

INVAR[®] M93

**THE CRYOGENIC ALLOY
TAILOR-MADE FOR GAS TRANSPORTATION**



INVAR[®] M93

- Basic reason to choose **INVAR[®]** m93
- Ductility and toughness at LNG temperature
- No embrittlement
- Weldability
- Forms and parts available
- Corrosion resistance
- Theoretical thermal stress
- All values
- Long experience of service to shipyards
- Contacts

BASIC REASON TO CHOOSE INVAR® M93

INVAR® M93, thanks to its near zero thermal expansion (and low modulus of elasticity), is the key to the flat membrane of the **Gaztransport** LNG carriers.

The theoretical thermal stress is given by :

$$\sigma = E \cdot \alpha \cdot \Delta T$$

E	=	Modulus of elasticity (MPa)
α	=	Coefficient of thermal expansion (10^{-6})
ΔT	=	Between RT* and LNG temperature (°C)

⇓

$$\sigma = 140.000 \cdot (\leq 2) \cdot 180$$

⇓

$$\sigma \leq 50 \text{ MPa}$$

In practice this low stress is not present because the slight contraction of the membrane between RT* and LNG temperature (< 16 mm for a 45m strake) merely results in perfect flattening of the membrane

* Room temperature

DUCTILITY AND TOUGHNESS AT LNG TEMPERATURE

At room temperature, high ductility results in easy forming of the flanges of the strakes.

When temperature is lowered from room temperature to LNG temperature :

- Tensile properties are doubled without any loss of ductility,
- Fatigue strength is multiplied by 1.7 in the base metal and 1.2 in the TIG lap-welds.
- Toughness, measured by impact strength, notched tensile strength and fatigue crack propagation, remains high.

These excellent properties are due to the fine grain austenitic structure of **INVAR® M93** and its perfect stability at cryogenic temperature.

NO EMBRITTLEMENT

Stressed specimens, both plain and welded, have shown no embrittlement and no change of microstructure after holding periods of several months in liquid nitrogen or hydrogen. This same stability of the austenitic microstructure is verified after a plastic deformation of 20 % at -160 °C.

WELDABILITY

The excellent weldability of **INVAR® M93**, in seam welding, TIG and MIG (with **INVAR® M93** welding wire in the latter cases) is basic to the use of high-speed automatic welding machines.

Chemical composition and steel-making process result in zero tendency to either solidification or reheat cracking.

Varestraint tests have shown that **INVAR® M93** behaves similar to 316 with regard to solidification cracking.

Cross bead tests show no sign of cracking in the first bead, even when the second bead is performed under an applied tensile stress of 150 mpa. These excellent results are in agreement with the ductility in tension in the 800-1000 °c temperature range, which is much higher for **INVAR® M93** than conventional Invar®.

This capacity of **INVAR® M93** to resist, in the 800-1000 °c temperature range, a level of stress and strain well above those which can be present during welding, assures that welds which cross each other (and multipass welds) are performed without any problem.

Weld pool cleanliness and adequate Viscosity of the liquid metal result in excellent control of the shape of the tig lap-welds. This is essential because the fatigue strength of a lap-weld is determined by the dimension of its " throat ".

FORMS AND PARTS AVAILABLE

The great majority of the **INVAR® M93** is delivered in 0.7 mm thick strips ready to be uncoiled and flanged into strakes inside the tank. The straightness on edge, better than +/- 0.5 mm per meter and non cumulative, which permits forming into strakes and positioning by simple light-weight machines, is obtained thanks to a proprietary finishing process.

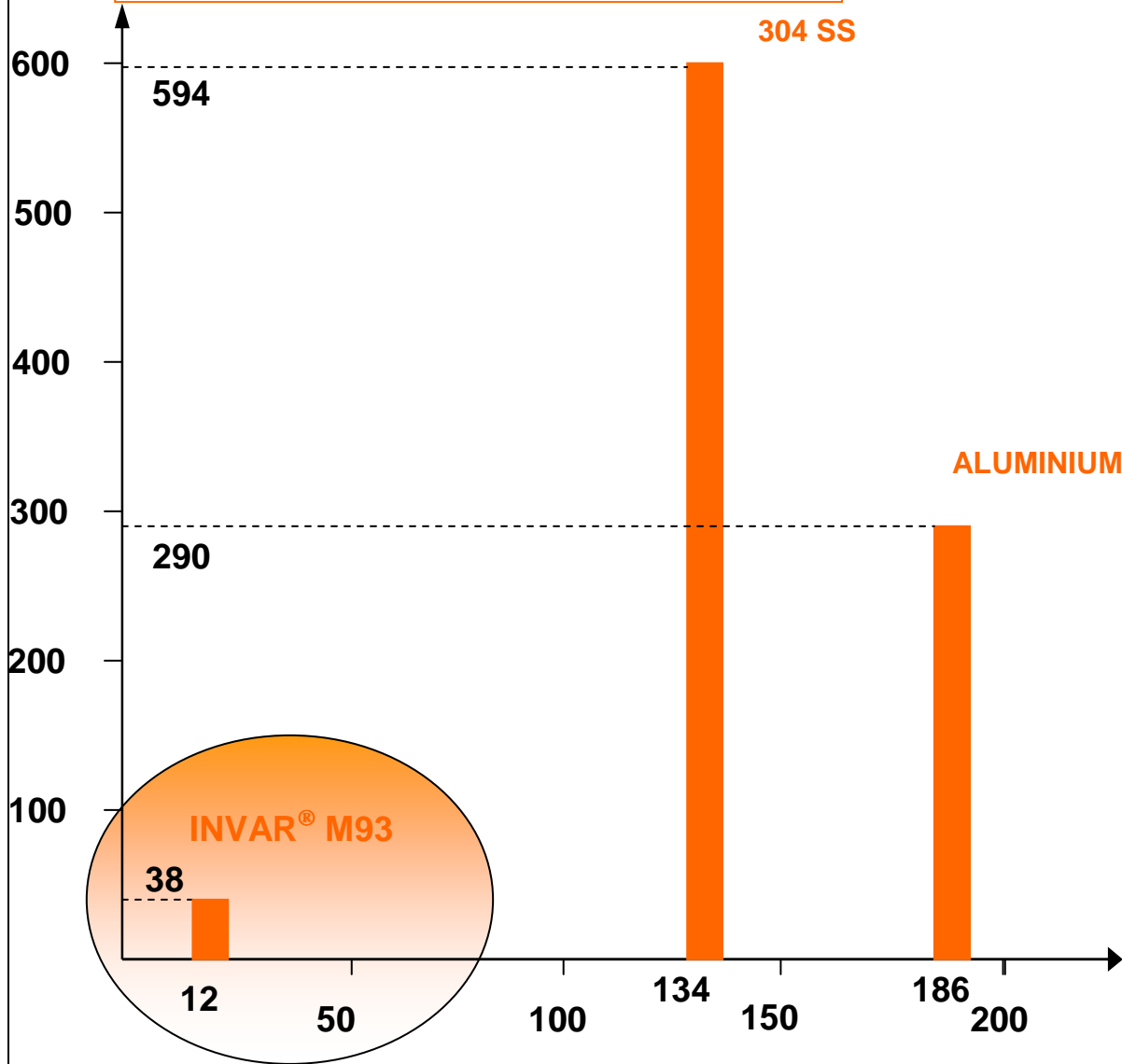
The alloy is also delivered in all the forms, including 8mm/3 mm thick strip for the trihedrons and welding wire, necessary for the construction of the membrane. The packing is organized so that the pre-fabrication shop on the one hand, and each point of the tank on the other hand receive exactly the parts which are needed for the construction of the membrane, right on schedule.

CORROSION RESISTANCE

While not being stainless, **INVAR® M93** has a corrosion resistance much greater than mild steel. simple precautions, like handling with the gloves the workers wear to protect their hands, have proved fully effective to build perfect membranes in the marine atmosphere of a shipyard..

**THEORETICAL THERMAL STRESS
(MPa)**

$$\sigma = E \cdot \alpha \cdot \Delta T$$



	α ($10^{-6}/^{\circ}\text{C}$)	E (MPa)
INVAR [®]	1.5	140.000
304 SS	16.5	200.000
Al	23	70.000

**CONTRACTION OVER 45 m
 ΔL (in mm)**

PROPERTIES

STANDARD CONDITION

Since the construction technique involves the welding together of cold-rolled strips, the alloy is normally delivered annealed.

The properties given below are therefore measured in this condition.

COMPOSITION IN WEIGHT (%)

C	Si	Mn	S	P	Ni	Fe
≤ 0.04	≤ 0.25	0.2–0.4	≤ 0.0015	≤ 0.008	35–36.5	Balance

PHYSICAL PROPERTIES

Guaranteed coefficient of thermal expansion between 0 to – 180 °C	$1.5 \pm 0.5 \cdot 10^{-6} / ^\circ\text{C}$
Density	8.125 (g/cm ³)
Curie point	240 °C
Modulus of Elasticity at 20 °C	142 000 MPa
Young Modulus at –160 °C	136 000 MPa
Shear Modulus at 20 °C	57 000 MPa
Shear Modulus at –160 °C	52 000 MPa
Specific Heat, average between -196 °C and 20 °C	0.385 J. g ⁻¹ .K ⁻¹
Thermal Conductivity at 20 °C	0.147 J. cm ⁻¹ .s ⁻¹ .k ⁻¹
Thermal Conductivity at –160 °C	0.084 J. cm ⁻¹ .s ⁻¹ .k ⁻¹

Units : 1 J = $0.48 \cdot 10^{-4}$ B.T.U. = 0.24 cal

MECHANICAL PROPERTIES

- Tensile properties**

	Y S (MPa)	T S (MPa)	E L (%)
at 20 °C	≥ 280 (320)	≥ 470 (510)	≥ 30 (40)
at - 196 °C	(680)	(980)	≥ 30 (40)

() indicates typical values for 0.7 mm strip

- Ductility and Formability**

In addition to the high value of elongation in tension, the following properties show that the ductibility of **INVAR®** M93 is excellent at low temperature as well as at room-temperature.

- Charpy V notch (J/cm²)**

at 20 °C	≥ 200 (300)
at - 196 °C	≥ 120 (200)

() indicates typical values. Specimen are cut from 100 mm thick slabs (logitudinal)

- Notched Tensile Tests**

Tests performed on 1.5 mm strip in the annealed condition show that with $K_t = 3.8$, the ratio TS notched vs. TS un-notched is between 1.10 and 1.20 both at -196 °C and at room-temperature.

- Formability**

Bending tests (bending through 90° on a mandrel) with the bending axis parallel to the rolling direction have given the following results :

Sheet thickness (mm)	Ø of mandrel (mm)	Result
0.5	0.25	No crack
1.5	0.80	No crack

- Absence of low-temperature embrittlement**

This is guaranteed by the perfect stability of the austenitic structure and has been verified by testing groups of tensile (notched and un-notched) and Charpy V notch specimen after long holding times at -196 °C. The same result is obtained after holding in liquid hydrogen (4K).

- Fatigue**

Fatigue testing has been performed in alternating bending and in tension-tension on strip material (in the annealed condition). The following table gives the values obtained for the fatigue limit at 10^7 cycles :

	Alternate bending (MPa)	Tension – Tension ($\sigma_{min} = 0.1 \sigma_{max}$)
at 20 °C	210	$\sigma_{max} = 320$
at - 196 °C	400	$\sigma_{max} = 540$

These results are confirmed by test results obtained on bar material in rotating bending tension-tension compression.

FURTHER INFORMATION

- **Magnetic and electric properties**

	Magnetic Flux density	Electrical resistance
at 20 °C	1.3 T	80 μΩ.cm
at -196 °C	1.4 T	50 μΩ.cm

- **Effect of grain-size on mechanical properties**

ASTM Grain-Size	Vickers Hardness	Proof Stress σ 0.2 (MPa)
10	155	340
8	145	300
6	140	290

- **Expansion coefficient**

Temperature Range (°C)	Mean coefficient of Linear Expansion (10 ⁻⁶ /°C)
-180 to 0	1.5
-120 to 0	1.4
- 60 to 0	1.1
0 to 100	1.3
0 to 200	2.5
0 to 300	5.2

- **Cold work**

Amount of cold work %	0	15	25	50
Vickers Hardness	140	200	215	230

LONG EXPERIENCE OF SERVICE TO SHIPYARDS

For ArcelorMittal – Stainless & Nickel Alloys, Invar® is a long fascination story starting in 1896 with the first heat melted to the specification of Charles-Edouard Guillaume who later received the Nobel Prize.

Since 1968, **INVAR® M63** and more recently **INVAR® M93**, have been delivered to 13 shipyards for the construction of 87 LNG carriers, and more than 47 under construction or contracted.

We have also delivered **INVAR® M93** strip in Japan to Mitsubishi and to Mitsui for the Malaysian project, and is supplying the Daewoo shipyards, Izar in Spain and Chantier de l'Atlantique for CS1 new technology in France. All these orders confirm ArcelorMittal – Stainless & Nickel Alloys as the world leader in the production of **INVAR® M93** for this application.

ArcelorMittal - Stainless & Nickel Alloys is used to establishing with customers of all over the world a working partnership which combines a precise quality plan to prevent and quick action to solve problems of any kind.

We also bear shipowners and shipyards in their investigations after a long time running.

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