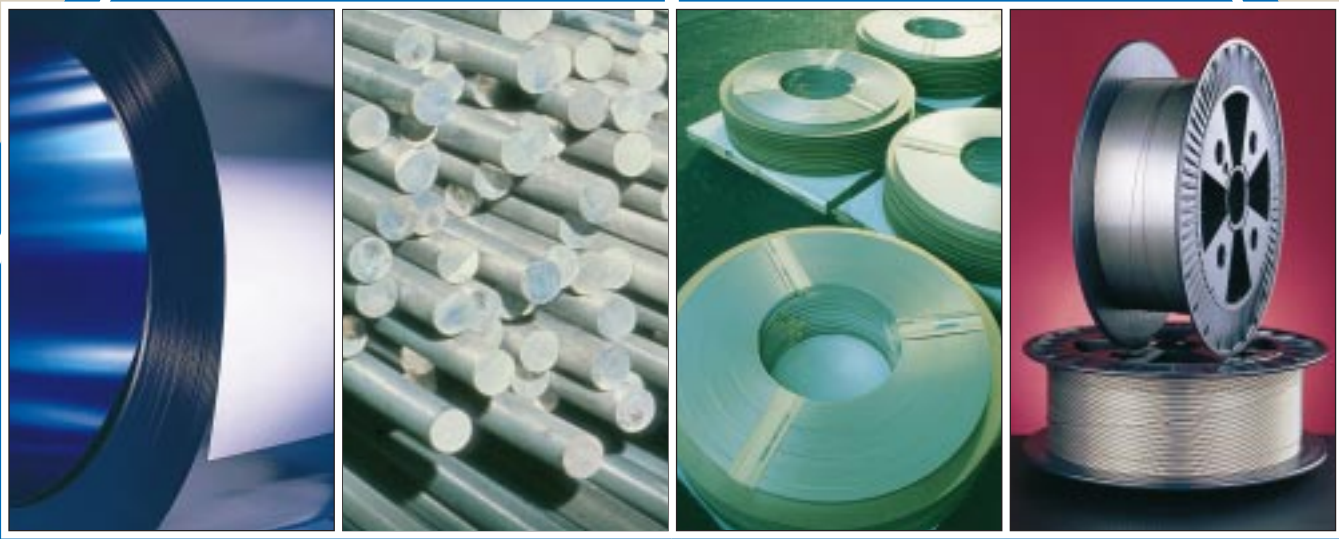




# High-Performance Alloys for Automotive Engineering



## Quality & Accreditations

As suppliers to the automotive industry, Special Metals Corporation is committed to providing products and services that meet or exceed customer expectations. Our objective is the provision of the highest possible quality at the lowest possible cost. To that end, we are able to offer our own, accredited, testing facilities. Our laboratory in the USA is A2LA accredited for mechanical and chemical testing, and customers can accept our certifications without further testing. Our laboratory in Europe is UKAS-accredited.

We have developed in-house quality systems to meet the demands of major standards, including the automotive industry's QS-9000. Our quality management systems were approved to ISO 9002 in 1990, in Europe, and in 1993, in the USA. Building on this strong base and expanding quality systems to meet QS-9000, we continue to meet a wide range of automotive industry requirements as contained in the AIAG Manuals.



Throughout this publication, we quote the appropriate AMS, ASTM, AWS and BS specifications, and UNS and Werkstoff materials designations for our alloy products. As one of the world's leading suppliers of high-performance, nickel-base alloys, for applications ranging from aerospace to sub-sea oil and gas extraction, it should be noted that we are also working every day to meet the requirements of ASME, DIN, ISO, AECMA and other specifications defined and audited by our major customers worldwide.

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Data contained in this publication, derived from laboratory testing and service experience, are typical for the properties described, but are not suitable for specifications unless given as limiting.

# Solutions to Materials Problems



From the beginning, certainly from the introduction of assembly line production, the auto industry was focused on a product cost/performance ratio that excluded high-performance alloys from typical bills of materials. Except for some notable applications in competition motoring, the alloy performance levels were always an over-specification. Who needed alloy components with life cycles that would outlast the vehicles? Today, the picture has changed. Manufacturers are calling for higher levels of strength and corrosion-resistance, to improve performance and to help meet new legislation for higher standards of pollution control.

Material selection is moving into the realms of alloy science and technology; not surprising with the business facing up to mandatory standards for exhaust systems of 100,000 miles (160,000 km), or ten years' trouble-free motoring.

This publication offers a brief overview of the developing uses for high-performance alloys in exhaust systems and a range of other automotive applications where they are, now, the cost-effective option. Materials proposals are offered for:

## **Exhaust Systems**

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# Exhaust Systems

## Flexible Couplings and EGR Tubes

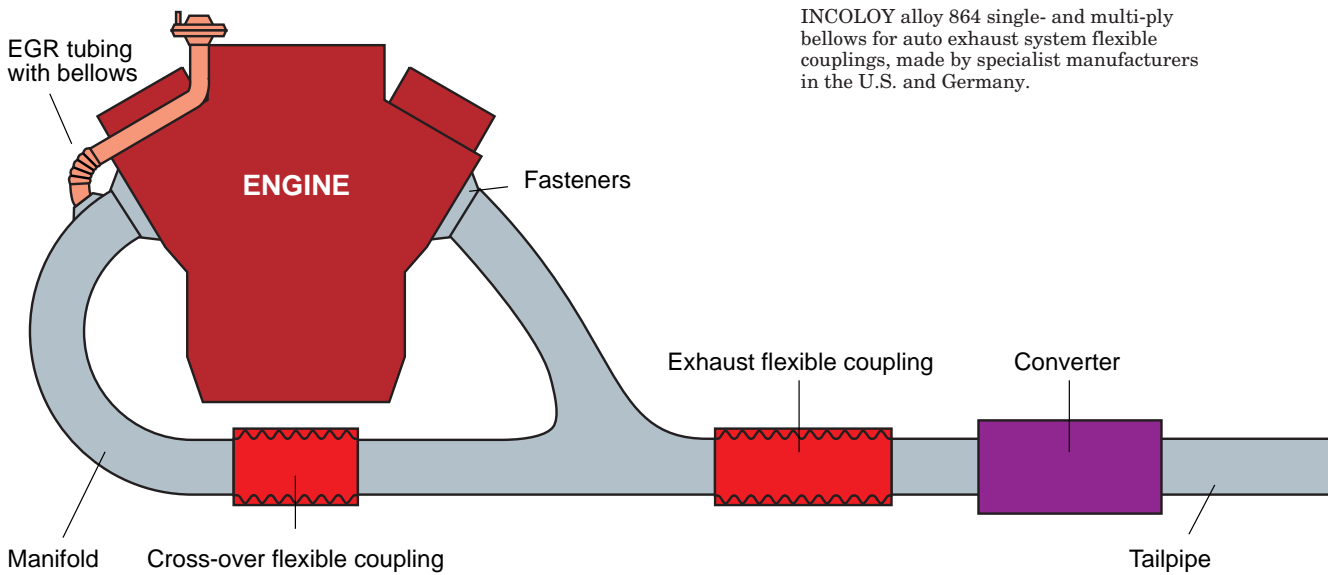
Alloy	Nominal Composition, % wt.					Designations	Specifications
	C	Ni	Cr	Fe	Others		
INCONEL alloy 625LCF	0.02	61.0	21.5	2.5	Mo 9.0, Nb 3.6	UNS N06626 Werkstoff Nr. 2.4856	SAE AMS 5879
INCOLOY alloy 864	0.03	34.0	21.0	39.5	Mo 4.2, Si 0.8, Ti 0.6	UNS S35135	ASTM A240

Flexible couplings for automotive exhaust systems are a very demanding application because they are susceptible to attack by a wide range of corrosion mechanisms encountered in everyday driving, particularly road deicing salts. Depending on the design and location in the exhaust system, potential failure mechanisms include fatigue, corrosion fatigue, oxidation, hot-salt corrosion, stress-corrosion cracking, pitting and general corrosion. Similar to the flexible coupling, the exhaust gas recirculation (EGR) tube may also be exposed to fatigue and corrosion. It is important to recognize the potential for failure and select the most cost-effective materials. The trend towards higher exhaust temperatures and leak-free system warranties to 100,000 miles or ten years makes a strong case for high-performance alloys to replace stainless steels for these key components.



INCOLOY alloy 864 single- and multi-ply bellows for auto exhaust system flexible couplings, made by specialist manufacturers in the U.S. and Germany.

Automotive exhaust system applications for high-performance alloys.



Two of the Special Metals high-performance alloys demonstrate exceptional properties for flexible couplings: INCONEL alloy 625LCF and INCOLOY alloy 864. Adopted after many years of successful service in the aerospace industry, INCONEL alloy 625LCF is the premier material for flexible couplings used in the automotive industry, worldwide. INCOLOY alloy 864 was developed specifically for the automotive industry as a cost-effective alloy designed to provide better performance than stainless steels for flexible coupling bellows

and other exhaust system applications. Both alloys are produced in thin strip suitable for bellows and EGR tubes, and both are readily formed and welded.

Fabricated bellows are the heart of the flexible coupling and must resist degradation to maintain a long, leak-free life. High temperatures, fatigue, and road salt can take their toll on stainless steel bellows, see Figures 1 and 2.

The thin walls of flexible coupling bellows cannot tolerate corrosion penetration very deeply without reducing the life of the bellows. As illustrated,



Figure 1 – This two-ply AISI 321 stainless steel bellows failed primarily due to pitting corrosion, general corrosion, and chloride stress-corrosion cracking. INCOLOY alloy 864 and INCONEL alloy 625LCF resist the type of attack illustrated.

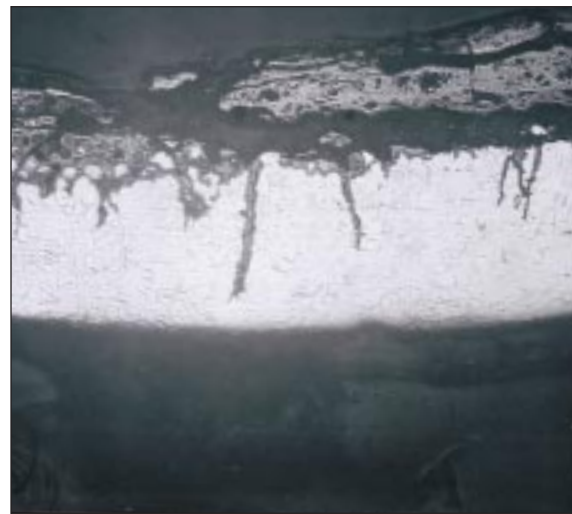


Figure 2 – Transverse section of the inner ply of an AISI 321 bellows, showing transgranular stress-corrosion cracking and intergranular corrosion originating on the outside diameter.

Table 1 — Typical Comparative Tensile Properties										
Alloy	At Room Temperature					At 1200°F (649°C)				
	Yield Strength, 0.2% Offset		Ultimate Tensile Strength		Elong.	Yield Strength, 0.2% Offset		Ultimate Tensile Strength		Elong.
	1000 psi	MPa	1000 psi	MPa	%	1000 psi	MPa	1000 psi	MPa	%
INCONEL alloy 625LCF	74	510	136	938	47	61	420	121	834	34
INCOLOY alloy 864	38	262	95	655	45	23	159	68	469	22
AISI 316Ti	40	276	90	620	50	20	138	56	386	44
AISI 321	35	241	90	620	45	18	124	44	303	43

# Exhaust Systems

## Flexible Couplings and EGR Tubes (continued)

road-salt exposure has caused the transgranular stress-corrosion cracking almost through the wall of an AISI 321 stainless steel bellows inner ply. Also note the presence of intergranular cracking from hot salt. Tables 2 and 3 show the excellent resistance of INCOLOY alloy 864 and INCONEL alloy 625LCF to hot-salt stress-corrosion cracking and intergranular corrosion as compared to stainless steels.

Fatigue resistance is critical to the survival of a flexible coupling bellows in automotive service. Figures 3 and 4 demonstrate the advantages of INCONEL alloy 625LCF and INCOLOY alloy 864 over stainless steels in resistance to fatigue at room temperature and at the high temperatures encountered in exhaust systems.

Manufacture of automotive flexible coupling bellows involves forming and welding of strip to make tubing, followed by hydroforming of bellows convolutions in the seam-welded tubing. The resulting bellows are then welded to liners, flanges and other parts of the exhaust system. INCOLOY alloy 864 and INCONEL alloy 625LCF are readily formed and welded using typical manufacturing techniques. Figure 5 illustrates the comparative work hardening rates of INCOLOY alloy 864, INCONEL alloy 625LCF and stainless steel. The forming behavior of INCOLOY alloy 864 is similar to that of stainless steels.

<b>Table 2 — Hot-Salt Stress-Corrosion Cracking Test Results</b> (15 min heating/5 min cooling, 7.5% NaCl + 2.5% CaCl <sub>2</sub> , dip daily)			
Alloy	Depth of Cracking, mils (mm). Average of Duplicates		
	At 800°F (427°C) and 1387 Cycles	At 1050°F (566°C) and 750 Cycles	At 1150°F (621°C) and 1386 Cycles
INCONEL alloy 625LCF	0	0	0
INCOLOY alloy 864	0	0	—
AISI 316Ti	2 (0.05)	2 (0.05)	—
AISI 321	1 (0.03)	3 (0.08)	13 (0.33)

U-bent specimens, stressed greater than the yield strength.

<b>Table 3 — Hot-Salt Intergranular Corrosion Test Results</b> (15 min heating/5 min cooling, 7.5% NaCl + 2.5% CaCl <sub>2</sub> , dip daily)			
Alloy	Depth of Cracking, mils (mm). Average of Duplicates		
	At 800°F (427°C) and 1387 Cycles	At 1150°F (621°C) and 1386 Cycles	At 1400°F (760°C) and 1400 Cycles
INCONEL alloy 625LCF	0	1 (0.025)	2 (0.05)
INCOLOY alloy 864	1 (0.03)	2 (0.05)	6 (0.15)
AISI 316Ti	2.5 (0.06)	4 (0.10)	18 (0.46)
AISI 321	3 (0.08)	10 (0.25)	22 (0.56)

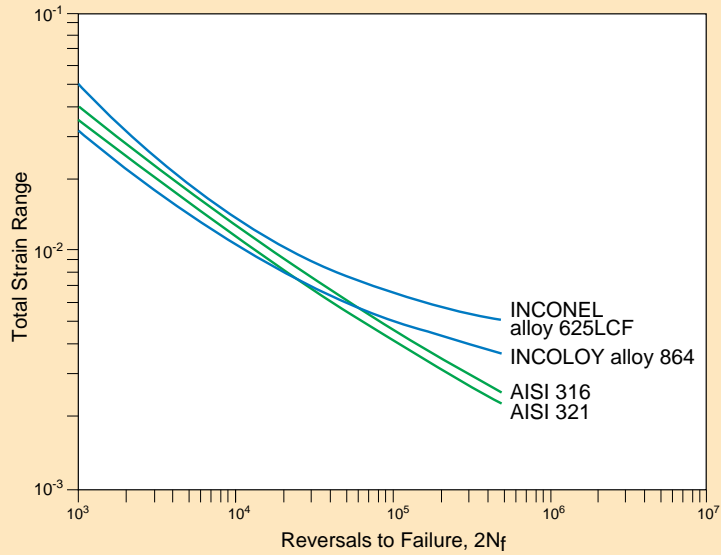


Figure 3 – Total strain range vs. reversals to failure at 75°F (24°C).

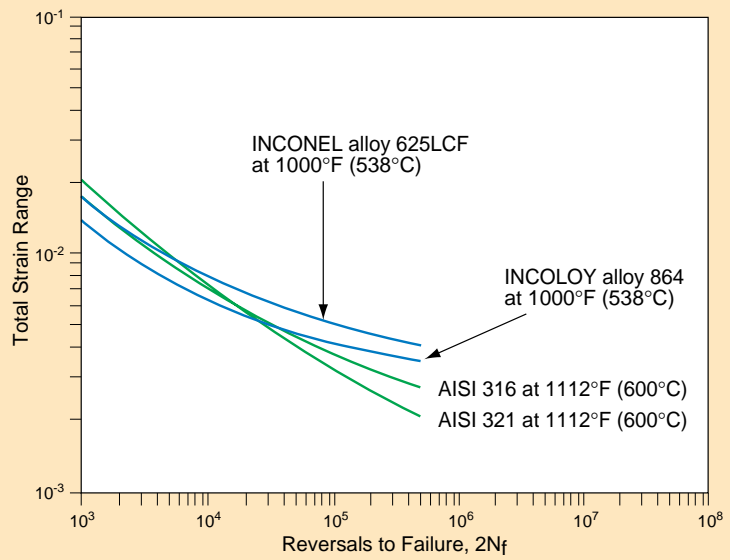


Figure 4 – Total strain range vs. reversals to failure at high temperature.

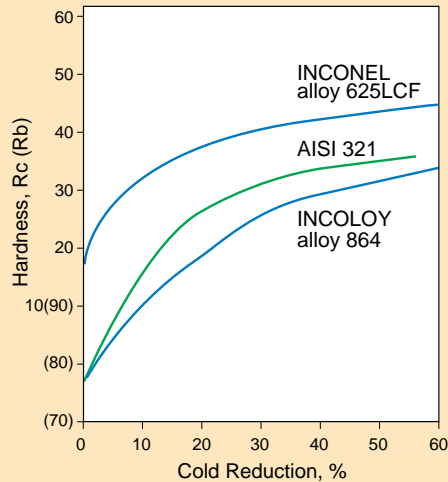


Figure 5 – Effect of cold work on hardness values.

# Exhaust Systems

## Manifolds and Tailpipes

Alloy	Nominal Composition, % wt.				Designations	Specifications
	Ni	Cr	Fe	Others		
INCOLOY alloy 800	32.5	21.0	46.0	Al + Ti 0.3-1.2	UNS N08800 Werkstoff Nr. 1.4876	ASTM B409, B515, B751 SAE AMS 5871
INCOLOY alloy 803	35.0	25.0	40.0	Al + Ti 0.3-1.2	UNS S35045	ASTM A240
INCOLOY alloy 840	20.0	20.0	60.0	—	Werkstoff Nr. 1.4847	—
INCOLOY alloy 864	34.0	21.0	39.5	Mo 4.2, Si 0.8, Ti 0.6	UNS S35135	ASTM A240
INCONEL alloy 601	60.5	23.0	14.1	Al 1.4	UNS N06601 Werkstoff Nr. 2.4851	ASTM B168 SAE AMS 5870

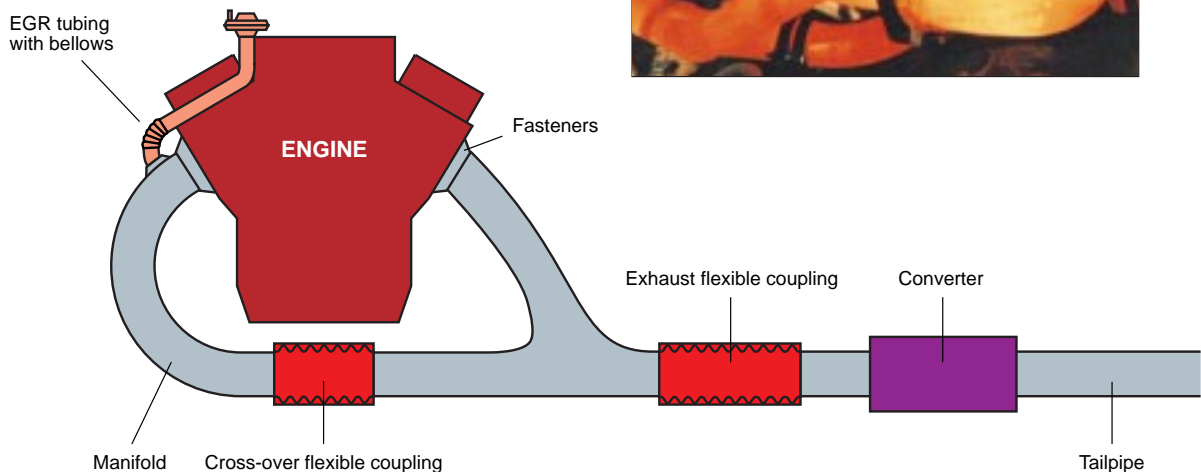
Today's sophisticated exhaust systems are critical to the life expectancy of an automobile. As engine outputs and emission demands go up and exhaust system operating temperatures rise, automotive engineers are also looking to high-performance alloys to solve materials problems for manifolds and exhaust piping. Traditional stainless steels do not always meet these tough demands. Several INCOLOY and INCONEL alloys can be selected for their high-temperature strength, thermal expansion and conductivity, resistance to thermal fatigue, hot-salt corrosion and stress-corrosion cracking resistance, and resistance to oxidation and scaling from combustion gases. They all offer excellent cold formability and weldability.

Exhaust system alloys must resist oxide spalling to maintain a protective surface for long life. This is especially important at the higher temperatures encountered in manifolds. A good measure of an alloy's resistance to spalling is a cyclic oxidation test which subjects the material to heating and cooling cycles in air. The expansion and contraction will tend to spall off the oxide which forms. Better alloys

Exhaust manifolds can run at temperatures that call for optimum performance heat-resistant alloys.



Automotive exhaust system applications for high-performance alloys.



resist the build-up of thick oxide and subsequent spalling, which is measured by weight gain and loss. The lower the weight gain and the lower the weight loss, the better the alloy resists oxidation and spalling,

as shown in Table 6. Several INCOLOY and INCONEL alloys have good-to-excellent oxidation- and spalling-resistance for exhaust system applications in place of ferritic or austenitic stainless steels.

Alloy	At Room Temperature					At 1400°F (760°C)					At 1800°F (982°C)				
	Yield Strength, 0.2% Offset		Ultimate Tensile Strength		Elong.	Yield Strength, 0.2% Offset		Ultimate Tensile Strength		Elong.	Yield Strength, 0.2% Offset		Ultimate Tensile Strength		Elong.
	1000 psi	MPa	1000 psi	MPa	%	1000 psi	MPa	1000 psi	MPa	%	1000 psi	MPa	1000 psi	MPa	%
INCOLOY alloy 800	43	296	86	593	45	22	152	32	221	84	9	62	11	76	105
INCOLOY alloy 803	46	317	87	600	42	26	179	65	448	67	9	62	14	97	64
INCOLOY alloy 840	27	234	78	538	50	20	138	29	200	67	9	62	10	69	110
INCOLOY alloy 864	38	262	95	655	45	21	145	68	469	57	9	62	14	97	69
INCONEL alloy 601	66	455	111	765	40	32	221	70	483	75	8	55	9	62	140
AISI 409	35	241	65	448	33	6	41	9	62	67	—	—	—	—	—
AISI 309	42	290	90	621	45	20	138	36	248	40	9	62	11	76	65

Alloy	400°C (752°F)	600°C (1112°F)	800°C (1472°F)	1000°C (1832°F)
INCOLOY alloy 800	15.5 (8.61)	17.0 (9.44)	18.0 (10.00)	19.0 (10.55)
INCOLOY alloy 803	16.3 (9.1)	16.7 (9.3)	—	—
INCOLOY alloy 840	16.6 (9.20)	17.5 (9.70)	18.1 (10.05)	18.7 (10.40)
INCOLOY alloy 864	15.9 (8.83)	16.4 (9.11)	17.2 (9.58)	17.6 (9.80)
INCONEL alloy 601	14.8 (8.24)	15.6 (8.67)	16.7 (9.26)	17.8 (9.90)
AISI 409	12.2 (6.75)	12.7 (7.05)	13.5 (7.50)	—
AISI 309	17.0 (9.45)	17.6 (9.80)	19.4 (10.75)	20.7 (11.5)

Alloy	Weight Change (Scale Not Removed), g/m <sup>2</sup> , at:			
	1300°F (704°C)	1500°F (816°C)	1800°F (982°C)	2000°F (1093°C)
INCOLOY alloy 800	0.3	3.2	8.6	-560
INCONEL alloy 601	0.1	1.2	10	-2.1
AISI 409	0.1	0.8	+1430 <sup>a</sup>	-10,000 <sup>b</sup>
AISI 304	0.2	1.7	-3,400	-10,000 <sup>c</sup>

<sup>a</sup>Removed after 36 h.  
<sup>b</sup>Removed after 12 h.  
<sup>c</sup>Removed after 24 h.

# Exhaust Systems

## Manifolds and Tailpipes (continued)

Resistance to oxide formation and spalling is illustrated in Figures 7 and 8. Both INCOLOY alloy 864 and AISI 321 were exposed to a severe 1750°F (954°C) burner rig test for 500 h. The INCOLOY alloy 864 forms an adherent, protective oxide which protects the underlying base metal from rapid deterioration. The AISI 321 cannot form a protective oxide and experiences rapid and severe oxidation and spalling which leads to complete deterioration of the base metal. Burner rig data for several alloys are shown in Figure 9.

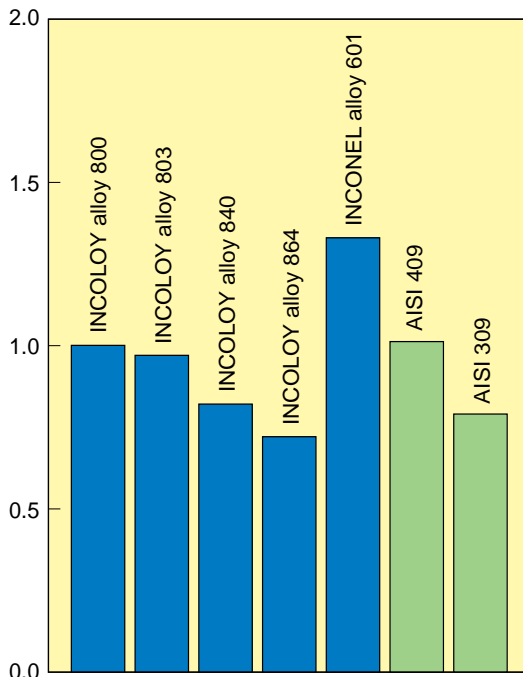


Figure 6 – Thermal fatigue index\* cycling from room temperature to 1400°F (760°C). A higher fatigue index indicates a greater resistance to thermal fatigue. Data normalized with respect to alloy 800.

$$*\text{Index} = \frac{\text{YS} \times \text{Elongation} \times \text{Thermal Conductivity}}{\text{Young's Modulus} \times \text{COE} \times \Delta T}$$



Figure 7 – Photomicrograph of the as-polished cross section of an INCOLOY alloy 864 burner rig sample after 500 h exposure. Magnification: 500X.

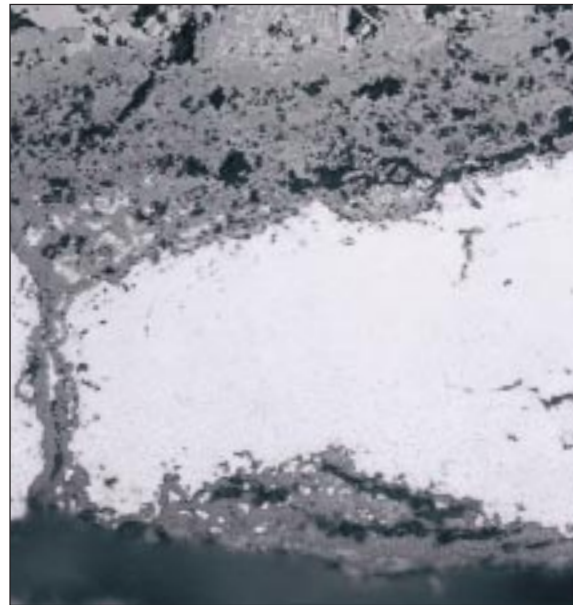


Figure 8 – Photomicrograph of the as-polished cross section of an AISI 321 stainless steel burner rig sample after 500 h exposure. Magnification: 500X.

In addition to oxidation and corrosion from combustion gases on the inside of exhaust system piping, hot-salt corrosion can occur on the outside of the pipe where the system is exposed to road salt deposits. Hot-salt corrosion failures can occur as intergranular oxidation, chloride stress-corrosion cracking, general corrosion, and oxidation. Certain nickel alloys have shown good to excellent resistance to

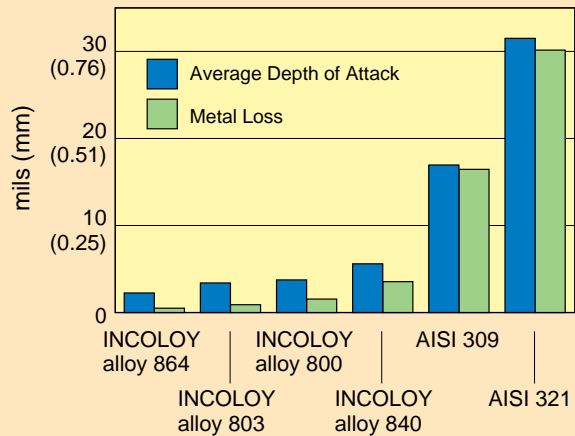
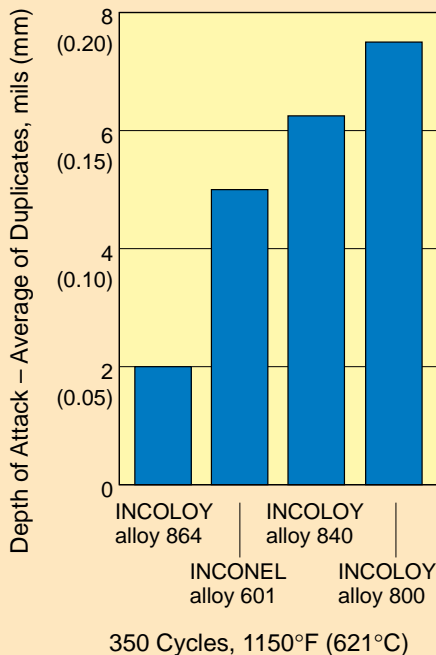


Figure 9 – Metal loss in burner rig samples at 950°C (1742°F) in JP-4 fuel (no salt). Exposed for 500 h.



hot-salt corrosion, as illustrated in Fig. 10. In particular, INCOLOY alloy 864 has been designed with a balance of elements (Ni, Cr, Mo, Si, Ti) to provide excellent resistance to hot-salt corrosion for road-salt vulnerable exhaust system applications.

When considering the selection of an alloy for a high-performance exhaust system application, the automotive engineer is concerned about the formability and fabricability of alloys which must be manufactured cost-effectively into intricate shapes in high volume. The INCOLOY and INCONEL alloys exhibit very good fabricability and can be hydroformed and stamped and then joined successfully by most welding techniques. In addition to the room temperature mechanical properties for these alloys (Table 4), the springback calculations in Fig. 11 demonstrate typical behavior of the Inco Alloys International high-performance, exhaust system alloys.

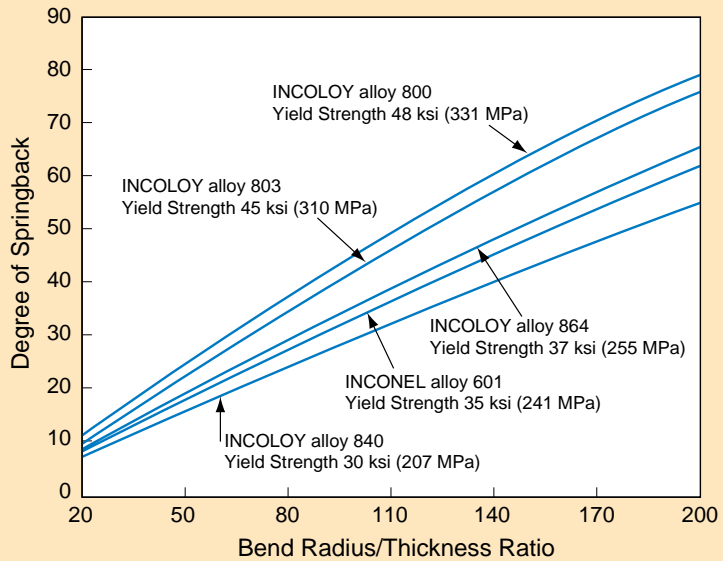


Figure 11 – Springback calculation based on Kock's work hardening model (90° bend).

Figure 10 – Hot-salt corrosion test results. (15 min heating/5 min cooling, 7.5% NaCl + 2.5% CaCl<sub>2</sub>, dip daily)

# Exhaust Systems

## Catalytic Converters

Alloy	Nominal Composition, % wt.					Designations	Specifications
	Ni	Cr	Fe	Al	Others		
INCONEL alloy 601	60.5	23.0	14.1	1.4	—	UNS N06601 Werkstoff Nr. 2.4851	ASTM B 166
INCONEL alloy X-750	73.0	15.5	7.0	0.7	Ti 2.5, Nb 1.0	UNS N07750 Werkstoff Nr. 2.4669	SAE AMS 5698 and 5699

At the heart of gasoline engine emissions control is the catalytic converter, mounted in the exhaust system close to the manifold. The converter must withstand the high-temperature corrosion of combustion products as well as oxidation in air, and resist thermal and mechanical fatigue at temperatures to 900°C (1652°F) or higher. One of the critical components of the ceramic monolith type converter is the wire mesh support system. INCONEL alloy 601 and age-hardenable INCONEL alloy X-750 are used for the knitted wire mesh because of their excellent high-temperature mechanical properties, resistance to hot-corrosion, and good fabricability.



Applications for INCONEL alloy 601 wire products in ceramic monolith catalytic converters. These support wraps, gas seals, pipe spacer mesh, and gas separation rings are made by Catalytic Support Systems Ltd., Warrington, U.K., who are supplying critical exhaust system components to vehicle builders throughout Europe.

Alloy	At Room Temperature		At 1300°F (704°C)	
	1000 psi	MPa	1000 psi	MPa
INCONEL alloy 601	66	455	40	276
INCONEL alloy X-750	122	841	100	689
AISI 309	45	310	22	151

# Exhaust Systems

## High-Temperature Fasteners

Alloy	Nominal Composition, % wt.				Designations	Specifications
	Ni	Fe	Cr	Others		
INCOLOY alloy A-286	25.5	56.5	15.0	Ti 2.1, Mo 1.3	UNS S66286 Werkstoff Nr. 1.4980	ASTM A453 SAE AMS 5731, 5732, 5734, 5737
NIMONIC alloy 80A	76.0	—	19.5	Ti 2.4, Al 1.4	UNS N07080 Werkstoff Nr. 2.4952	ASTM B 637
INCONEL alloy 718	54.0	18.5	18.0	Nb 5.0, Mo 3.0, Ti 0.9, Al 0.5	UNS N07718 Werkstoff Nr. 2.4668	ASTM B 637 SAE AMS 5662, 5663, 5664, 5832

The high-temperature strength and excellent fabricability of INCOLOY alloy A-286 make the alloy useful for fastener applications in engine and manifold components subjected to high heat and stress. INCOLOY alloy A-286 is an economical alloy which provides excellent properties in the age-hardened condition. More highly alloyed, age-hardenable NIMONIC alloy 80A offers even higher stress-rupture strength for critical automotive fasteners, and superalloy INCONEL alloy 718 provides exceptional properties at 1200°F (649°C). All three alloys are readily hot and cold formed.



These high-strength fasteners have been manufactured from INCOLOY alloy A-286 for demanding automotive applications.



High-temperature fasteners for automotive engineering. (KAMAX-Werke Rudolf Kellermann GmbH & Co. KG, Germany)

Alloy	Yield Strength (0.2% Offset)				Stress to Produce Rupture in 1000 h at 1200°F (649°C)	
	Room Temperature		1200°F (649°C)			
	1000 psi	MPa	1000 psi	MPa	1000 psi	MPa
INCOLOY alloy A-286	105	725	88	605	46	315
NIMONIC alloy 80A	90	620	80	550	61	420
INCONEL alloy 718	163	1,125	140	965	86	595

# Exhaust Systems

## Welding Products

Alloy	Nominal Composition, % wt.				Designations
	Ni	Fe	Mn	Others	
NI-ROD 44 filler metal	44.0	45.0	11.0	C 0.3	UNS N02216
NI-ROD 44HT	44.0	36.0	11.0	Cr 8.0, Nb 1.0	—

The manufacture and assembly of automotive exhaust systems require welded combinations of different cast and wrought alloy compositions and structures.

NI-ROD 44 filler metal and NI-ROD 44HT are strategic compositions specially formulated for welding oxidation- and carburization-resistant ductile iron castings. They have excellent weldability, strength, and good coefficient of thermal expansion (CTE) matches with both ductile irons and the AISI 400 stainless steels.

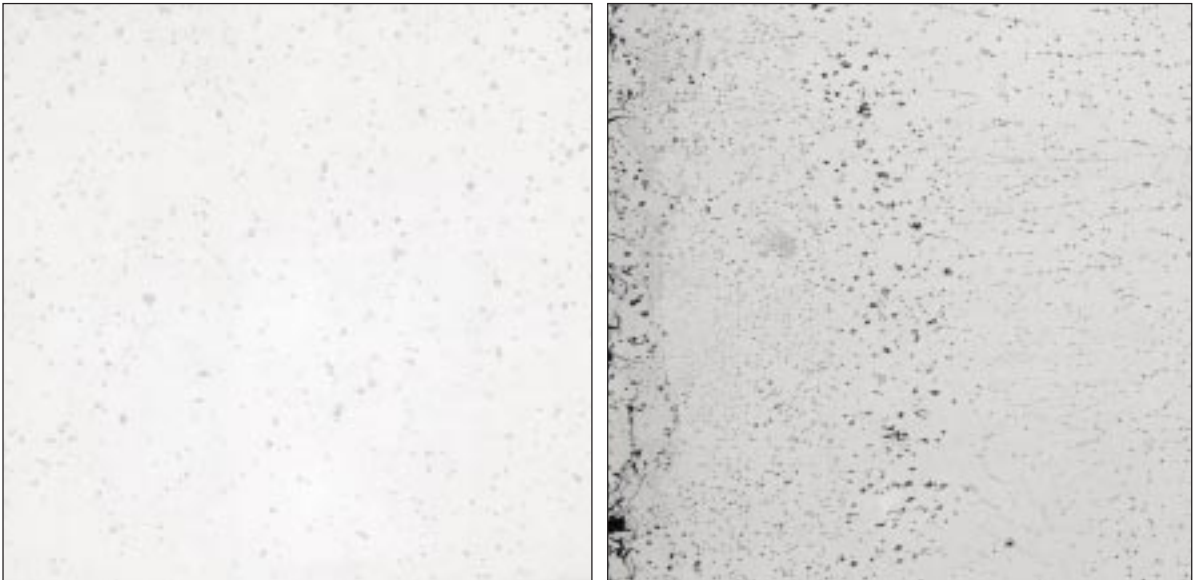
NI-ROD 44 filler metal was one of the first welding products used for joining ductile iron in automotive applications. As operating temperatures rose, Special Metals recognized the need for a product with greater oxidation-resistance and metallurgical stability against graphitization. NI-ROD 44HT (“HT” for high temperature), a developmental alloy, was patented in 1995 for this precise purpose.

Figure 12 shows the difference between a deposit made with NI-ROD 44HT and one made with a competitive product. Note the absence of graphite in NI-ROD 44HT versus its widespread occurrence in the other weld. Graphite greatly reduces strength and ductility in nickel alloy weld metals used in high-temperature exhaust components.

NI-ROD 44 filler metal is available only through Special Metals Corporation Welding Products Company. Further information regarding NI-ROD 44HT and its commercial availability can be obtained from our offices in the USA and Europe.

Alloy	Tensile Strength		Elongation
	1000 psi	MPa	%
NI-ROD 44 filler metal	100	690	30

Figure 12 – After 1272 hours at 1300°F (704°C), NI-ROD 44HT, on the left, shows absence of graphite compared with its presence in the competitive product weld, on the right.

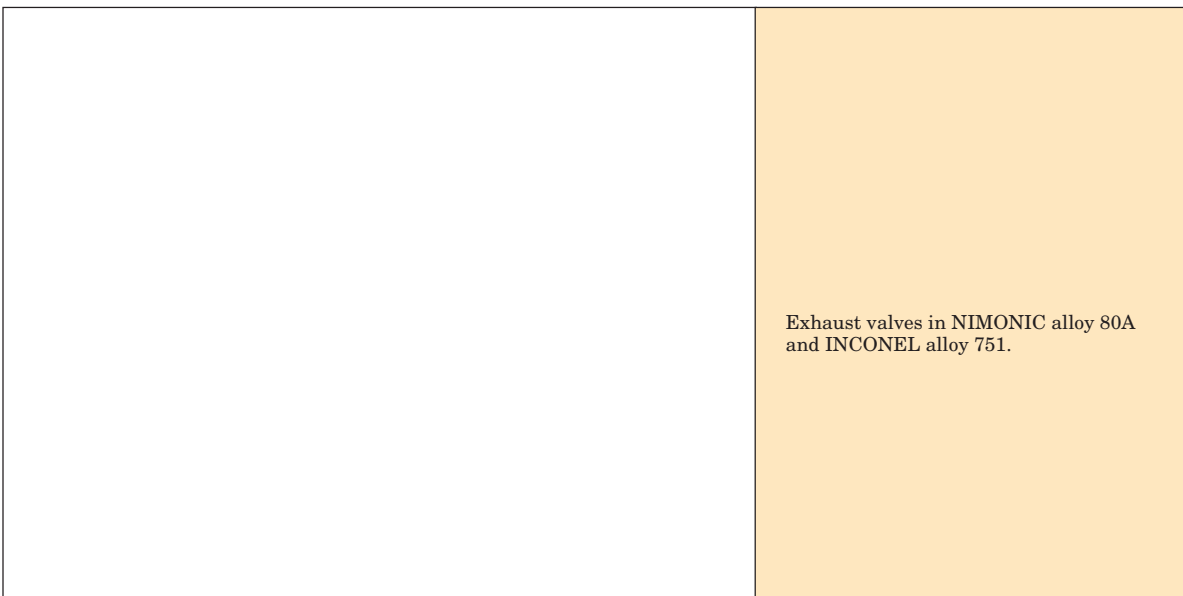


# Exhaust Valves

Alloy	Nominal Composition, % wt.				Designations	Specifications
	Ni	Cr	Fe	Others		
<b>INCONEL alloy 751</b>	73.0	15.0	7.0	Ti 2.5, Al 1.1, Nb 1.0	UNS N07751 Werkstoff Nr. 2.4669	—
<b>NIMONIC alloy 80A</b>	76.0	19.5	—	Ti 2.4, Al 1.4	UNS N07080 Werkstoff Nr. 2.4952	ASTM B 637
<b>NIMONIC alloy 81</b>	67.0	30.0	—	Ti 1.8, Al 0.9	—	—
<b>NIMONIC alloy 90</b>	60.0	19.5	—	Co 16.5, Ti 2.5, Al 1.5	UNS N07090 Werkstoff Nr. 2.4632	—

High-performance diesel and gasoline engines, operating at high temperatures and high exhaust gas pressures, require exhaust valve alloys with excellent hot strength and hardness, and good hot corrosion- and wear-resistance. Under these conditions, traditional valve steels are inadequate and valve

designers turn to INCONEL alloy 751 and NIMONIC alloys 80A, 81 and 90. These age-hardenable nickel alloys develop exceptional properties and are readily forged into exhaust valves for the most demanding service conditions.



Alloy	Yield Strength, 0.2% Offset		Stress to Produce Rupture in 1000 h	
	1000 psi	MPa	1000 psi	MPa
<b>INCONEL alloy 751</b>	129	889	40	276
<b>NIMONIC alloy 80A</b>	80	550	61	420
<b>NIMONIC alloy 81</b>	72	495	53	365
<b>NIMONIC alloy 90</b>	99	685	66	455
<b>21-4 N Valve Steel*</b>	48	330	30	207

\* not age-hardened

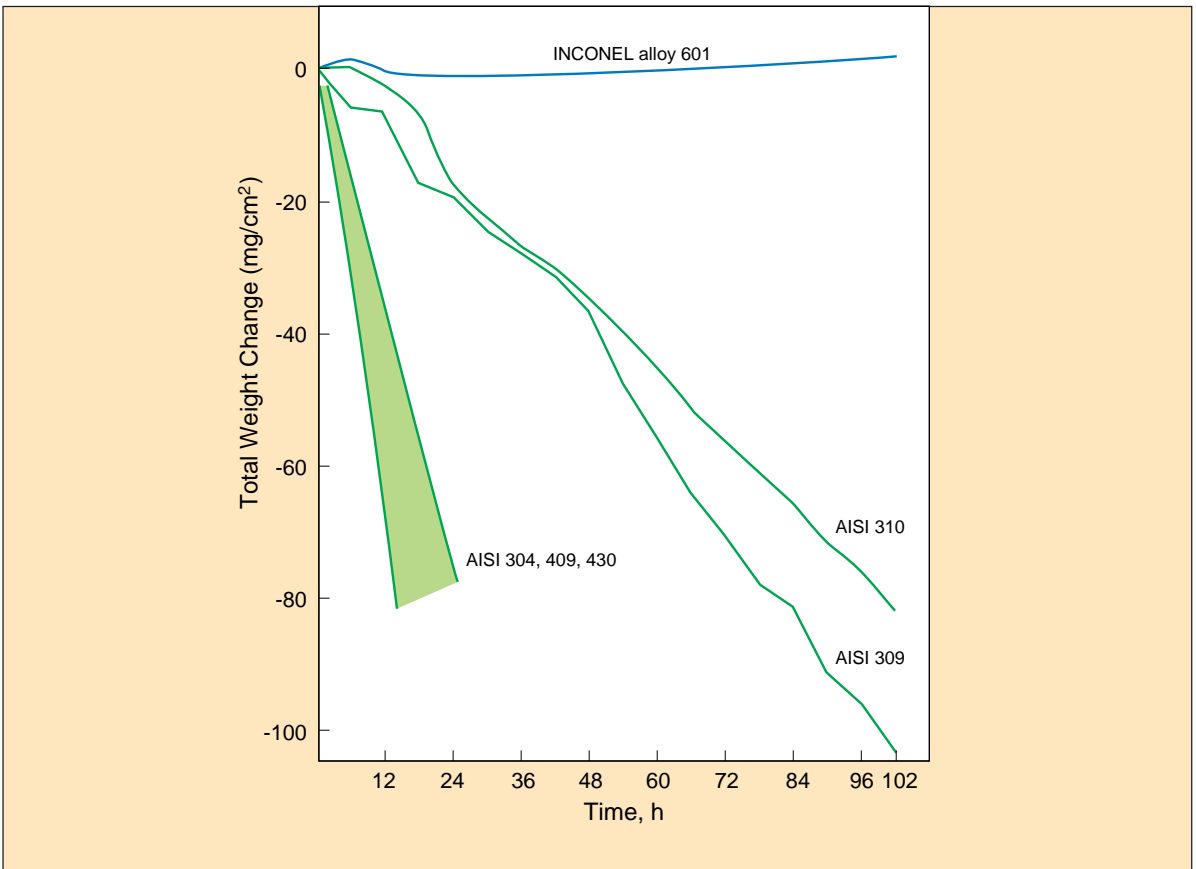
# Sensors for Fuel Level and Oxygen Control

Alloy	Nominal Composition, % wt.				Designations	Specifications
	Ni	Cr	Fe	Al		
Nickel 200	99.6	—	—	—	UNS N02200 Werkstoff Nr. 2.4060/66	ASTM B 162
INCONEL alloy 601	60.5	23.0	14.1	1.4	UNS N06601 Werkstoff Nr. 2.4851	ASTM B 168 SAE AMS 5870

Commercially pure wrought nickel (Nickel 200) is used for spring trailing contacts in fuel sensors, selected for its resistance to corrosion, its spring properties, and its amenability to the high-pressure forming operation in which the contacts are pressed from strip.

INCONEL alloy 601 is often used for the protective shield in oxygen sensors, which helps assure emissions performance. Dependable, long life in these high-temperature components is essential. The protective shield of the oxygen sensor is subjected to very hot engine exhaust which can degrade the shield material by oxidation and carburization. INCONEL alloy 601 was designed to resist these forms of high-temperature corrosion by forming an adherent scale which protects underlying metal from progressive attack. It is one of the most oxidation-resistant alloys available to the automotive industry, and can be readily cold formed.

**Figure 13 – Cyclic corrosion behavior of INCONEL alloy 601 and stainless steels in gasoline engine exhaust at 1800°F (982°C) cycled every six hours. Weight loss indicates spalling of protective scale.**





Fuel level sensors made by Scandmec AB, Sweden. The spring trailing contacts are pressed from Nickel 200 pure nickel strip.

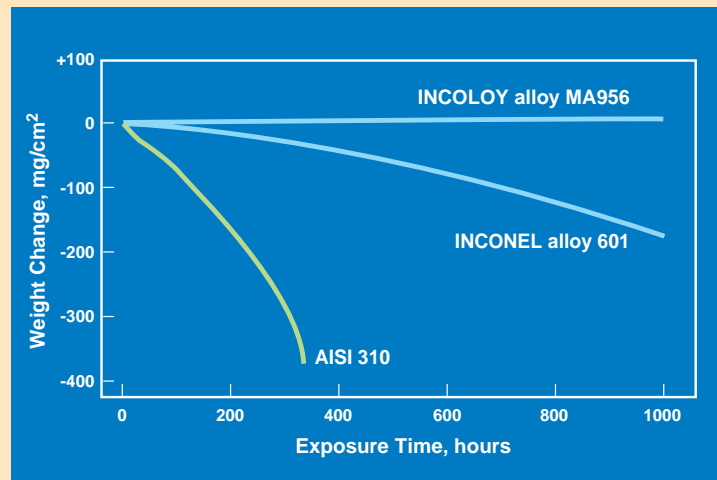
# Compression Ignition (Diesel) Engines

Alloy	Nominal Composition, % wt.					Designations	Specifications
	Ni	Fe	Cr	Al	Others		
INCOLOY alloy MA956	—	74.0	20.0	4.5	Ti 0.5, Y <sub>2</sub> O <sub>3</sub> 0.5	UNS S67956	—
INCONEL alloy 601	60.5	14.1	23.0	1.4	—	UNS N06601 Werkstoff Nr. 2.4851	ASTM B 166 SAE AMS 5870

Compression ignition, or diesel, engines place special high-performance demands on components in the fuel injection and ignition systems. Two Special Metals products, INCOLOY alloy MA956 and INCONEL alloy 601, are used in diesel engines. INCOLOY alloy MA956 is an oxide-dispersion-strengthened iron-chromium-aluminum superalloy with outstanding hot strength. INCONEL alloy 601 is a nickel-iron-chromium alloy with good hot strength and excellent fabricability. Both alloys exhibit exceptional oxidation- and scaling-resistance at extremely high operating temperatures.

Compression ignition (diesel) engines employ glow plugs which have an electric heating element protected by a tubular sheath deep drawn from nickel-chromium-iron alloy strip. Glow plugs must operate at temperatures often exceeding 1100°C (2012°F) in a corrosive combustion environment. INCONEL alloy 601 is specified for the sheathing due to the alloy's exceptional oxidation-resistance at very high temperatures, coupled with good fabricability.

Figure 14 – Comparative cyclic oxidation-resistance of INCOLOY alloy MA956, INCONEL alloy 601 and AISI 310 at 1200°C (2192°F). The cycle was 20 minutes heating/10 minutes cooling.



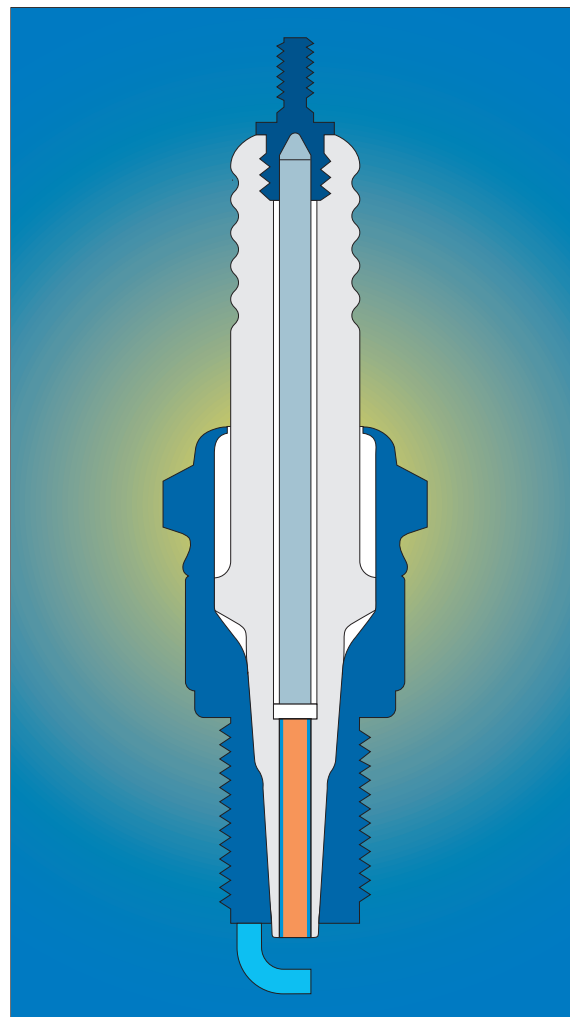
INCOLOY alloy MA956 having been used in diesel engine applications for many years, has been specified for an advanced, cleaner combustion engine that relies on an atomizing pin, machined from INCOLOY alloy MA956, to distribute the fuel evenly within the pre-combustion chamber. The engine achieves cleaner combustion by initiating burn before the fuel enters the main chamber, minimizing the emission of carbon particles. The pin is machined from 8.2 mm (0.3 in) diameter alloy wire to form an elliptical shape, complete with retaining head.

# Ignition Components

Automotive Spark Plug Alloys*								
Alloy	Nominal Composition, % wt.						Designations	Specifications
	Ni	Cr	Mn	Si	C	Others		
Nickel 240	94.8	1.8	1.95	0.45	0.05	Ti 0.3, Zr 0.15	—	—
Nickel 243	96.2	1.6	1.6	0.55	0.05	—	—	—
INCONEL alloy 600SP	76.8	14.6	0.3	0.4	0.02	Fe 7.6, Al 0.065, Ti 0.061, Zr 0.01	UNS N06600 Werkstoff Nr. 2.4816	ASTM B 166 SAE AMS 5687

\* Other compositions available on request.

The unique characteristics of nickel alloys make them ideal for several applications in automotive engine ignition systems. There are several carefully crafted compositions utilized in spark plugs for gasoline engines. These provide a balance of properties, including thermal conductivity, electrical conductivity, and resistance to spark erosion and corrosion. A conventional spark plug design may have a round center electrode of solid nickel alloy or a nickel-chromium outer sheath and a copper alloy inner core. The outer sheath must resist the corrosive gases from combustion, and the inner core must have good thermal conductivity to dissipate heat. The rectangular/rhomboidal ground electrode typically is also a nickel-chromium alloy. Operating temperatures range from 400°C (752°F) to 900°C (1652°F). Spark plug alloys must perform well for many years in long-life designs of higher output engines.

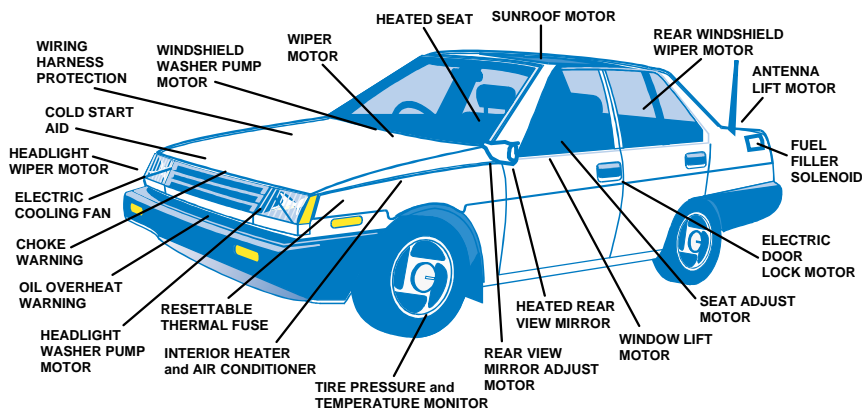


A typical spark plug design where the round center electrode would have a nickel alloy inner core or a nickel-chromium outer layer and a copper alloy inner core, and the rectangular/rhomboidal section ground electrode is in nickel-chromium alloy. Operating temperatures are typically 400 to 900°C (752 to 1652°F).

# Electrical and Electronic System Components

Alloy	Nominal Composition, % wt.				Designations	Specifications
	Ni	Cu	Mn	Others		
Nickel 205	99.6	—	—	Mg 0.04	UNS N02205 Werkstoff Nr. 2.4061	ASTM F1 and F3 SAE AMS 5555
Nickel 211	95.0	—	4.75	—	UNS N02211	ASTM F290
MONEL alloy 400	65.1	32.0	1.1	Fe 1.6	UNS N04400 Werkstoff Nr. 2.4360	ASTM B 127 SAE AMS 4544, 4731
MONEL alloy 404	52.5	47.0	—	—	UNS N04404	ASTM F96
FERRY alloy	45.0	55.0	—	—	Werkstoff Nr. 2.0842	ASTM B 267

Several pure nickel grades and other nickel-copper and copper-nickel alloys are used in automotive electrical and electronic components because of their electrical and thermal properties. Examples of such applications include terminals, lead wires, connectors, diodes, resistors, thermostats, magnetostrictive devices and housings.



This outline sketch gives some indication of the locations in a typical automobile where nickel alloys could be used for electrical components.



FERRY copper-nickel alloy strip is used for the contacts of bi-metal, snap action switches from thermostats, circuit breakers, sensors and motor protectors to programmable electronic controllers.

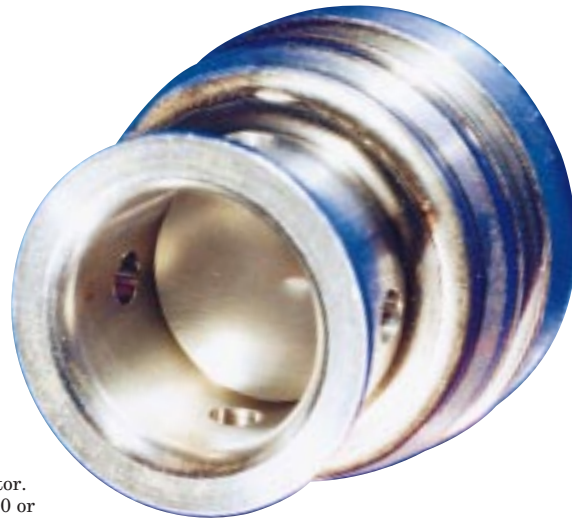
**Table 11 — Thermal and Electrical Properties at Room Temperature**

Alloy	Thermal Conductivity		Electrical Resistivity	
	Btu•in/ft <sup>2</sup> •h•°F	W/m•°C	ohm•circ mil/ft	μ Ω • m
Nickel 205	520	75.0	57	0.095
Nickel 211	306	44.2	102	0.170
MONEL alloy 400	151	21.8	329	0.547
MONEL alloy 404	146	21.1	300	0.500
FERRY alloy	155	22.4	295	0.490

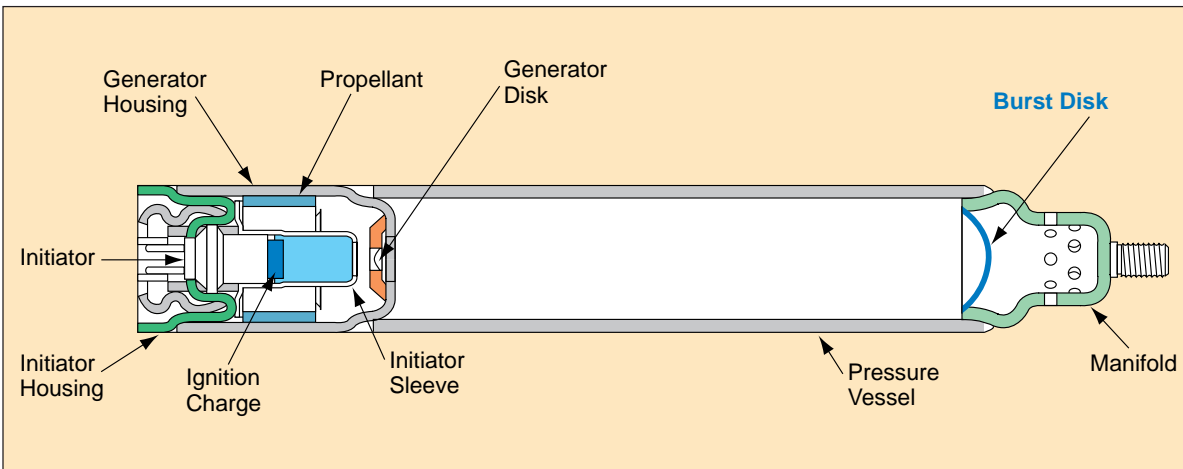
# Passenger Safety Systems – Air Bag Inflators

Alloy	Nominal Composition, % wt.				Designations	Specifications
	Ni	Cr	Fe	Others		
INCONEL alloy 600	76.0	15.0	8.0	—	UNS N06600 Werkstoff Nr. 2.4816	ASTM B 168 SAE AMS 5540
INCONEL alloy 625LCF	61.0	21.5	2.5	Mo 9.0, Nb 3.6	UNS N06626 Werkstoff Nr. 2.4856	ASTM B 443 SAE AMS 5599 and 5879

Supplemental restraint systems using airbags employ initiators which start the inflation process upon collision. A pyrotechnic gas generator inflates the airbag in milliseconds, and precise release of the gas (argon, helium, nitrogen) is critical. A key component in the initiator is the burst disk, which must hold high-pressure gas leak-tight for several years of driving time until it might be called upon in a collision, at which time the disk must “fail” dependably, within a wide range of vehicle exposure temperatures, in order to release the generator gas. Thin strip in INCONEL alloys 600 or 625LCF is used for the all-important burst disks due to the alloys’ excellent mechanical properties, corrosion resistance, fabricability, and weldability.



A burst disk assembly for an air bag initiator. The disks are made in INCONEL alloys 600 or 625LCF strip.



Alloy	Tensile Strength		Yield Strength		Elongation
	1000 psi	MPa	1000 psi	MPa	
INCONEL alloy 600	97	669	46	317	39
INCONEL alloy 625LCF	137	945	70	483	47

# Manufacturing Applications in the Automotive Industry

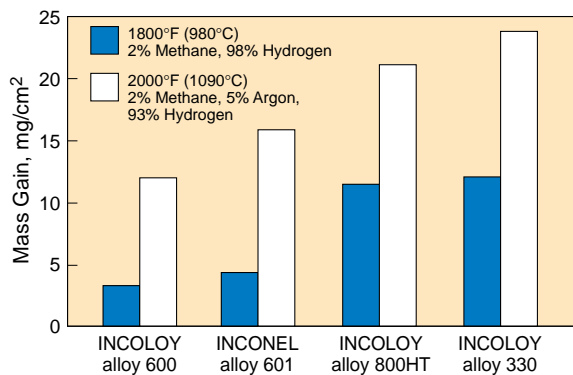
Alloy	Nominal Composition, % wt.				Designations	Specifications
	Ni	Cr	Fe	Others		
INCONEL alloy 600	76.0	15.5	8.0	—	UNS N06600 Werkstoff Nr. 2.4816	ASTM B166, B167, B168 SAE AMS 5540, 5665
INCONEL alloy 601	60.5	22.0	14.1	Al 1.4	UNS N06601 Werkstoff Nr. 2.4851	ASTM B166, B167, B168 SAE AMS 5715 and 5870
INCOLOY alloy 800HT	32.5	21.0	46.0	C 0.08, Al + Ti 1.0	UNS N08811 Werkstoff Nr. 1.4876	ASTM B407, B408, B409
INCOLOY alloy 803	35.0	25.0	36.0	Al 0.6, Ti 0.6, Si 0.6, Mn 0.9, C 0.09	UNS S35045	ASTM A240
INCOLOY alloy 330	35.5	18.5	44.0	Si 1.2	UNS N08330 Werkstoff Nr. 1.4864	ASTM B512, B536 SAE AMS 5592, 5716
NIMONIC alloy 75	80.0	19.5	—	—	UNS N06075 Werkstoff Nr. 2.4951	BS HR203, HR504

## Special Metals Corporation's High-Temperature Alloys Serve the Automotive Parts Industry in Heat Treating Equipment

Automotive parts manufacturing often requires metal components to be heat treated to develop intermediate or final properties. These high-temperature processes may include nitriding, carburizing, malleablizing, tempering, and annealing. The wrought or cast parts may be processed on wire belts or alloy trays, in corrugated boxes, welded baskets and fixtures, and in retort, muffle and radiant tube type furnaces. Several INCOLOY, INCONEL and NIMONIC alloys have the necessary hot strength, thermal fatigue-resistance, and resistance to the furnace atmospheres to be preferred worldwide in heat treating equipment in the automotive parts industry.



Figure 15 – Resistance to gas carburization at 1800°F (980°C) and 2000°F (1090°C). Test duration of 100 h.



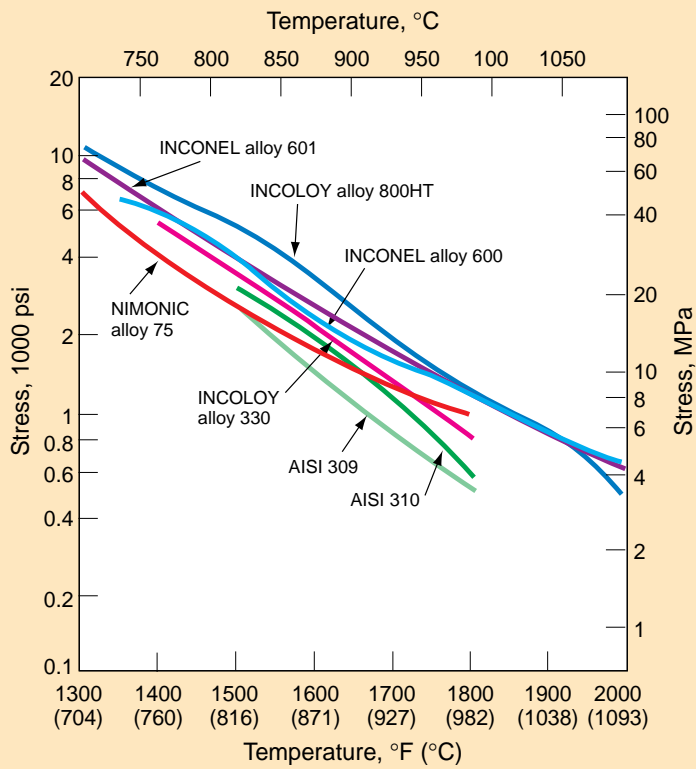


Figure 16 – 10,000-hour rupture strength of candidate materials for thermal processing applications.

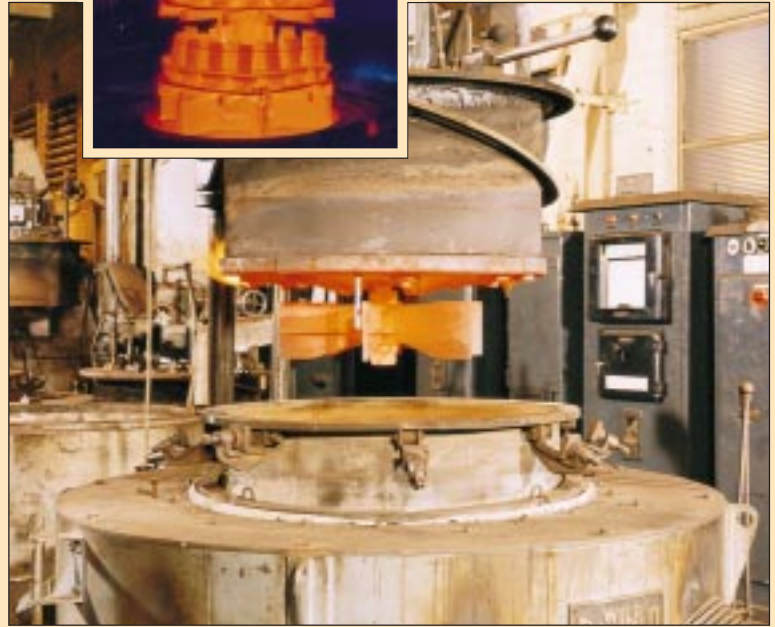


Table 13 — Yield Strength, 0.2% Offset

Alloy	70°F (20°C)		1600°F (871°C)	
	1000 psi	MPa	1000 psi	MPa
INCONEL alloy 600	35	241	9	62
INCONEL alloy 601	35	241	18	124
INCOLOY alloy 800HT	34	234	17	117
INCOLOY alloy 803	45	310	18	124
INCOLOY alloy 330	39	269	17	117
NIMONIC alloy 75	42	290	17	117



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