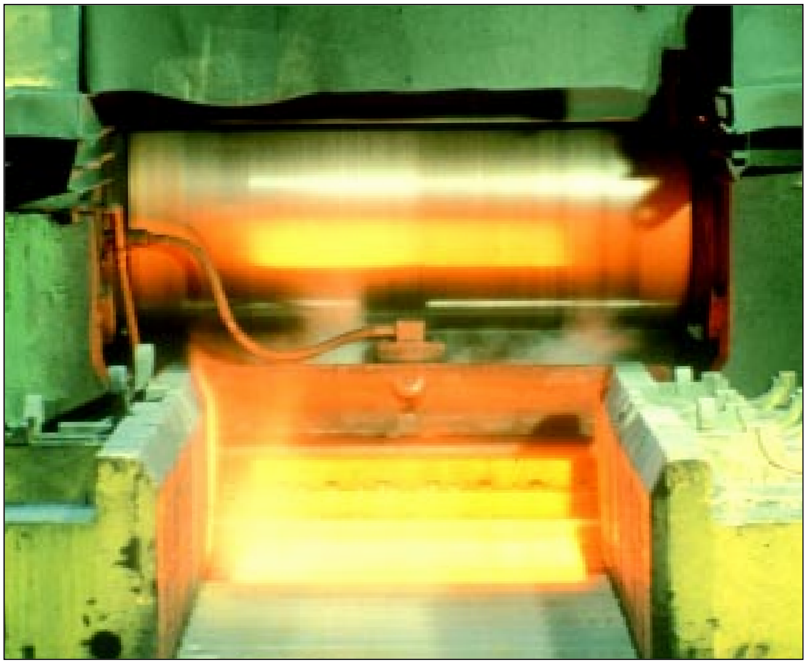
A Word About "Invar"

At Special Metals Corporation we are very particular about the use and recognition of our trademarks. This publication features the properties and applications of the NILO® series of nickel-iron alloys used for tooling to produce composites. We use the trademark "NILO" to define our own products and, like all our other trademarks, it can only be applied to alloys of our manufacture.

INVAR® is also a manufacturer's trademark, even though it is often loosely, and wrongly, used as a generic description for nickel-iron alloys, particularly those with a nickel content of around 36%. That alloy was invented, in 1896, by the Swiss physicist Charles-Edouard Guillaume, working at the International Bureau of Weights and Measures, in France. It was named "Invar" because of its "invariable effect". Searching for a more economical alternative to platinum-iridium bars as standards of metric measurement, Monsieur Guillaume created the first of what was to become a series of nickel-iron alloys destined to revolutionize precision engineering.

The aerospace industry has been using nickel-iron alloys for the manufacture of tooling for composites since nickel-iron alloy plate was first specified in the mid-1980s. In spite of the fact that the word "Invar" is often applied generically to these nickel-iron alloys, the Special Metals NILO alloys are the materials of choice in the industry. To be assured of the quality and experience of the market leader, we urge all designers, fabricators, engineers and purchasers to be as "precise" as the product itself. Ask for the NILO alloys by name.

NILO alloy plate for composite tooling applications is hot-rolled at the Special Metals facility in Huntington, West Virginia.



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For the manufacture of tooling for composites, the NILO® nickel-iron alloys offer a unique combination of matched thermal expansion to avoid warping during the curing cycle, along with strength, rigidity, durability, ease of fabrication and availability.

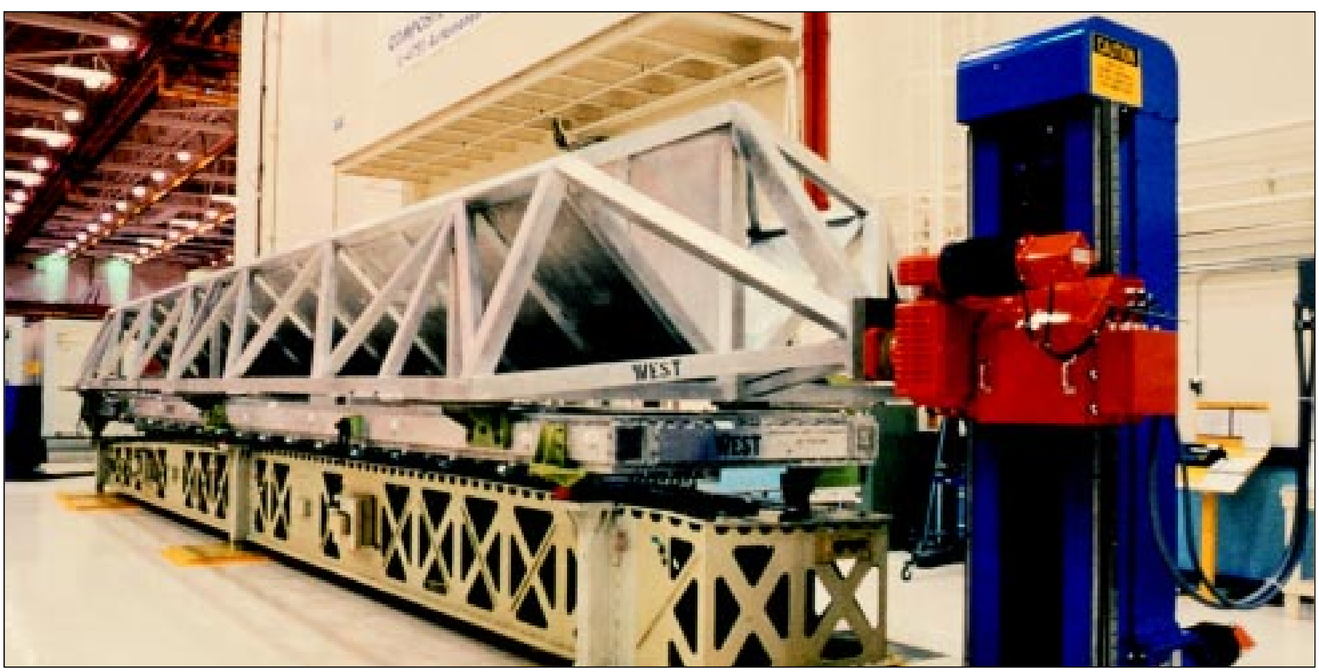
The construction of aircraft surfaces and structures is moving from the use of aluminum to carbon fiber-reinforced thermoset and thermoplastic resins; composite materials with high strength-to-weight ratios that are less subject to corrosion and fatigue. Current applications include aircraft control surfaces such as ailerons and flaps, body fairings and, most recently, some primary structural members. The manufacture of these composite components is quite different from the techniques used for conventional metal working.

Composite pieces range in size from 2 ft^2 (0.2 m^2) to items that are more than 40 ft (12 m) long and weigh more than 22,000 lb (10 tonnes). The need for precise aerodynamic surfaces and an exact fit of mating parts makes their manufacture particularly demanding, calling for precision molds and tools that are very close to the shape and size of the finished component.

This NILO alloy 36 flat plate tool was the first full-scale prototype in service at Boeing over ten years ago. It was in use more than 500 production cycles later, the performance having exceeded steel, aluminum and graphite epoxy tools for consistency and reliability. Special Metals was told that Boeing would not give up the alloy tool for "post mortem" analysis — it was still required for production.

The composite piece is built up on the tool by precise layering of cloth fibers impregnated with thermoset or thermoplastic resins. The complete tool, with the layered composite in place, is placed in an autoclave where a vacuum is applied to the tool face to hold the composite to the shape of the tool. The whole assembly is "cured" at around 350°F (175°C) for thermoset epoxy graphite systems, or up to 800°F (430°C) for thermoplastic resins. The cured composite component, a dense and accurate "aircraft quality" part, is stripped from the tool and the process is repeated.

For the production of the Boeing 777, the lower left hand horizontal stabilizer skin panel lay-up mandrel is 43 ft (13.1 m) long, 8 ft (2.4 m) wide, and 3 ft (0.9 m) deep. It weighs 27,000 lb (12.15 tonnes). Four of these tools, incorporating NILO alloy 36 materials, were made for first production.



The tools themselves, and the selection of materials for their construction, are critically important. They must be rigid, durable and, if tight tolerances are to be maintained on finished parts, they must offer a coefficient of thermal expansion (CTE) that matches that of the composite piece. The first metal tools were made from aluminum, steel or electroformed nickel, with design adjustments to compensate for the differences in expansion rates between the tool materials and the composites. Other tools have been made out of the composite materials themselves, thus ensuring an absolute CTE match, but offering poor durability and a tendency to become easily damaged in service.

The NILO alloys, made by Special Metals Corporation, meet the requirements as close-to-ideal materials for most composite tools. NILO alloy 36 is most often used for the thermoset epoxy systems. Since Boeing Commercial Airplane Group first used a nickel-iron alloy tool, in 1985, hundreds have been built by Boeing and by specialist tool makers to support a range of aerospace applications.

For the newer thermoplastic resin systems, the curing temperatures are higher. At temperatures above 390°F (200°C), the CTE of NILO alloy 36 begins to rise sharply. For these applications, NILO alloy 42 maintains its low CTE at higher temperatures.

Table 1 – Nominal compositions (%) of the NILO® alloys used for composite tooling

Alloy	Ni	Fe	Others
NILO alloy 36	36.0	Balance	–
NILO alloy 42	42.0	Balance	–
NILO alloy 365	43.5	Balance	Nb 3.3,Ti 1.4, C 0.02

Reference to the balance of a composition does not guarantee this is exclusively of the element mentioned but that it predominates and others are present only in minimal quantities.

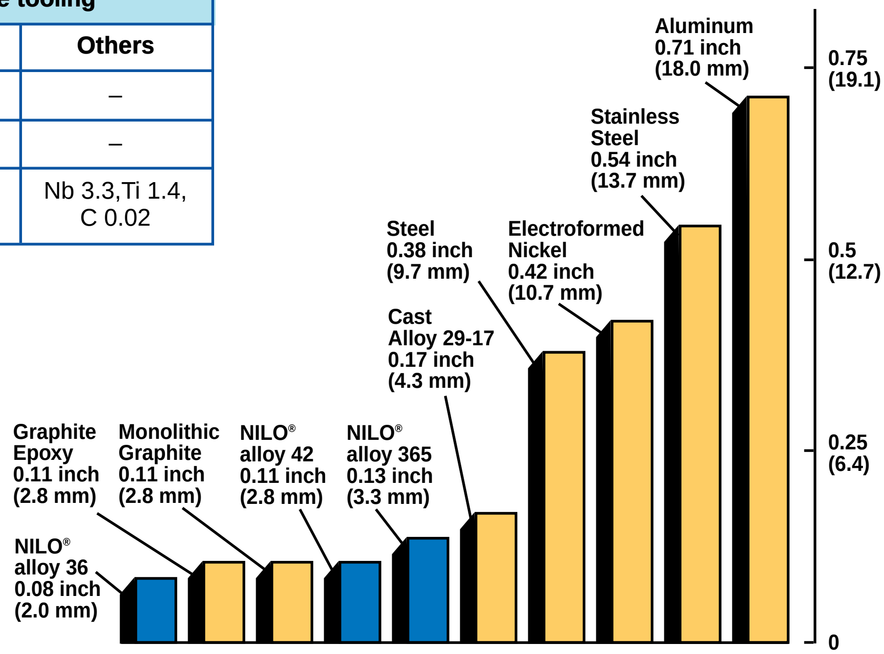


Figure 1.
Total thermal expansion for a variety of tooling materials in a 16 ft (4.9 m) tool, heated to 350°F (177°C). Note the close match between the NILO alloys and graphite epoxy.

Table 2 – Physical properties of some candidate materials for composite tooling applications

Material	Density		Thermal Conductivity		Specific Heat Capacity		Energy needed to heat 1 m³ of tool to 180°C	
	lb/in³	g/cm³	Btu in/ft² h °F	W/m °C	Btu/lb °F	J/kg °C	kW h	MJ
NILO alloy 36	0.293	8.11	73	10.5	0.12	500	186	670
NILO alloy 42	0.293	8.11	73	10.5	0.11	460	168	605
NILO alloy 365	0.293	8.11	86	12.4	0.12	500	180	648
Graphite Epoxy	0.058	1.6	24	3.5	0.18	750	54.2	195
Monolithic Graphite	0.060	1.67	—	—	0.31	1300	95.9	345
Electroformed Nickel	0.311	8.65	761	110	0.11	460	176	635
Aluminum	0.098	2.73	1127	163	0.22	920	111	400
Steel	0.283	7.85	299	43.3	0.12	500	175	630
Stainless Steel	0.289	8.03	113	16.3	0.12	500	175	630

Table 3 – Typical room-temperature mechanical properties						
Alloy	Tensile Strength		0.2% Yield Strength		Elongation on 2 in (50 mm)	Reduction of Area
	ksi	MPa	ksi	MPa	%	%
Annealed						
NILO alloy 36	71	490	35	240	42	70
NILO alloy 42	71	490	36	250	43	72
NILO alloy 365	104	717	59	407	41	63
Annealed & Age-Hardened						
NILO alloy 365	184	1269	146	1007	16	36

NILO alloy 36 is also being used for resin transfer molded (RTM) tools, a process in which the carbon fibers are laid up and the resin is injected into the tool mold.

The latest addition to the NILO series, NILO alloy 365, offers further improvements in strength and performance, and is a candidate material for all these applications including the new RTM technology.

The NILO alloys maintain their desirable properties through long production runs, producing thousands of components over a period of years. At 40 ksi (276 MPa) yield strength, 20 x 10^3 ksi (138 GPa) tensile elastic modulus, and 50% elongation, combined with low work hardening/ low elastic spring back, the NILO alloys can be easily hot- and cold-formed by press, roll, chip or bump processes. They offer high strength and rigidity, dimensional stability, the high levels of integrity inherent in wrought metals, and good thermal properties. Similar to other metallic tools, they require more energy to heat than graphite epoxy. However, once tool substructure designs are optimized for lightness and efficient air flow, heat-up rates typical of standard ramp rates are achieved.

Hot-Rolled Plate and Extruded Profiles

Most of the tooling applications for the NILO alloys are covered by the supply of hot-rolled alloy plate made at the Special Metals facility in Huntington, West Virginia. For some specialist applications in Europe, Special Metals Wiggin Ltd., Hereford has produced extruded profiles in the NILO alloys.

A NILO alloy 36 mandrel on a tool assembly for the Boeing 757.

NILO alloy 365

In addition to the longer-established NILO alloys 36 and 42, Special Metals has developed a new product with significant property improvements for tooling applications. This new alloy was invented essentially to meet demands from Boeing engineers for improved manufacture of durable, close-tolerance tooling for composite components. It is an age-hardenable alloy, strengthened by heat treatment to reach property levels well above those of conventional nickel-iron alloys; the first high-strength, age-hardenable alloy produced specifically for tooling applications.

45 ft (13.7 m) bond jigs in NILO alloy 36 for the upper and lower wing skins of the Bell Helicopter V22 *Osprey*. (Remmele Engineering, Inc., General Machining Division, New Brighton, Minnesota, USA).

The new alloy's higher hardness helps minimize tool surface damage during handling, reducing repair and maintenance costs. Higher strength and modulus enable tools to be designed using less material which, in turn, means lighter tooling and quicker autoclave heat-up rates. The all-important coefficient of thermal expansion (CTE) remains low in the composite curing range of 400-700°F (200-370°C).

NILO alloy 365 has 43% nickel and is strengthened by additions of 1.4% Ti and 3.3% Nb. Strengthening occurs during the aging heat-treatment – 1250°F (677°C) for 4 hours, furnace cool at 100°F (38°C) per hour to 1150°F (621°C) for 4 hours, air cool – producing a gamma prime precipitate. Age-hardened NILO alloy 365 develops higher room-temperature hardness (Rockwell C39) and four times the yield strength – 146 ksi (1006 MPa) – compared with annealed 36% Ni-Fe alloys. Creep strength (resistance to deformation under load) is also much higher.

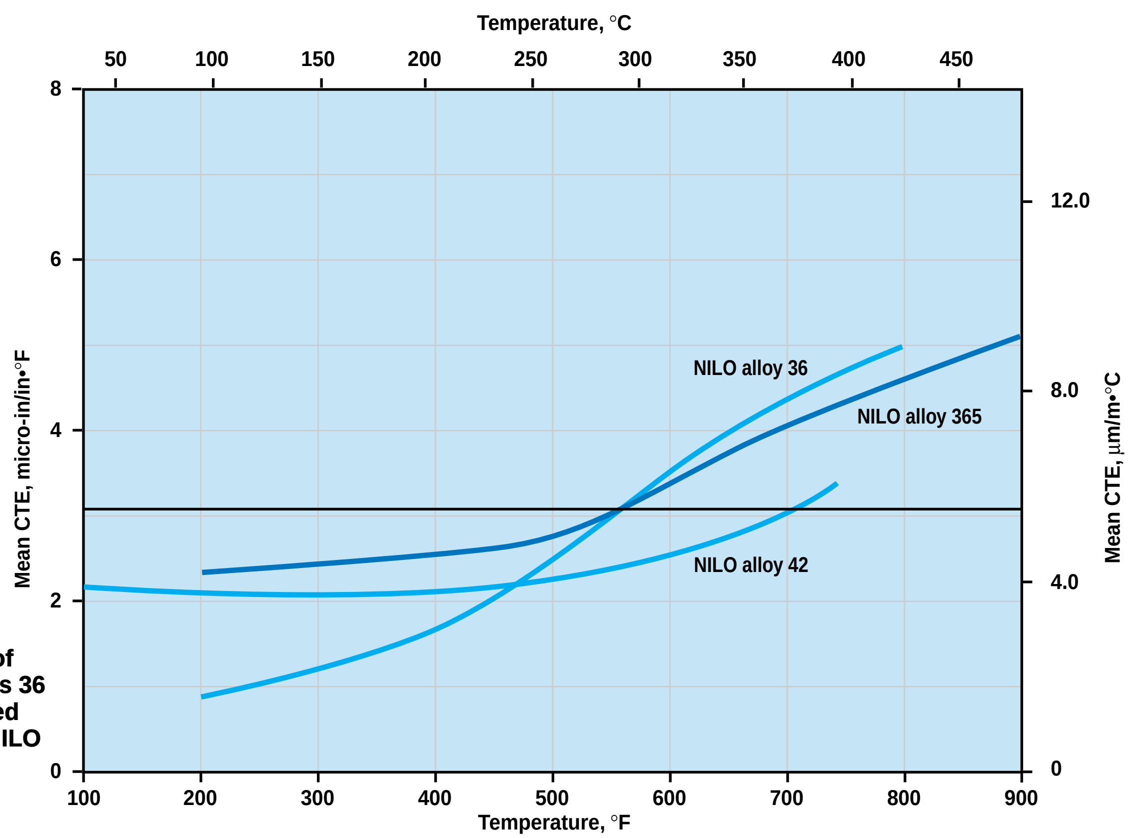


Figure 2.
A CTE comparison of annealed NILO alloys 36 and 42, with annealed and age hardened NILO alloy 365.

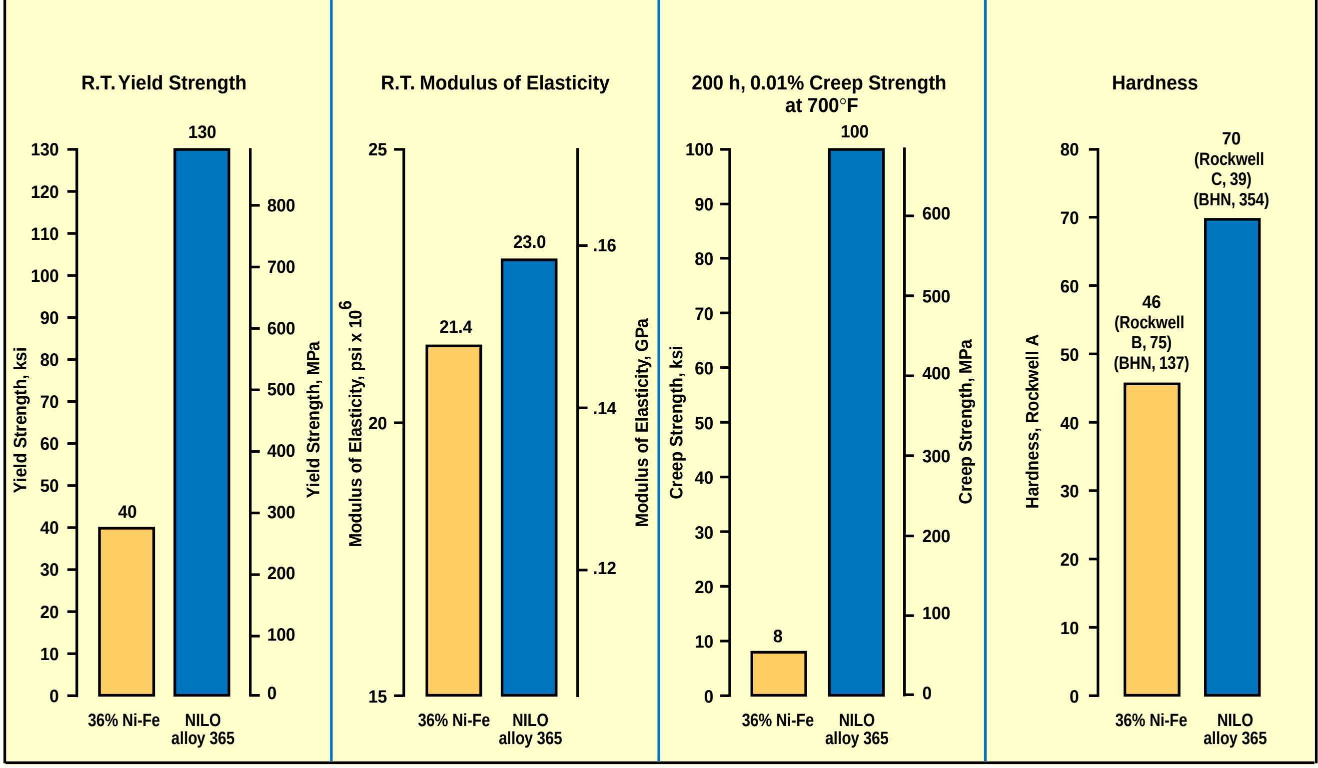


Figure 3 – Mechanical property comparisons between annealed and age-hardened NILO alloy 365 and a typical, annealed, 36% nickel-iron alloy. Note the moduli data offering the opportunity to reduce cross-sectional area in larger tools, thus a reduction in the amount of alloy used for the tool. Also, note the higher hardness for better protection against scratching by knives during the laying-up process.

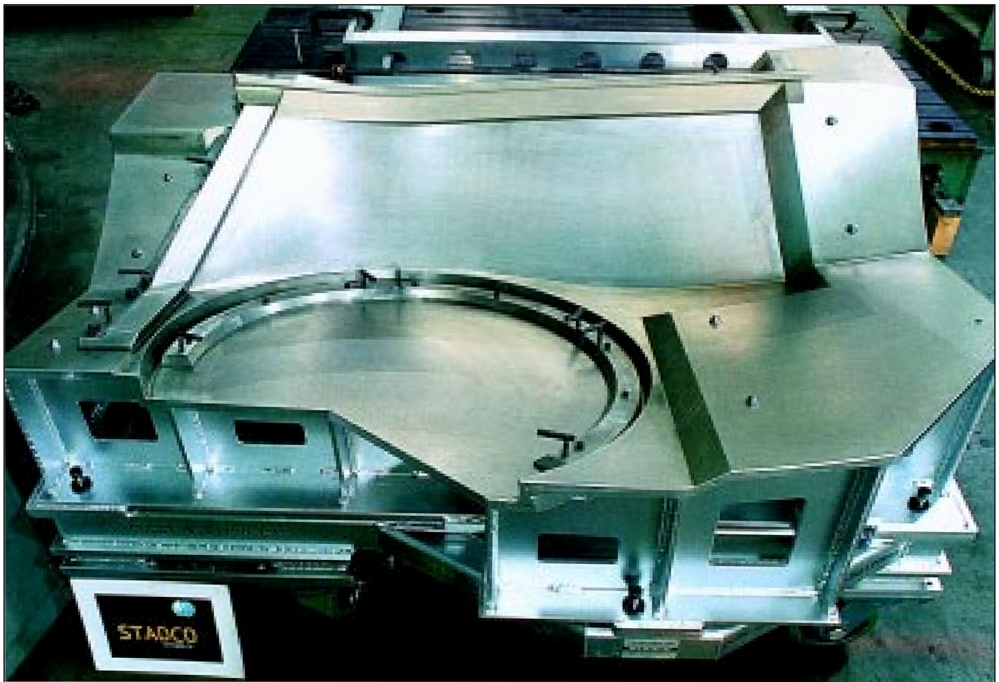
NILO alloy 365 has a higher modulus of elasticity at room and curing temperatures, promoting improved stiffness. At a typical curing temperature of 400°F (204°C), the new alloy's coefficient of thermal expansion falls midway between those of NILO alloys 36 and 42.

Produced by air induction melting, with precise control of composition, NILO alloy 365 is available in the same plate thicknesses as NILO alloy 36 and is equally straightforward to fabricate, weld and machine.

Fabrication

NILO alloy 365 hot-rolled plate is supplied in the annealed temper. Cutting, forming, welding and rough machining should be carried out on annealed material, followed by age hardening and final machining. During the aging cycle, a slight contraction (approximately 0.04%) occurs in NILO alloy 365, similar to other age-hardenable nickel alloys. This movement of the fabricated tool during heat treatment is minimal and poses no problems during tooling manufacture or use.

The alloy plate can be readily cold-formed in the annealed condition and machined easily as annealed, or in the annealed and age-hardened temper. Due to its higher strength and hardness, age-hardened NILO alloy 365 is less "gummy" during machining than the softer, annealed, NILO alloy 36.



A NILO alloy 36 tool for the upper skin of the Sikorsky *Comanche* helicopter. This intricate mold shows removable inserts allowing undercut contours without creating lock-on conditions. (STADCO, Los Angeles, USA).

A mid-engine cowl bond jig tool in NILO alloy 42 for a Pratt & Whitney engine on *Airbus 340*.
(STADCO, Los Angeles, USA).

Part of a resin transfer molding (RTM) tool in NILO alloy 36 for a military aircraft development project. (UCAR Composites, USA).

A NILO alloy 36 tool for the horizontal stabilizer of a McDonnell-Douglas F-18E/F. The inset picture shows the actual part produced with co-cured titanium root fittings.

A complex NILO alloy 36 tool, 25 ft (7.6 m) long, made to ± 0.005 in (0.13 mm) tolerances. (STADCO, Los Angeles, USA).

A NILO alloy 36 lay-up tool for the canopy structure of the Sikorsky *Comanche* helicopter. Inset, one of these tools is being probe tested to confirm the high-precision manufacturing tolerances. (Remmele Engineering, Inc., General Engineering Division, New Brighton, Minnesota, USA).

Welding

The use of nickel-iron alloys for composite tooling was, at one time, limited by the lack of welding consumables that would produce sound welds with matching CTE. Matched composition weld metals were prone to cracking. Those problems have been overcome by the development in Special Metals Corporation's welding research laboratories of NILO filler metals CF36 and CF42; filler wires with expansion rates similar to those of the base metals, producing high-quality, crack-free, vacuum-tight welds by the submerged-arc, gas-metal-arc, and gas-tungsten-arc processes.

These Nb-C modified compositions were formulated for nickel-iron alloy welding and have proved to be superior to earlier Mn-Ti modified compositions, sometimes known as "Invar" rod, which are crack-sensitive and have a CTE approximately three times that of NILO filler metal CF36. Selection of the appropriate filler metal should be made to meet the thermal expansion behavior required of the weld.

As this publication goes to press, the scientists at the Special Metals Technology laboratories are working on the development of a new consumable for use with NILO alloy 365.

Table 4 – Nominal compositions (%) of NILO filler metals CF36 and CF42, and a submerged-arc-welding deposit

	NILO filler metal CF36	NILO filler metal CF42	SAW Deposit
C	0.2	0.2	0.2
Mn	0.4	0.4	1.5
Fe	Balance*	Balance*	Balance*
Ni	36.0	41.5	†
Nb	1.5	1.5	1.5

* Reference to the balance of a composition does not guarantee this is exclusively of the element mentioned but that it predominates and others are present only in minimal quantities.

† 36% if NILO filler metal 36 is used; 41.5% if NILO filler metal 42 is used.

Gas-Metal-Arc Welding

GMAW parameters (Table 5) produce a weld metal deposition rate of approximately 9.4 lb (4.2 kg)/h. Weld quality is excellent. The use of 100% inert shielding gases is recommended. Care should be taken to limit the maximum interpass temperature to 300°F (150°C) to avoid oxidation and undercutting. Weld beads on pickled or unprepared plate will, typically, result in the GMA cleaning action undercutting any oxide layer present. This should be remedied by removing oxides before welding. If this preparation is not possible, the SAW process should be considered since the flux used with SAW will allow welding without undercutting. If SAW is not possible, GMAW attachment quality weldments can be produced, free of undercutting, by the use of the short-circuiting parameters listed in Table 5.

Submerged-Arc Welding

NILO filler metals CF36 and CF42 have exceptional SAW characteristics. The use of INCOFLUX® 6 is strongly recommended for best results. SAW can be performed at conventional parameters listed in Table 6 or at even higher deposition rates. The conventional parameters should result in deposition rates of approximately 10 lb (4.5 kg)/h and excellent quality welds have been made at rates up to 18 lb (8.1 kg)/h.

A typical high deposition rate, 0.75 in (19 mm) thick, beveled butt joint would be completed in 3 weld beads with a 40° included angle and no root gap. The first pass is made at 15 in (380 mm)/minute with a 0.75 in (19 mm) stick-out to limit penetration. The next two passes are made at 12 in (305 mm)/minute and a 0.5 in (13 mm) stick-out. This type of SAW productivity and quality are unheard of with any other austenitic filler metals.

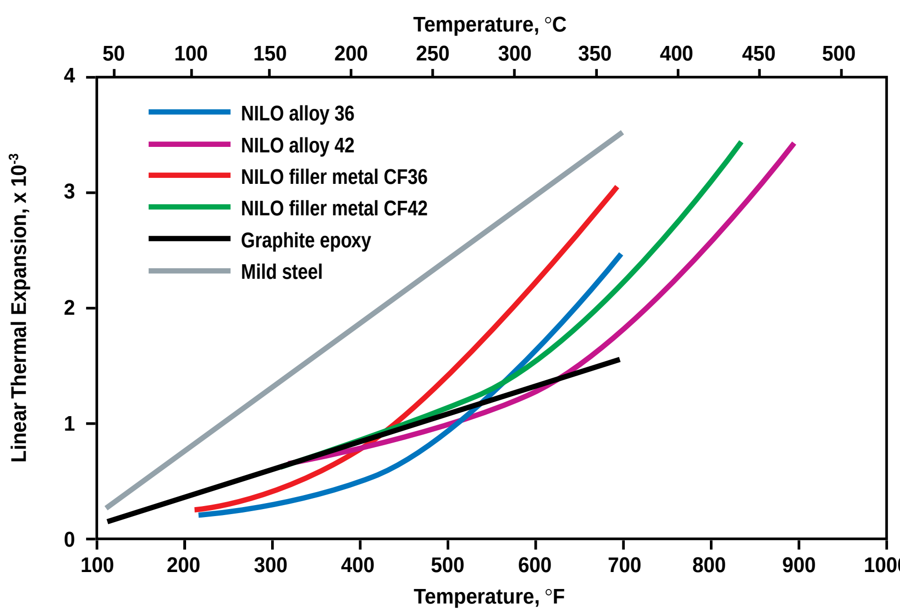


Figure 4. Linear thermal expansion comparisons of NILO alloys 36 and 42, NILO filler metals CF36 and CF42, graphite epoxy and mild steel.

Table 5 – GMAW parameters for NILO filler metals CF36 and CF42, 0.045 in (1.1 mm) diameter wire				
Transfer Type	Wire Feed Speed		Voltage	Current
	in/min	m/min	V	A
Spray	300-400	7.6-10.2	29-33	200-270
Short Circuit	500	12.7	25-27	220-260
Pulsing Arc				
60 Pulses/Second	250	6.3	21 (background)	400 peak/150 average
120 Pulses/Second	320	8.1	21 (background)	400 peak/170 average

100% inert shielding gas – argon, helium, or a mixture of the two. The use of helium requires slightly higher voltages.
Typical shielding gas flow, 50 ft^3/h (1.4 m^3/h). Torch angle should be perpendicular to the work ± 15°.

Table 6 – SAW parameters for NILO filler metals CF36 and CF42, 0.045 in (1.1 mm) diameter wire						
	Wire Feed Speed		Voltage	Current	Travel Speed	
	in/min	m/min	V	A	in/min	mm/min
Typical	370	9.4	31-34	230-260	8-12	203-305
High Deposition	650	16.5	32	320-360	8-15	203-381

Using INCOFLUX® 6, with an electrode extension of 0.5-0.75 in (13-19 mm), DCEP (reverse polarity).

Table 7 – Typical room-temperature mechanical properties of longitudinal all-weld-metal samples from NILO alloy 36 welds							
Welding Process	Tensile Strength		0.2% Yield Strength		Elongation	Impact Strength*	
	ksi	MPa	ksi	MPa	%	ft-lbf	J
Unwelded Base Metal	71	490	35	241	42	141	191
GMAW†	79.9	551	59.1	407	22	41	56
SAW†	71.5	493	49.8	343	29	72	98

* Average of three tests.
† Three side-bend tests (2T) showed zero fissures.