MLX®17

X1CrNiMoAlTi12-11-2

A very high strength stainless steel

AUBERT&DUVAL

> THE INDUSTRIAL ENVIRONMENT

The use of Precipitation Hardening Stainless Steels for structural parts has been in place for a while considering their superior environmental robustness. The pressure to use this type of martensitic stainless material has grown stronger and stronger due to the need to remove harmful protective coatings, such as chromates and Cadmium, that are now on the list for removal under environmental legislation such as REACH (Registration, Evaluation, Authorization and restriction of CHemicals) in Europe.
Aubert & Duval has therefore adapted its high strength steel offering with the development of MLX®17, a high corrosion resistant grade capable of 1700 MPa (247 Ksi) with high fracture toughness and excellent corrosion resistance

> MLX®17 STEEL GRADE DEVELOPMENT

Aubert & Duval has made major advances in improving the strength of high-performance corrosion-resistant steels, particularly with its MLX® grade family. These high-strength stainless steels offer a replacement for low carbon steel from AISI 4340 to 35NiCrMo16. If the initial driver to develop MLX®17 has been structural aerospace components, other applications are now also targeted.

MLX®17 steel provides:

- High resistance
- Excellent balance between strength and toughness properties
- Good fatigue behavior
- Stress corrosion cracking (SCC) resistance

Thanks to its high resistance to corrosion, high strength and toughness combination, MLX®17 steel is the best candidate in demanding aerospace parts without the use of toxic Cadmium coatings.

> SPECIFICATIONS

X1CrNiMoAlTi12-11-2
Numerical designation : 1.4612
European Standard : EN 4656, 4657, 4659 and 4670
UNS S11100
AMS 5937 (bar and forging)
MMPDS allowable design data available from the 8th version

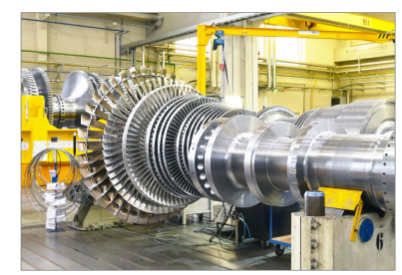
> APPLICATIONS

Aerospace parts

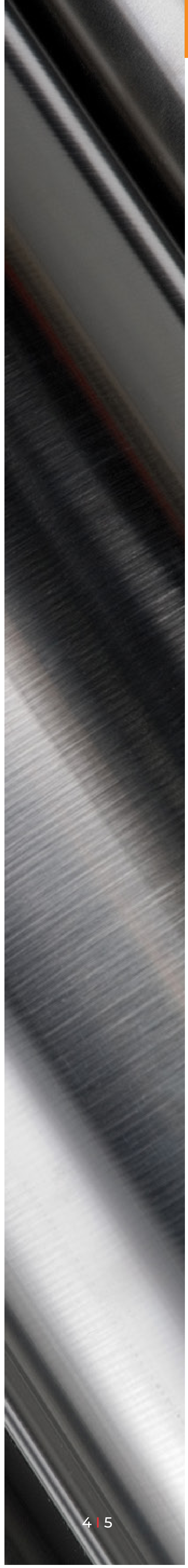
Corrosive environment

Motorsport

Defense - Missiles

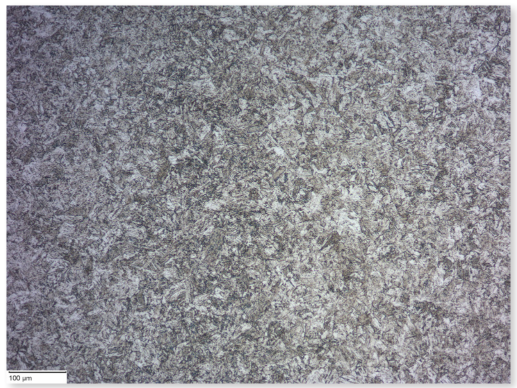


Land gas turbine

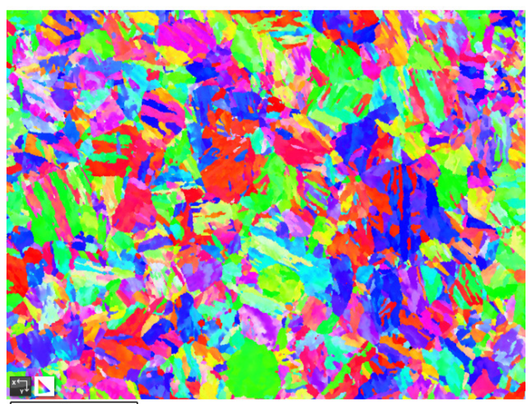


> CHEMICAL COMPOSITION (weight %)

	C	Mn	Si	Cr	Mo	Ni	Ti	Al
Mini	/	/	/	11.00	1.75	10.25	0.20	1.35
Maxi	0.02	0.25	0.25	12.50	2.25	11.25	0.50	1.75



Martensitic matrix (optical microscopy)



SEM-EBSD image of a MLX®17 H950 treated sample (showing martensite laths)

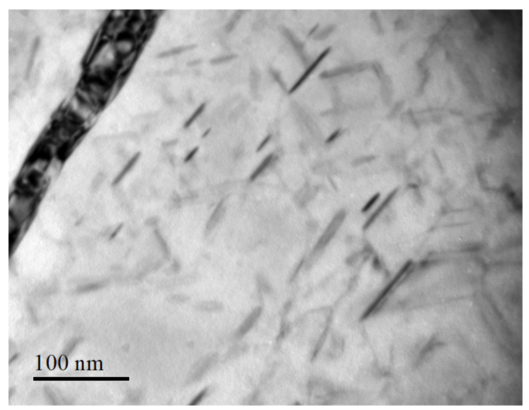


Image of a MLX®17 H950 treated sample (showing hardening precipitates)

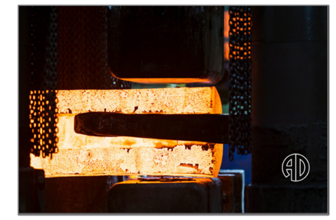
- Chromium and Molybdenum, in solid solution in the martensitic matrix, contribute to the corrosion resistance of MLX®17
- High Nickel content contributes in building reverse austenite phasis, highly favorable to achieve high toughness performances.
- Nickel, Titanium and Aluminum percentages have been selected to achieve the best UTS/K_{IC} combination through the nanometric precipitates of Ni_3Ti and NiAl.

> PROCESS

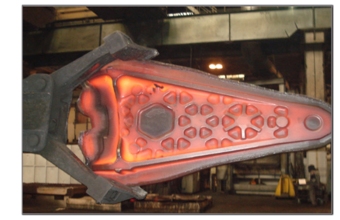
MLX®17 steel is at least double vacuum melted (i.e., vacuum induction melted and then vacuum arc remelted or «VIM/VAR»).

Melting, Remelting

Rolling



Open-die forging



Closed-die forging

HEAT TREATMENT

Bars, wires, and forgings shall be solution heat treated by:

- Heating to 840°C ± 14°C (1544 °F ± 25°F), holding at temperature for 2 hours
- Quenching in oil, polymer or water
- Cooling to -73 °C (-100 °F) or colder, holding at that temperature for not less than 8 hours,
- Warming in air to room temperature.

We usually deliver the material in the solution heat treated condition, ready to be machined and aged.

We can also deliver the material in the natural state condition or solutioned and aged state.

> MAIN PHYSICAL PROPERTIES

Density

Temperature		Aged 510°C / 950°F		Aged 540°C / 1000°F	
°C	°F	g/cm³	lb/in³	g/cm³	lb/in³
20	68	7.67	0.2769	7.67	0.2769
100	212	7.66	0.2765	7.66	0.2765
150	302	7.65	0.2762	7.65	0.2762
200	392	7.63	0.2755	7.63	0.2755
250	482	7.62	0.2751	7.62	0.2751
300	572	7.60	0.2744	7.60	0.2744
350	662	7.59	0.2740	7.59	0.2740
400	752	7.58	0.2736	7.58	0.2736
430	806	7.57	0.2733	7.57	0.2733

Mean coefficient of thermal expansion (α)

Temperature		Aged 510°C / 950°F		Aged 540°C / 1000°F	
°C	°F	10^{-6} m/m/°C	10^{-6} in/in/°F	10^{-6} m/m/°C	10^{-6} in/in/°F
25/100	77/212	10.32	5.73	10.38	5.77
25/150	77/302	10.70	5.94	10.79	5.99
25/200	77/392	11.05	6.14	11.14	6.19
25/250	77/482	11.26	6.26	11.36	6.31
25/300	77/572	11.40	6.33	11.51	6.39
25/350	77/662	11.52	6.40	11.63	6.46
25/400	77/752	11.61	6.45	11.75	6.53
25/430	77/806	11.68	6.49	11.83	6.57

Thermal conductivity (K)

Temperature		Aged 510°C / 950°F		Aged 540°C / 1000°F	
°C	°F	W/m·K	Btu-in/hr/ft2/°F	W/m·K	Btu-in/hr/ft2/°F
20	68	17.3	119.5	15.9	110.2
100	212	18.0	124.7	17.5	120.9
150	302	18.8	130.2	18.6	128.9
200	392	18.9	130.9	19.5	134.8
250	482	19.8	137.2	20.3	140.7
300	572	20.1	139.2	20.5	142.1
350	662	21.0	145.5	21.1	145.9
400	752	21.7	150.0	22.1	152.8
430	806	23.0	159.3	22.7	157.0

Specific heat (°C/°F)

Temperature		Aged 510°C / 950°F		Aged 540°C / 1000°F	
°C	°F	J/kg.°C	Btu/lb.°F	J/kg.°C	Btu/lb.°F
20	68	481	0.12	489	0.12
100	212	510	0.12	508	0.12
150	302	522	0.13	524	0.13
200	392	536	0.13	539	0.13
250	482	556	0.13	557	0.13
300	572	568	0.14	569	0.14
350	662	592	0.14	593	0.14
400	752	616	0.15	621	0.15
430	806	658	0.16	650	0.16

MLX®17 is a registered trademark of Aubert & Duval

> MACROSTRUCTURE

The segregation, as measured on billets, complies with the tightest requirements.

Class	Type	Severity
1	Freckles	A
2	White spots	A
3	Radial segregation	A
4	Ring pattern	B

Macrostructure according to ASTM A604

> CLEANLINESS

The segregation, as measured on billets, complies with the tightest requirements.

Type	A		B		C		D		A+B+C+D
	Thin	Heavy	Thin	Heavy	Thin	Heavy	Thin	Heavy	
Max	1	1	1.5	1	1	1	1.5	1	≤ 10

According to ASTM E 45 Method D (max levels and value on 160 mm² surface)

> EVOLUTION OF MECHANICAL PROPERTIES WITH AGEING TEMPERATURE

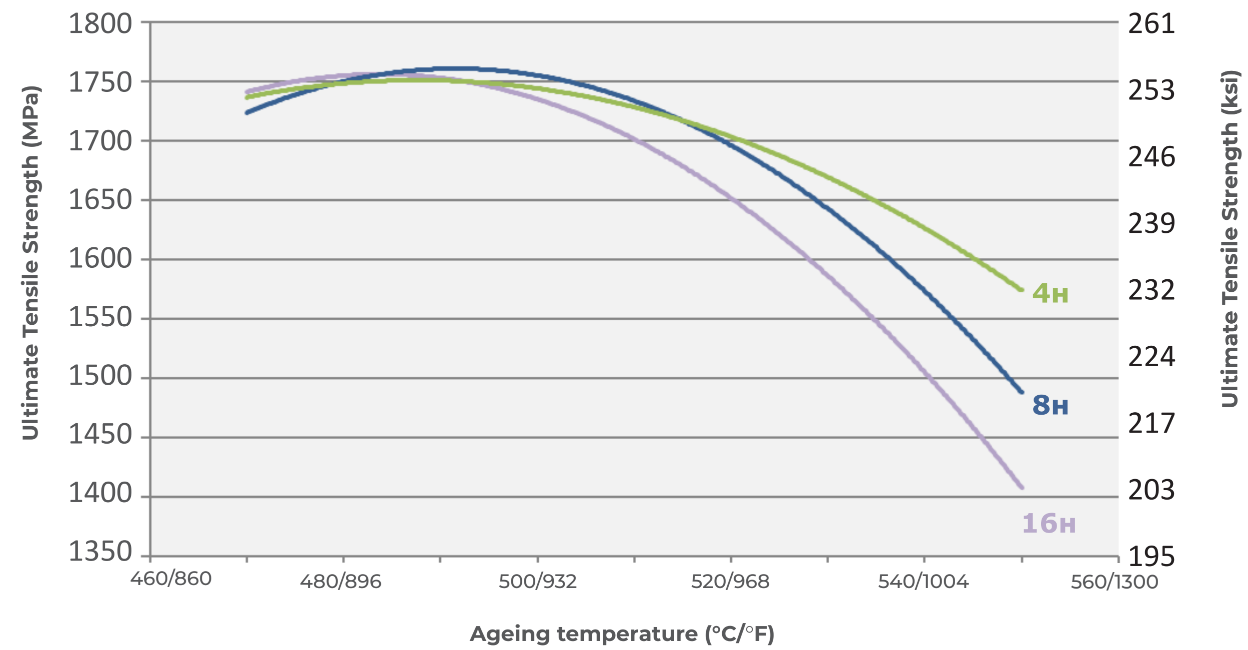
The typical ageing behavior of MLX®17 is given below, regarding evolution of Ultimate Tensile Strength, Yield Strength at 0.2% and fracture toughness with ageing time and temperature.

Solution heat treatment

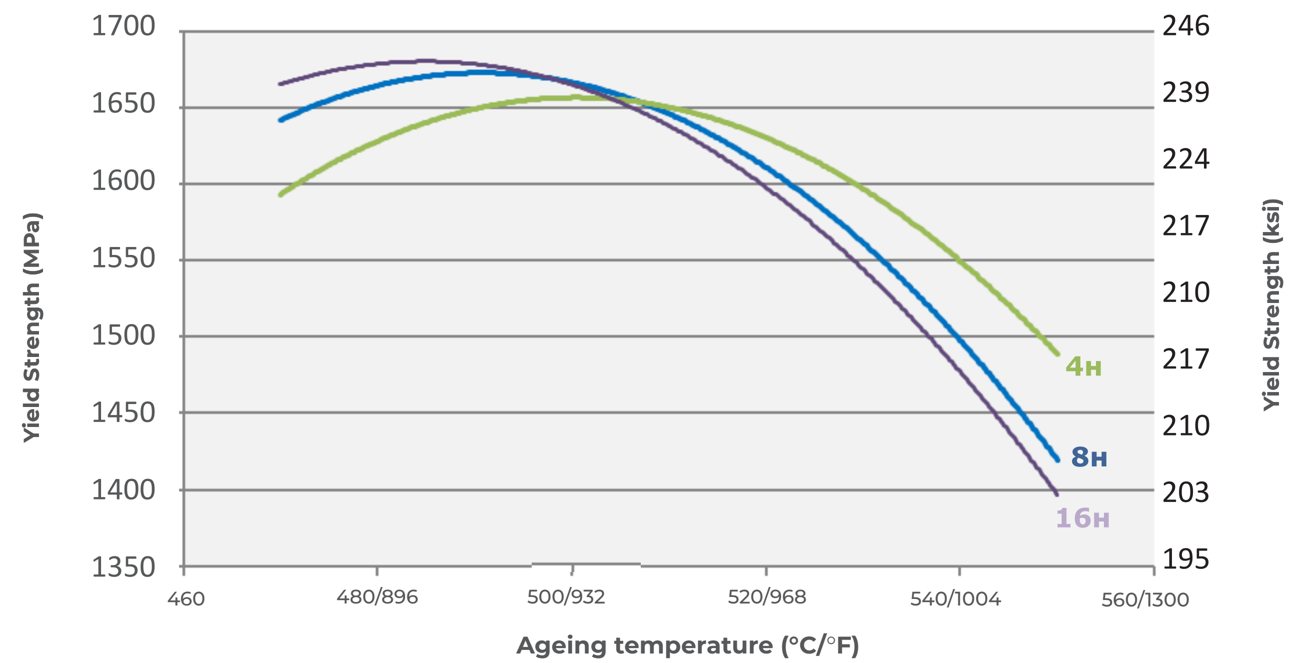
- Heating to 840°C ± 14°C (1544 °F ± 25°F), holding at temperature for 2 hours
- Quenching in oil, polymer or water
- Cooling to -73 °C (-110 °F) or colder, holding at that temperature for not less than 8 hours
- Warming in air to room temperature

In the solution treated state the hardness is approximately 33HRC.

The following graphs show the typical properties determined in the longitudinal direction. Ageing was performed on coupons extracted from solution heat treated bars.

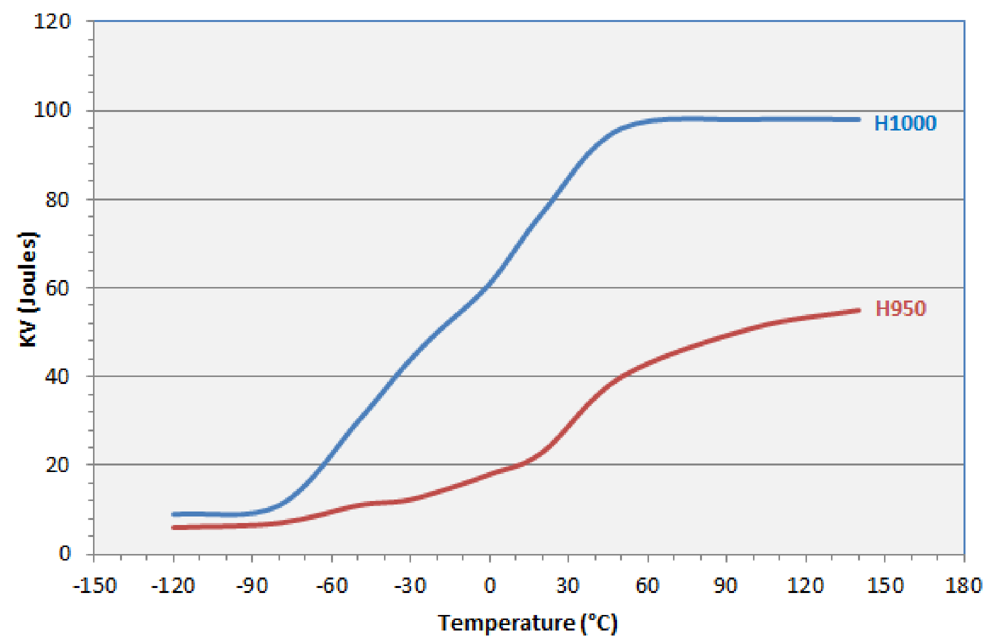


Properties depending on ageing time and temperature - UTS



Properties depending on ageing time and temperature - YS0,2

- 510°C (H950): this aging condition is used for high strength requirements such as aircraft structural parts
- 540°C (H1000): this aging condition is used for high strength requirements for specific mechanical parts where corrosion resistance is necessary.



Charpy test - transition curve - KV

Below are listed typical and minimum values of MLX®17 aged at 510°C (H950) and 540°C (H1000) for 8 hours.

H950 8 hours ageing	Direction	UTS (MPa) (ksi)	YS0.2 (MPa) (ksi)	A4d (%)	Reduction Aera (%)
AMS5937 min value	L (L-C)	1655 240	1517 220	10	45
	T (C-L)	1655 240	1517 220	8	35
MLX®17 Typical Values	L (L-C)	1710 248	1620 235	13	52
	T (C-L)	1710 248	1600 232	11	49

H1000 8 hours ageing	Direction	UTS (MPa) (ksi)	YS0.2 (MPa) (ksi)	A4d (%)	Reduction Aera (%)
AMS5937 min value	L (L-C)	1517 220	1379 200	10	50
	T (C-L)	1517 220	1379 200	10	40
MLX®17 Typical Values	L (L-C)	1580 229	1530 222	16	65
	T (C-L)	1580 229	1500 217	13	59

> GENERAL CORROSION RESISTANCE

TEST CONDITIONS:

- Heating to: 840°C ± 14°C (1544 °F ± 25°F), holding at temperature for 2 hours
- Quenching in water
- Cooling to -73 °C (-100 °F), 8 hours
- Ageing: 510°C (H950) 8 hours

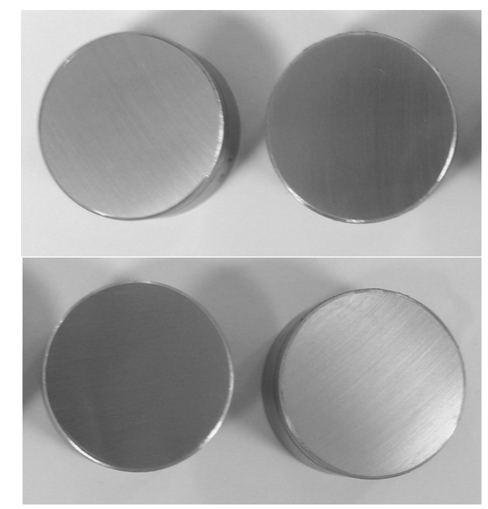
SALT SPRAY TEST:

Surface grinding in order to remove the small surface layer that was Chromium depleted following heat treatment (few hundreds of nanometers).

Salt spray test as per ASTM B117 have not shown any sign of corrosion on:

- Aged + machined samples after 700 hours
- Aged + machined + passivated samples after 1000 hours

When properly prepared as recommended above, the MLX®17 surface presents a general corrosion resistance similar with AISI 304 stainless steel.


Passivation: Type 8 as per AMS 2700
Salt spray test as per ASTM B117

For more details on passivation procedure, please contact us.

> STRESS CORROSION RESISTANCE

STRESS CORROSION CRACKING TEST:

- Stress corrosion cracking resistance performed according to ISO 7539-1 and ISO 7539-6

	MLX®17 Aged 510°C/950°F	PH 13-8Mo Aged 538°C/1000°F	Custom465® Aged 510°C/950°F
UTS (MPa / Ksi)	1710 / 248	1480 / 215	1740 / 252
Elongation (%)	13	14	13
HRC	48	44	48
K1C (MPa√m / Ksi√in)	90 / 82	97 / 88.3	90 / 82
K1scc (MPa√m / Ksi√in)	68 / 61.9	70 / 63.8	53 / 48.3

According to rising step loading method (ASTM F1624), K_{scc} determined for MLX®17 is mini. 75% of the K_{Ic} value.

RISING STEP LOAD:

- NaCl 35 g.L-1, ventilated environment, room temperature, relied on standard ASTM F1624
- Charge profiles : 10/5/2.4
- K1SCC average results on protection plateau

Grade	Thermal state	K_{scc} type (MPa√m)	K_{scc} /K_{IC} type (%)
MLX17	H950	81	86
13-8Mo	H1000	85	95
C465	H950	67	74
15-5PH	H905	134	95

According to rising step loading method (ASTM F1624), K_{scc} determined for MLX®17 is mini. 75% of the K_{Ic} value.

Custom465® is a registered trademark of Carpenter Technology

> FATIGUE PERFORMANCE

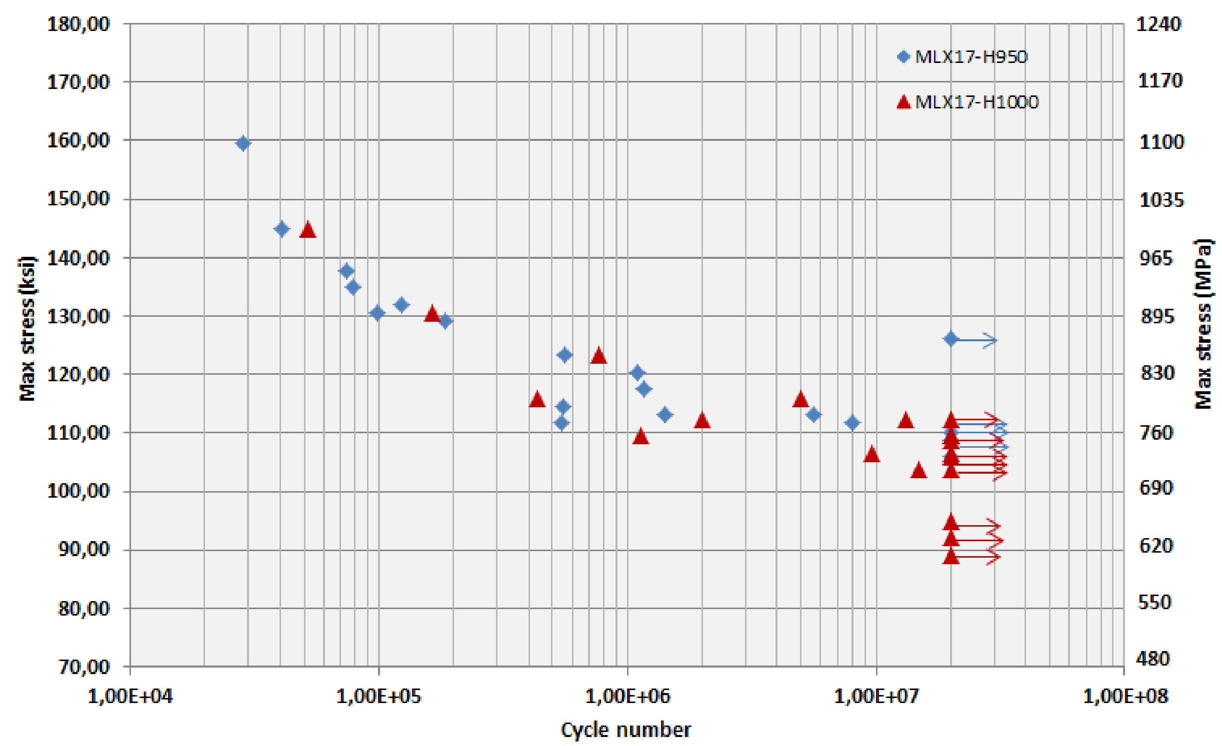
TEST CONDITIONS:

- Heating to 840°C ± 14°C (1544 °F ± 25°F), holding at temperature for 2 hours
- Quenching in water
- Cooling to -73 °C (-110 °F), 8 hours

Heat treated bars Properties determined in longitudinal direction Axial fatigue with R=0,1

Un-notched specimens, Kt=1,035 (preparation by machining in transverse direction and final grinding/polishing in longitudinal direction)

Test frequency: 15Hz



Ageing: H950 / H1000

Fatigue performance of MLX®17 is equivalent to equivalent to MLX®465 or Custom465®. Typical failure initiation is at a cleavage zone or starts at a Ti-C-N particle or both. This behavior is typical of any Ultra High Strength maraging steels hardened with a high amount of titanium and/or aluminum.

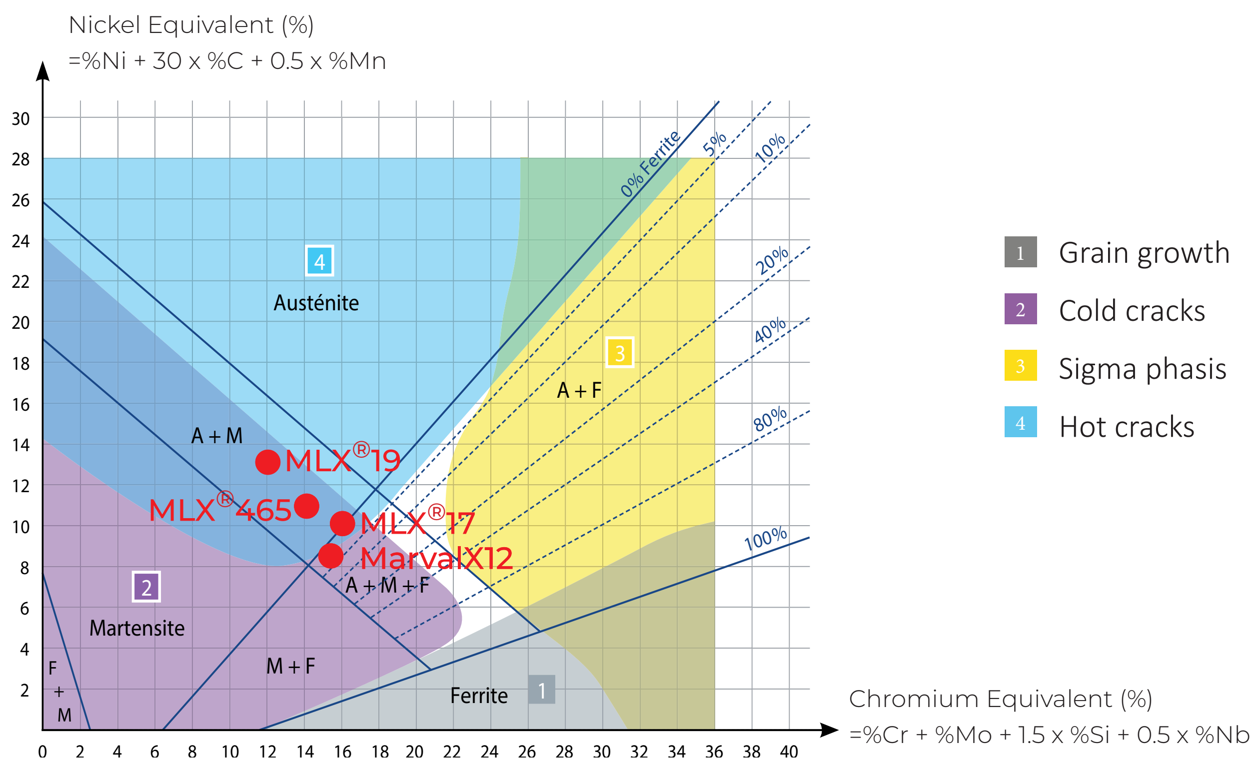
Custom465® is a registered trademark of Carpenter Technology

> WELDABILITY

MLX®17 can be successfully welded by the GTAW (Gas Tungsten Arc Welding) process using matching filler metal. According to the chemical composition and the solidification path, the main risk is the weld-bead hot cracking). When the GMAW (Gas Metal Arc Welding) process is employed, MLX®17 filler metal is suggested to provide high strength. Welds should be fabricated employing the minimum amount of heat-input required to achieve complete penetration. If lower strength can be tolerated, Marval®X12 filler metal may be used.

Oxyacetylene welding is not recommended, since carbon pickup in the weld may occur. Preheating is not required to prevent cracking during the welding of this alloy.

The material has been welded satisfactorily in the solution annealed condition. Direct ageing of weldments on annealed base metal is possible, but hardness throughout the weld is not uniform and fatigue performances might be decreased. The optimum combination of properties is obtained by solution annealing and deep freezing the weldment and then aging.



MLX®17 benefits:

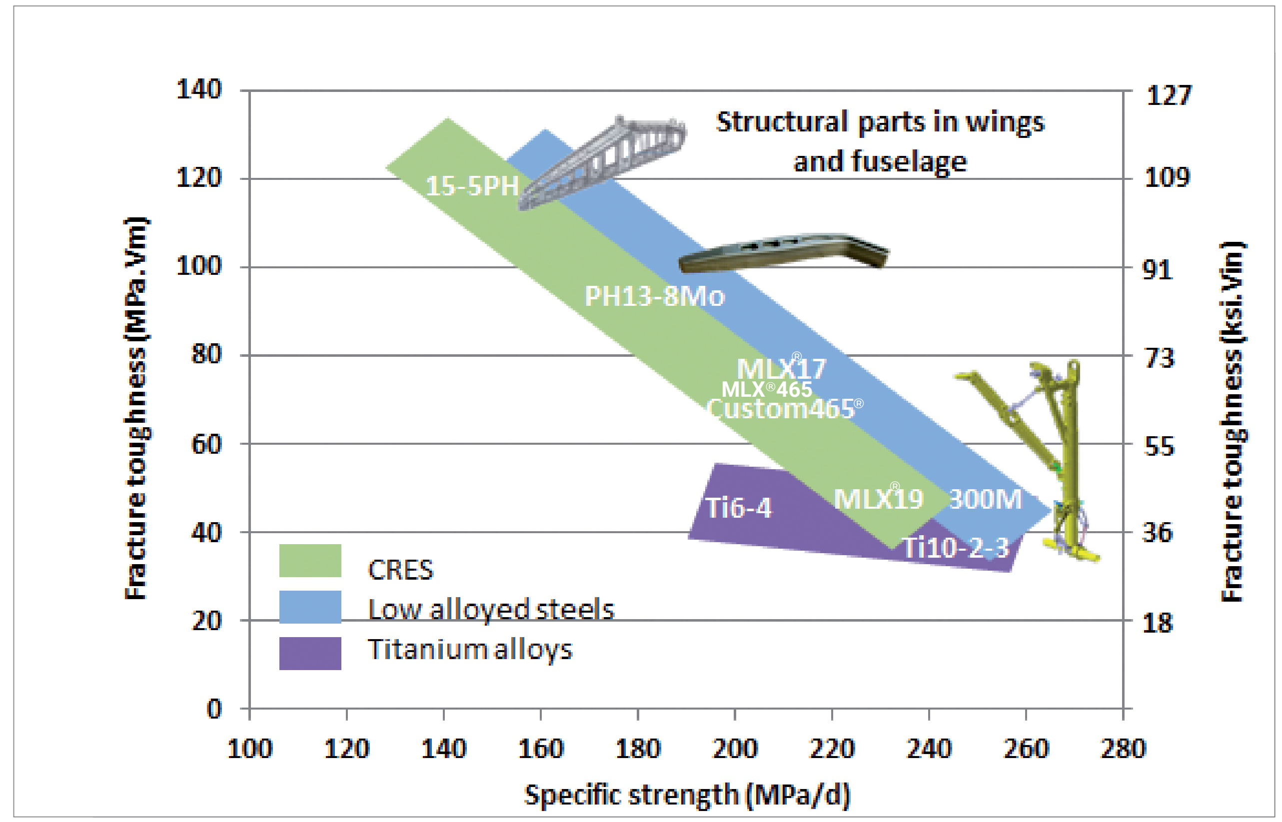
- Ultra High Strength to weight ratio
- High weldability (GMAW, EBW, etc...)
- Cold forming ability and suitability for a specific process like flow-forming and extrusion
- Excellent general corrosion resistance and stress corrosion cracking resistance

> APPLICATION IN AEROSPACE PARTS

TECHNICAL CHALLENGES FOR AEROSPACE PARTS

Critical aircraft structural parts used in extreme conditions require high performance materials. They are currently mainly made of low alloyed carbon steels, with surface coatings for corrosion resistance purposes.

These coatings require heavy maintenance procedures on aircraft in service, and some of them could be banned in the near future due to environmental regulations.



MLX®17, developed by Aubert & Duval, meets these requirements. The ambition is that structural parts using this material will be more resistant to corrosion, allowing maintenance overhaul to be extended.

For example, flap tracks are exposed to salty environment and require corrosion protection when they are manufactured from engineering steels. Using MLX®17 allows fewer protection corrosion coatings and is compliant with the latest regulations. In addition, it provides more potential cost saving for aircraft part manufacturers.

MLX®17 grade offers the best compromise of in-use properties: fracture toughness, general corrosion, Ultra High Yield strength, damage tolerance, and stress corrosion cracking.

It is an excellent candidate to substitute for AISI 4340 or to improve 15-5PH.

MLX®17 is a registered trademark of Aubert & Duval

EXISTING GRADE OFFER AND MLX®17 BENEFITS

The table below summarizes the main design properties requested for aircraft structural air parts. MLX®17 has the best balance of properties: general corrosion, Ultra High Yield strength, and stress corrosion cracking.

Brand names		Custom 465®	MLX®17	MLX®19	AISI 4340
AMS norms		5936	5937	5955	6414
UTS	MPa ksi	1740 252	1710 248	1895 275	1940 281
YS0.2	MPa ksi	1690 245	1620 235	1785 259	1670 242
Elongation (%)		13	13	12	10
K_{IC}	MPa.√m ksi.√in	104 99	90 82	54 49	53 48
K_{ISCC}	MPa.√m ksi.√in	65 59	68 62	44 40	14 12
K_{ISCC}/K_{IC} (%)		60	75	80	25
General corrosion		High	High	High	No

> APPLICATION IN POWER GENERATION

One of the main technical challenges to improve efficiency and reduce construction costs of power generation plants is to extend the last stage blades.

MLX®17 is currently among the best steel grades to design the longest end-blades of steam turbines thanks to its excellent combination of high toughness, high fatigue and stress corrosion cracking resistance.

> APPLICATIONS IN DEFENSE

TECHNICAL CHALLENGES FOR MISSILE BODY AND FITTINGS

In the 60's, the large solid-propellant rocket motor program sparked the considerable research and development that has been conducted to take advantage of the properties of the 18%Ni maraging steels. These steels, combining high strength to weight ratio with good fracture toughness, weldability and simple heat treatment, became available just when such properties were needed to permit a scale-up in missile-case dimensions.

The 18%Ni maraging steels became the ideal choice for the fabrication of small rocket / missile cases and fittings designed for high performances:

- Ultra High Tensile Strength enables the material to withstand high pressure and the ability to manufacture light and thin-wall cases
- Weldability and the possibility to cold form enable a very simple manufacturing process

The precipitation hardening stainless steels bring today the same advantages in terms of manufacturing ability, availability and have been used for decades to offer corrosion resistance and stress corrosion cracking compared with 18%Ni maraging.

Brand names		Marval® X12H	MLX®17	MLX®19	Maraging250 Marval® 18	Maraging300 MY19
AMS norms		5935	5937	5955	6512	6514
UTS	MPa ksi	1450 210	1710 248	1895 275	1792 260	2027 294
YS0.2	MPa ksi	1380 200	1620 235	1785 259	1758 255	1990 289
Elongation (%)		16	13	12	11	10
E modulus	GPa 10^3ksi	193 27.9	193 27.9	195 28.3	182 26.4	182 26.4
K_{IC}	MPa.√m ksi.√in	140 127	90 82	54 49	100 91	65 59
K_{ISCC}	MPa.√m ksi.√in	120 109	68 62	44 40	18 16	13 11
General corrosion		High	High	High	No	No

MLX®17 is a registered trademark of Aubert & Duval

NOTES:

NOTES:

MLX®17 is a registered trademark of Aubert & Duval

AUBERT&DUVAL

www.aubertduval.com