Effect of Carbon Content and Other Variables on

Yield Strength, Ductility and Creep Properties of Alloy 625

Ulrich Heubner, Michael Köhler

Krupp VDM
Plettenberger Strasse 2
D-58791 Werdohl, Germany

Abstract

Strength and ductility have been evaluated on various alloy 625 compositions, including carbon contents between 0.009 and 0.045 wt. % and iron contents between 1.1 and 4.2 wt. %. Grain size was between ASTM N° 3 and 7. Aging treatments at 600, 700 and 800°C up to 1000 hrs duration cause an increase of yield strength, being accelerated when aging is carried out at 700°C but with highest tensile elongation after aging at 600°C. Accordingly accompanying loss of ISO V-notch impact strength is least pronounced after aging at 600°C but more severe when the iron content is at 4.2 wt. % compared to lower iron alloyed material. The influence of carbon content on creep strength is the more pronounced the higher the temperature. If 10,000 and 30,000 hrs creep-rupture stress is considered, the influence of carbon is small at 650°C and more distinct at 850°C. In changing ASTM grain size N° from 6 to 3 the 30,000 hrs creep-rupture stress is increasing by about 4 % at 650°C and by about 43 % at 850°C. If creep stress for 1 % strain at 750 and 850°C is considered, the influence of carbon is very strong at carbon contents up to about 0,025 wt. %, improving 30,000 hrs creep stress for 1 % strain at 850°C by about 700 % when carbon content is increased from 0.015 to 0.025 wt. %. Creep deformation may be supposed to improve with decreasing carbon content.

Superalloys 718, 625, 706 and Various Derivatives
Edited by E.A. Loria
The Minerals, Metals & Materials Society, 1994

Introduction

Alloy 625 is one of the major commercial nickel base alloys due to its specific combination of mechanical properties and corrosion resistance. Specified according to ASTM B443 with a maximum carbon content of 0.1 wt % the alloy is available on the market in two versions: a low carbon version (less than 0.025 % C) which is with respect to wet corrosion application normally used in the soft annealed condition (grade 1) and a high carbon version (about 0.045 % C) which is used for high temperature applications in the solution annealed condition. Nevertheless, due to high contents of molybdenum, chromium and columbium, both versions of the alloy exhibit structural instability, if they are exposed to the temperature range of 600°C to 800°C. Since the early stage of development of this alloy (1-4) it is well known that the structural instability causes loss of ductility. In order to improve the degradation of room temperature ductility in addition to carbon the silicon and nitrogen contents are controlled to low levels by modern melting practice (5,6). The purpose of this investigation was to study the influence of carbon content and other variables on short time tensile properties and creep properties of alloy 625. The effect of aging on ductility loss at room temperature and at aging temperature has been studied as well.

Phase Stability of Alloy 625

The excellent high temperature strength of alloy 625 can be assigned to solid solution hardening by molybdenum and columbium. Furthermore, carbide hardening and a very complex precipitation behaviour in the temperature interval between 600°C and 800°C contributes to strengthen the alloy. The time-temperature-precipitation diagram and the recrystallization behaviour have been investigated in detail (7-10). Based on the published work it can be stated that the microstructural changes in the temperature range of 600°C to 1000°C are well understood. Nevertheless there are some small differences with respect to precipitation temperatures and times which might have been caused by the different experimental techniques.

Independent of the previous condition the microstructure of alloy 625 shows primary carbides and carbonitrides of the type Cb(C,N). Secondary intergranular carbides are formed during an annealing treatment in the temperature range of 700°C to 1050°C. M_6C has been detected after a precipitation treatment between 1050°C and 800°C while the precipitation of $M_{23}C_6$ occurs at temperatures between 950°C and 700°C. Precipitation of metastable (coherent tetragonal) $Ni_3(Cb,X)$ phase which, however, can be transformed to the orthorombic phase $Ni_3(Cb,Mo)$, had been observed in the temperature range of 600°C to 850°C. The precipitation of the intermetallic phases during aging causes a remarkable increase in hardness, yield strength and tensile strength as well as a significant decrease of elongation. Increasing the temperature shifts the increase of strength to shorter times and above 750°C a remarkable overaging has been observed.

Experimental

The material to be evaluated was manufactured from industrial heats using VOD melting practice. Table I shows the chemical composition of the alloys investigated.

Table I: Chemical composition of 625 alloys investigated in comparison to ASTM B 443 requirements, wt %, balance nickel

heat	Cr	Mo	Fe	Mn	Si	Ti	Cb+Ta	Al	C	N
ASTM B 443	20-23	8-10	<5.0	<.5	<.5	<.4	3.15-4.15	<.4	<.1	-
A	22.3	8.9	1.1	.02	.11	.2	3.75	.18	.045	.018
B	22.0	8.9	1.3	.03	.14	.2	3.38	.12	.029	.046
C	21.9	8.9	1.4	.03	.04	.18	3.74	.16	.030	.017
D	21.8	9.0	3.2	.03	.15	.16	3.42	.10	.025	.051
E	22.3	9.0	1.4	.05	.13	.19	3.58	.14	.015	.037
F	22.3	9.3	2.1	.1	.09	.3	3.42	.14	.011	.011
G	22.5	9.2	4.2	.1	.09	.25	3.38	.11	.009	.011

The carbon content ranged from 0.009 to 0.045 wt. %. To avoid the appearance of nitride or carbonitride stringers with their adverse effects on ductility the nitrogen content was kept as low as possible. Silicon is restricted to max. 0.15 wt % since silicon is known to promote the precipitation of intermetallic phases in nickel-chromium-molybdenum alloys (11). The product forms, annealing conditions and grain sizes considered are presented in Table II showing in addition the corresponding room temperature tensile properties and ISO V-notch impact strength.

Table II: Product forms, annealing conditions, grain size, room temperature tensile properties and ISO V-notch impact strength of alloy 625 under investigation

heat	product form	dimension, mm	annealing condition	grain size ASTM No.	$R_{p0.2}$ N/mm²	R_m N/mm²	A_5 %	A_V J
A	plate	17	1160°C/ 30min/H_2O	3	356	815	48	n.d.
B	tube	19x2	1160°C/ 30min/H_2O	3	351	821	59	n.d.
C	plate	20	1120°C/ 60min/H_2O	6	414	834	60	150
D	plate	12	1120°C/ 50min/H_2O	6	343	837	62	n.d.
E	plate	20	1120°C/ 60min/H_2O	5	470	853	51	n.d.
F	plate	12	1120°C/ 50min/H_2O	5	382	831	64	167
			980°C/ 60min/H_2O	6	482	906	50	121
G	plate	19	980°C/ 60min/H_2O	7	460	912	58	151
ASTM B443	plate	<70	>1093°C	-	>276	>690	>30	-
	plate	<70	> 871°C	-	>379	>758	>30	-

To study the ductility loss as a function of aging temperature and time samples have been annealed up to 1000 hrs at temperatures between 600 and 1000°C.

Creep data have been evaluated on four heats in the temperature range of 650°C to 850°C up to 37,000 hrs according to DIN 50118. Based on the experimental data, creep-rupture stress and creep stress for 1 % strain after 10,000 and 30,000 hrs have been inter- and extrapolated according to Larson-Miller.

Results and Discussion

Room temperature mechanical properties

Figure 1 shows the influence of aging on yield strength and tensile elongation for heats F and C, differing with respect to both carbon content and grain size. Aging causes an increase of yield strength, being accelerated when carried out at 700°C but with highest tensile elongation after aging at 600°C. Both heats behave very similarly, the differences might be due more to the difference in grain size than in carbon content.

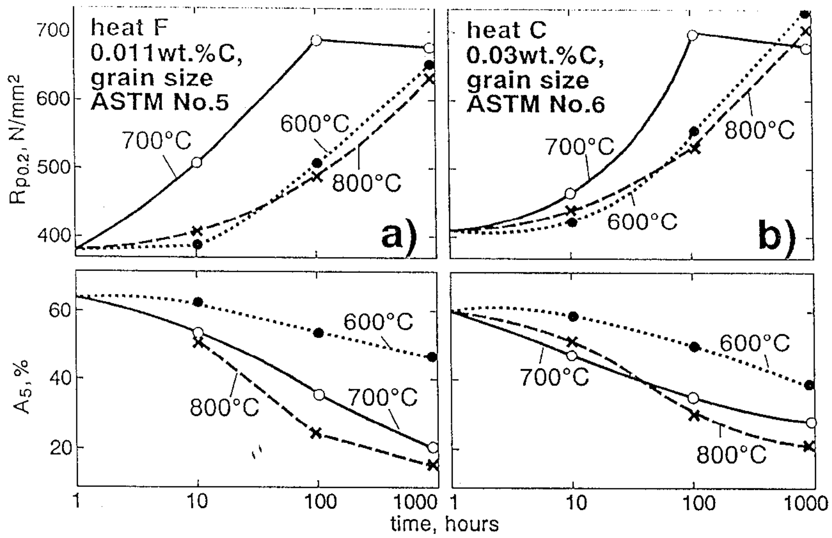
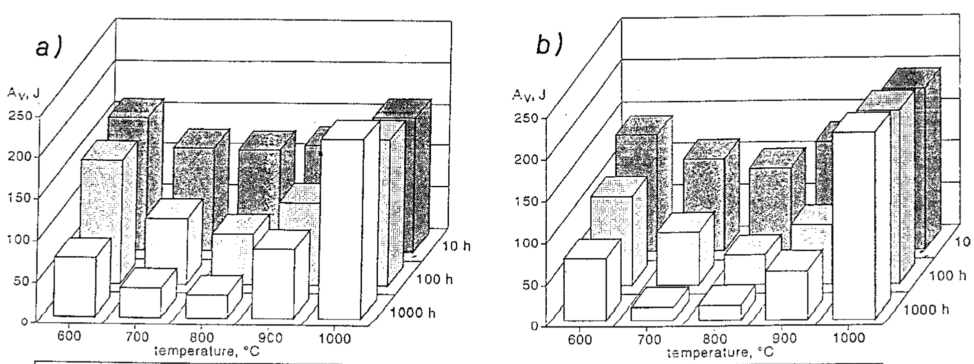


Figure 1: Effect of aging at 600, 700 and 800°C on room temperature yield strength $R_{p0,2}$ and tensile elongation A_5 of alloy 625, solution annealed starting condition
a) heat F: 0.011 wt. % C, ASTM grain size N° 5
b) heat C: 0.030 wt. % C, ASTM grain size N° 6

The influence of aging on ISO V-notch impact strength is shown in Figures 2a and 2b. The data have been established on samples of heats F and G which had been soft annealed before aging.



a)

	600	700	800	900	1000
10 h	163	125	123	130	165
100 h	150	79	62	99	177
1000 h	72	35	27	84	217

b)

	600	700	800	900	1000
10 h	142.5	112.5	99.5	132	195
100 h	107.5	64.5	35	72.5	210.5
1000 h	73.5	16.5	17	58	221.5

Figure 2: Effect of aging at temperatures between 600 and 1000°C on room temperature ISO V-notch impact strength of alloy 625, soft annealed starting condition
a) heat F: 0.011 wt. % C, 2.1 wt. % Fe, ASTM grain size N° 6
b) heat G: 0.009 wt. % C, 4.2 wt. % Fe, ASTM grain size N° 7

With respect to chemical composition and grain size both heats are very similar, differing to a larger extent only in their iron content, being at 2.1 and 4.2 wt. % resp. whereas the soft annealed starting condition, according to Table II, heat G exhibits a somewhat higher impact strength than heat F. The effect of aging on impact strength is much more pronounced for the higher iron alloyed heat G than for the lower iron alloyed heat F as Figures 2a and 2b clearly demonstrate. So it may be concluded that in addition to carbon and columbium (5), silicon and nitrogen also the iron content has to be restricted to e.g. max. 2.5 wt. % in order to achieve the best combination of creep strength and low ductility loss during service at intermediate temperatures. Also in past developmental work on Ni-Cr-Mo alloys a restriction of the iron content has proved to be an effective measure for reducing intermetallic phase precipitation (12).

High temperature short time tensile properties

If tensile testing of alloy 625 after aging is done directly at aging temperature, the resulting yield strength $Rp_{0.2}$ shows a somewhat similar dependency on aging time as the corresponding room temperature yield strength. This becomes obvious when comparing Figure 3 with Figure 1.

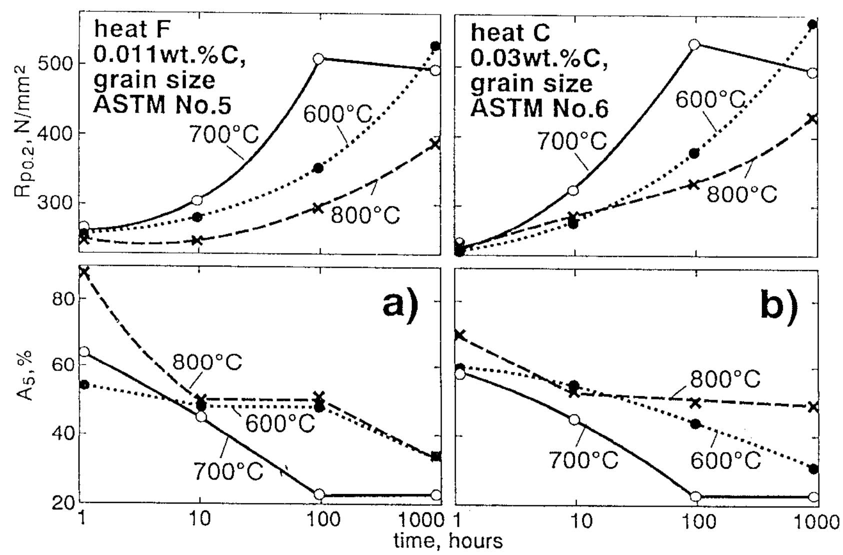


Figure 3: Effect of aging at 600, 700 and 800°C on high-temperature yield strength $Rp_{0,2}$ and tensile elongation A_5, both determined at aging temperature, of alloy 625, solution annealed starting condition

a) heat F: 0.011 wt. % C, ASTM grain size N° 5

b) heat C: 0.030 wt. % C, ASTM grain size N° 6

Tensile elongation after aging at 800°C if determined directly at 800°C is on a higher level than the corresponding room temperature tensile elongation data.

Creep Data

Creep data have been evaluated on heats A, B, D and E which, according to Table I and Table II, are different mainly with respect to their carbon content and to the final annealing treatment resulting in different grain size. The creep test results are compiled in Table III including both creep-rupture stress and creep stress for 1 % strain after 10,000 and after 30,000 hrs at 650, 750 and 850°C.

Table III: Creep-rupture stress R_m, N/mm^2, and creep stress for 1 % strain $Rp_{1,0}$, N/mm^2, after 10,000 and 30,000 hrs at 650, 750 and 850°C of alloy 625, solution annealed, starting condition according to Table II

	10000 hrs						30000 hrs					
	650°C		750°C		850°C		650°C		750°C		850°C	
heat	$Rp_{1.0}$	Rm	$Rp_{1.0}$	Rm	$Rp_{1.0}$	Rm	$Rp_{1.0}$	Rm	$Rp_{1.0}$	Rm	$Rp_{1.0}$	Rm
A	265	290	80*	118*	22*	42	206	244	61*	98*	16*	31*
B	--	267*	--	119*	--	36*	--	236*	--	94*	--	28*
D	215	275	69*	98*	20	30	180	230	55*	79*	16*	22
E	240	300	44*	96*	7*	32*	167*	237*	32*	78*	2*	25*

heat	wt.% carbon	ASTM grain size No
A	0.045	3
B	0.029	3
D	0.025	6
E	0.015	5

*The data marked by an asterisk have been obtained by inter- or extrapolation

Figure 4 shows the creep-rupture stress data from Table 3 as a function of carbon content.

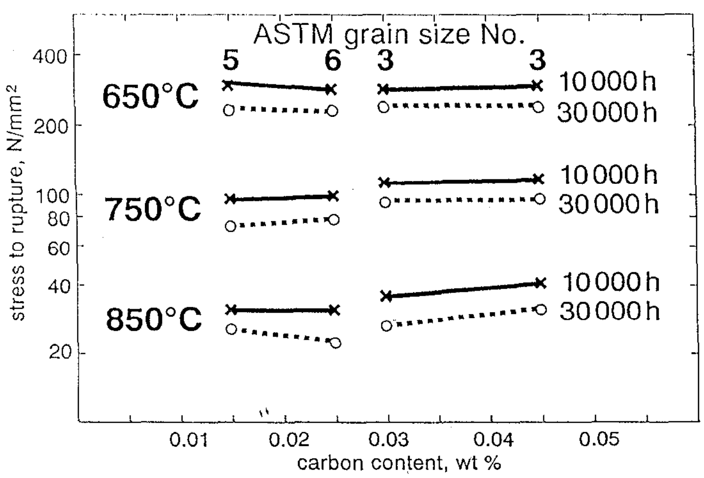


Figure 4: Creep-rupture stress of alloy 625 at different temperatures and exposure times as a function of carbon content

Apparently, within the same grain size range of ASTM N^o 3, the influence of carbon content on creep-rupture is small at 650°C and more distinct at 850°C, resulting in an augmentation of 10,000 and 30,000 hrs creep-rupture stress at 850°C by 17 % and 11 % resp. when carbon is increased from 0.029 to 0.045 wt. %. Between 0.015 and 0.025 wt. % carbon any potential influence of increasing carbon content on creep-rupture stress is obviously more or less counteracted by the grain size difference of ASTM N^o 6 compared to ASTM N^o 5. Figure 5 classifies the 30,000 hrs creep-rupture stress data according to the ASTM grain size numbers.

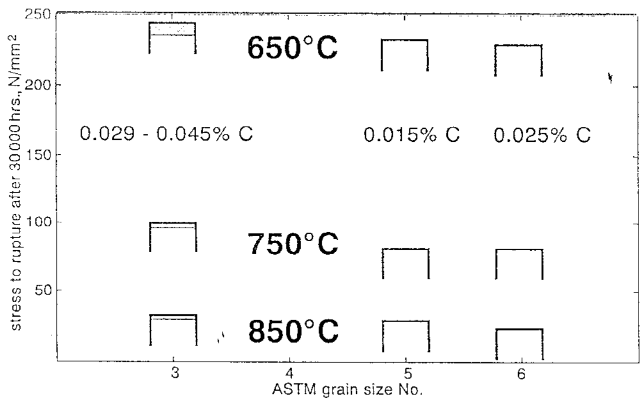


Figure 5: 30,000 hrs creep-rupture stress of alloy 625 at different temperatures as a function of ASTM grain size N^{o}

There is a slight influence of grain size on 30,000 hrs creep-rupture stress already at 650°C, indicating on the average an increase by about 4 % when the ASTM grain size number is changed from 6 to 3. This increase becomes more important the higher the temperature, being at about 22 % at 750°C and 43 % at 850°C.

So all creep-rupture stress data fit more or less reasonably well within a Larson Miller plot according to Figure 6, showing a straight mean curve and a scatterband of ± 20 %.

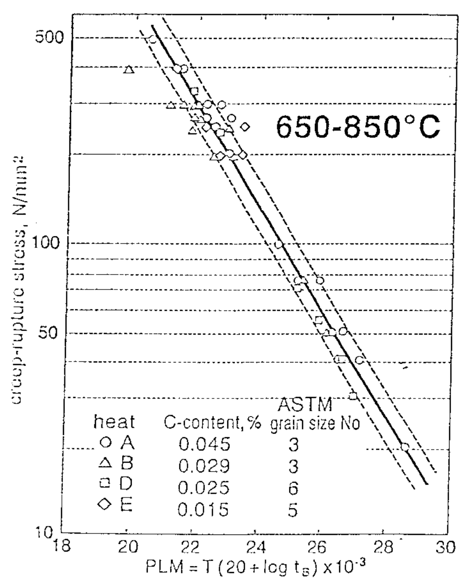


Figure 6: Larson Miller plot of creep-rupture stress data of alloy 625 between 650 and 850°C

According to experience with other materials (13) the scatterband width can easily be made smaller in considering material the grain size and carbon content of which is more uniform.

When creep stress for 1 % strain at 750 and 850°C is considered there is a great influence of carbon content up to about 0.025 wt. % C. This is demonstrated in Figure 7.

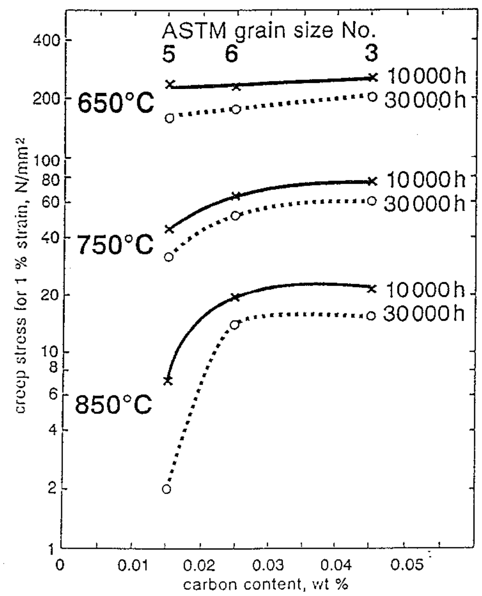


Figure 7: Creep stress for 1 % strain of alloy 625 at different temperatures and exposure times as a function of carbon content

Below about 0.025 wt. % carbon creep stress for 1 % strain increases strongly with increasing carbon content despite the smaller grain size at 0.025 wt. % carbon. The 30,000 hrs creep stress for 1 % strain at 850°C is improved by 700 % when the carbon content is increased from 0.015 to 0.025 wt. %. Between 0.025 and 0.045 wt. % carbon the increase of stress for 1 % strain as shown in Figure 7 is much smaller and can be due either to the higher carbon content or to the larger grain size of ASTM N° 3 or both.

Reduction of area after creep-rupture is shown in Figure 8. Apparently there is an appreciable amount of creep deformation which might be supposed to be the larger the smaller the grain size and the carbon content. But the data obtained so far do not allow a final conclusion with respect to this point.

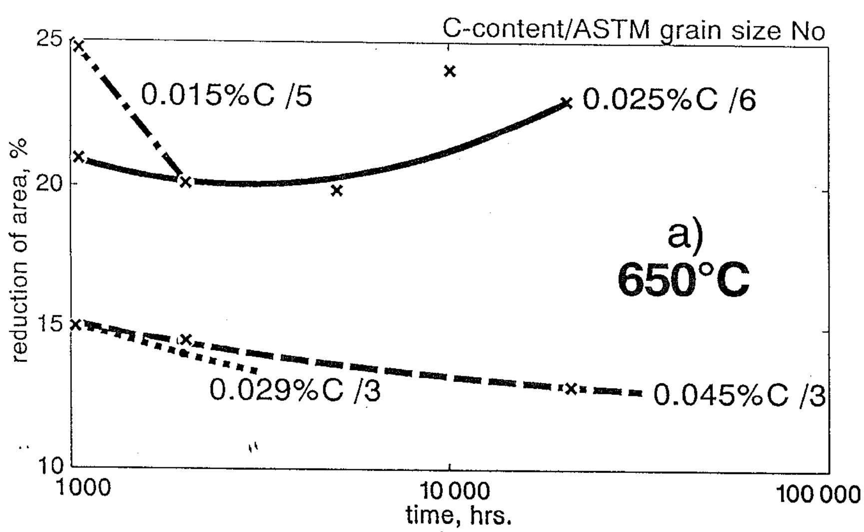


Figure 8: Reduction of area after creep-rupture of alloy 625
a) at 650°C

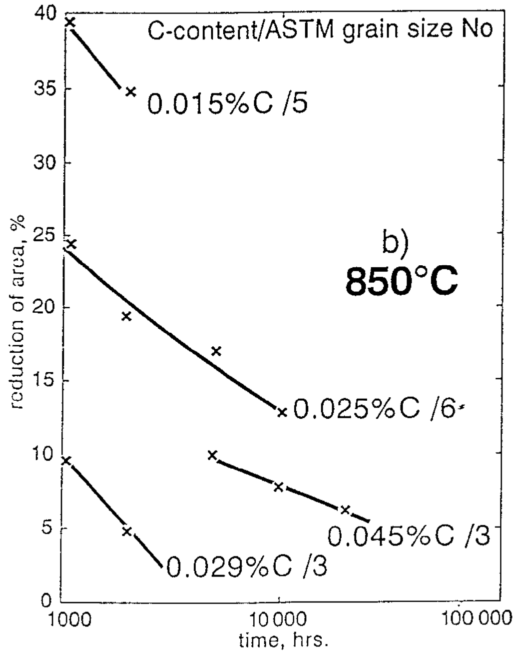


Figure 8: Reduction of area after creep-rupture of alloy 625
b) at 850°C

Conclusions

- Whereas the greatest increase in yield strength of alloy 625 is obtained after aging at 650°C (5), this temperature must not be exceeded. Otherwise the accompanying loss of tensile elongation and ISO V-notch impact strength will be more severe.

- During aging loss of ductility of alloy 625 is the more severe the higher the iron content. So a low carbon version of alloy 625 with restricted contents of max. 0.15 wt. % silicon, max. 0.025 wt. % nitrogen and max. 2.5 wt. % iron in the solution annealed starting condition and a grain size of ASTM 3 will give the best combination of high creep strength at intermediate temperatures and low ductility loss during service.

- The influence of carbon content on creep strength of alloy 625 is the more pronounced the higher the temperature.

- The influence of carbon content on 10,000 and 30,000 hrs creep-rupture stress of alloy 625 is resulting in an 11 % increase of 30,000 hrs creep-rupture stress at 850°C if carbon is increased from 0.029 up to 0.045 wt. %. At lower carbon contents its influence on creep-rupture stress is less.

- Contrary to creep-rupture stress, creep stress for 1 % strain of alloy 625 is influenced by increasing carbon contents primarily in the low carbon range, improving 30,000 hrs creep stress for 1 % strain by about 700 % when carbon content is increased from 0.015 to 0.025 wt. %.

- In changing ASTM grain size N° from 6 to 3 the 30,000 hrs creep-rupture stress of alloy 625 is augmented by about 4 % at 650°C and by about 43 % at 850°C.

Acknowledgement

The authors wish to thank K. Drefahl and H.J. Henrich of Central Laboratory of Metallgesellschaft AG, Frankfurt, who performed the creep tests. The contribution of C. von Linden in preparing the manuscript is also gratefully appreciated. Part of this study was supported by the German Ministry of Research and Technology (BMFT) which is gratefully acknowledged.

References

1) H.L. Eiselstein and D.J. Tillack, The Invention and Definition of Alloy 625, "Superalloys 718, 625 and Various Derivatives", TMS 1991, pp. 1-14.

2) F.A. Comprelli and U.E. Wolf, United States Atomic Energy Commission, GEAP 4745 (1964).

3) F.A. Comprelli and J.E. Lewis, United States Atomic Energy Commission, GEAP 4751 (1965).

4) F.A. Comprelli, United States Atomic Energy Commission, GEAP 4794 (1965).

5) M. Köhler, Effect of the Elevated Temperature Precipitation in Alloy 625 on Properties and Microstructure, "Superalloys 718, 625 and Various Derivatives", TMS 1991, pp. 363-374.

6) G.D. Smith, D.H. Yates, Optimization of the Fatigue Properties of Inconel Alloy 625, "Superalloys 718, 625 and Various Derivatives", TMS 1991, pp. 509-517.

7) F. Gorzarolli, A. Gerscha, P. Franke, Z. Metallkd. Vol. 60 (1969), pp. 643-652.
8) H. Böhm, K. Ehrlich, K. Kramer, Metall, Vol. 24 (1970), pp. 139-144.

9) E. Schnabel, H.J. Schüller, P. Schwaab, Praktische Metallographie, Vol. 8 (1971), pp. 521-527.

10) J.R. Crum, M.E. Adkins and W.G. Lipscomb, Performance of High Nickel Alloys in Intermediate Temperature Refinery and Petrochemical Environments, Paper No. 208, Corrosion '86, The National Association of Corrosion Engineers, Houston, Texas, 1986.

11) D.C. Agarwal, U. Heubner, R. Kirchheiner, M. Koehler, Cost-Effective Solution to CPI Corrosion Problems With a New Ni-Cr-Mo Alloy, Paper No. 179, CORROSION 91, The National Association of Corrosion Engineers, Houston, Texas, 1991.

12) U. Heubner, M. Koehler, Time-Temperature-Precipitation and Time-Temperature-Sensitization Behaviour of Highly Corrosion Resistant Nickel-Chromium-Molybdenum Alloys (in German), Werkstoffe und Korrosion Vol. 43 (1992), pp. 181-190.

13) U. Brill, U. Heubner, K. Drefahl. H.-J. Henrich, Creep Data of High-Temperature Materials (in German), Ingenieur-Werkstoffe Vol. 3 (1991) No. 4, pp. 59-62.