text{O}_3$ -formation is favoured by the high grain boundary density, as grain boundary diffusion is much faster than lattice diffusion. The effective diffusion coefficient of chromium is more than two orders of magnitude higher than the lattice diffusion coefficient at 500 °C (935 °F) [9]. This difference decreases with increasing temperature, leading to a change in the morphology of the oxide layers.

In principle, a uniform protective  $\text{Cr}_2\text{O}_3$  layer is formed at the interface of the fine-grained steel during service conditions. A coarser grain size leads to an only partially present or absent  $\text{Cr}_2\text{O}_3$  layer depending on the grain size. A much thicker spinel-type scale of  $(\text{Fe,Cr})_3\text{O}_4$  is formed. An outer scale of  $\text{Fe}_3\text{O}_4$  is present on the surface [1].

In particular, the uniform protective  $\text{Cr}_2\text{O}_3$  layer with a good adherence to the base material is important as a means of increasing the corrosion resistance as it acts as a diffusion barrier. After an initially rapid formation of a  $\text{Cr}_2\text{O}_3$  layer of a certain thickness, the further increase of this layer is slowed down in the case of DMV 347 HFG material. Further oxide growth is determined by the solid diffusion of chromium and oxygen through the bulk or along grain boundaries of the oxide. This diffusion is much faster in the spinel-type scale of  $(\text{Fe,Cr})_3\text{O}_4$ , resulting in a higher degree of oxidation in the case of the coarse-grained 347 H material [1, 6, 7].

In addition to the decreased grain size, cold working and/or shot peening increase the oxidation resistance due to a further grain refinement on the inner surface. For the material DMV 347 HFG, nearly equivalent oxidation resistance is found compared to high chromium (25% Cr) grades, thus providing an economic alternative to these steels.

#### **2.4.2 Effect of service temperature and pressure**

The effect of service temperature and pres-

sure is examined in investigations of material in grade DMV 347 HFG which was installed in power plants [9, 10, and 11]. In all cases, the formation of a double-layered oxide is demonstrated, where each layer consists again of two or three layers or components. The outer layer consists of magnetite and an iron-nickel oxide, whereas the inner layer is formed by an iron-chromium-nickel and a chromium-rich oxide. The iron-chromium-nickel oxide in the inner layer has a spinel structure which cannot prevent further oxidation to the required degree. The chromium-rich oxide (optimal composition  $\text{Cr}_2\text{O}_3$ ) is, in contrast, a dense adherent layer capable of significantly reducing further oxidation. For steam oxidation resistance, the composition of the inner layer is of special interest. The composition and distribution of the phases change with temperature and pressure. Chromium diffusion increases with temperature. Thus, at lower temperatures (a borderline is at about  $600^\circ\text{C}$  ( $1110^\circ\text{F}$ ) [9]), the inner layer consists of an iron-nickel-chromium spinel surrounded by iron-chromium oxide. An irregular layer is formed. The morphology of  $\text{Cr}_2\text{O}_3$  is found to reproduce the original grain boundaries, as the chromium diffusion proceeds along these paths. A pitted structure where iron-chromium-nickel oxides are extended into the grains was also reported. The formation of this oxide is stopped by a healing layer of  $\text{Cr}_2\text{O}_3$  formed at the surrounding grain boundaries [10]. The formation of this healing layer is faster with

## 2 Material Properties

increasing temperature and leads to reduced pitting. With increasing temperature, a more protective  $\text{Cr}_2\text{O}_3$  layer is formed. Under optimum conditions, a flat and uniform layer is developed at the metal surface. This effect is assisted by increased pressure [9]. The mixed iron-chromium-nickel spinel is then formed above this layer, growing into the oxide scale. After initial formation of the  $\text{Cr}_2\text{O}_3$  layer, further thickening is very slow, resulting in superior oxidation resistance compared to the coarse-grained variant. The inner oxide layer is thicker at lower temperatures (500 to 600 °C or 935 to 1110 °F). A minimum is reached at about 600 to 650 °C (1110 to 1200 °F), indicating that the oxidation rate decreases with time by formation of a protective healing layer [9]. With further increase of the temperature, the oxidation rate again increases. At temperatures above 750 °C (1380 °F), the layer may consist of  $\text{Cr}_2\text{O}_3$  bands, increasing again the oxidation resistance because the growth rate oscillates [9]. Chromium diffusion into the outer bulk oxide layers can also take place. The diffusion of oxygen through the oxide scale is thus accelerated resulting in an increased oxidation rate.

In conclusion, it can be summarised that the steam corrosion resistance of fine-grained grade DMV 347 HFG is superior to other grades in a temperature range of 650 to 700 °C at comparably higher pressures [9, 10, and 11].



### 3.1 Tube bending

Boiler tubes manufactured in steel grade DMV 347 HFG are generally suitable for cold and hot bending. If hot forming is not performed using a controlled temperature process between 1170 °C (2138 °F) and 1210 °C (2210 °F), a new solution annealing is required. Cold-formed tubes must be newly solution-annealed if the cold deformation is too high.

If cold deformation exceeds the values given in Table 11, additional solution annealing after deformation is mandatory.

the welded component. It should have a high corrosion resistance and even better mechanical properties than the base material. To avoid hot cracks in the weld metal, the processes recommended by the filler producers have to be observed.

The material DMV 347 HFG is weldable using state-of-the-art technologies. The following fusion welding techniques are possible: metal gas-shielded welding with welding wires, welding sticks or with cored wire electrodes and metal arc welding with lime alkaline enclosed electrodes. It is nec-

Norm	Max. cold deformation	Radius to wall thickness ratio	Additional solution annealing temperature
VdTÜV Datasheet 547	>20 %	≤ 2,5	1180-1250°C (2156-2282 °F)

In order to maintain high corrosion resistance, a new solution-annealing is recommended, even after a small degree of cold deformation.

### 3.2 Welding

The weld joint is considered to be one of the weakest areas in a fabricated component. Therefore it is necessary to consider the characteristics of the weld material to avoid failures. Weldability is usually characterised by the resistance to hot cracking and the mechanical properties of the welded joints. The selection of filler material becomes an important factor for good properties of

essary to use approved filler materials which are also tested at the foreseen application temperature. Preheating and heat treatment after the welding process in the fabrication of DMV 347 HFG is not mandatory. However, if the material is sensitised after welding, then a post welding treatment (solution treatment) can be done to restore the properties, mainly to increase the wet corrosion resistance [VdTÜV material data sheet 547 (03.2007)]. Generally, austenitic stainless steels have a high susceptibility to hot cracking in the weld [12]. However, the hot cracking resistance of the fine-grained material DMV 347 HFG is higher than that of coarse-grained material.

## 4 References

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