



SURFACE VEHICLE STANDARD

J2515™

DEC2017

Issued 1999-08
Stabilized 2017-12

Superseding J2515 AUG1999

High Temperature Materials for Exhaust Manifolds

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1. **Scope**—A subcommittee within SAE ISTC Division 35 has written this report to provide automotive engineers and designers a basic understanding of the design considerations and high temperature material availability for exhaust manifold use. It is hoped that it will constitute a concise reference of the important characteristics of selected cast and wrought ferrous materials available for this application, as well as methods employed for manufacturing. The different types of manifolds used in current engine designs are discussed, along with their range of applicability. Finally, a general description of mechanical, chemical, and thermophysical properties of commonly-used alloys is provided, along with discussions on the importance of such properties.
- 1.1 **Background**—Figure 1 provides a diagram of a typical fabricated exhaust manifold, in this case for one side of an eight-cylinder engine. Cast versions are similar in geometry. In simple terms, it provides a means of containing exhaust gases generated from each cylinder within the engine block, combining the volume, and passing the gas on to the catalytic converter.

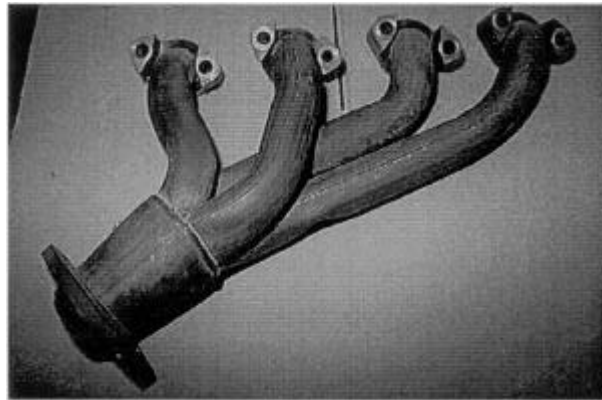


FIGURE 1—FABRICATED MANIFOLD

Operating demands on exhaust manifolds, as with many other elevated temperature engine components, have increased significantly over the past decade. There are numerous reasons why this has occurred, including the usually-cited reasons of tighter emissions requirements, improved fuel efficiencies, and design toward higher specific engine power (kW/kg), with a cumulative end-effect yielding higher exhaust gas temperatures. Techniques used to meet emissions requirements, such as the addition of air injection systems and the use of controlled variations in air-fuel ratios, have changed overall hydrocarbon levels, and, under certain conditions, have increased the emissivity of the exhaust gas, further raising the manifold inner wall temperature. This has led to much higher elevated temperature strength, creep, and fatigue demands on

exhaust manifold alloys. Radioactive heat shields that are now used to protect underhood electronics from high temperatures further exacerbate the issue by reflecting otherwise lost heat back on to the manifold.

Such thermal demands lead to reduced alloy strength simply from the higher temperatures, but perhaps more importantly higher internal stresses can also develop from the higher thermal gradients via thermal expansion mismatch considerations in the cylinder head - manifold interface. The cumulative effect then becomes higher temperatures in combination with higher cyclic stresses. Thermal fatigue, a condition in which time-dependent stress variations occur directly as a result of thermal expansion mismatch and mechanical constraint, becomes an important issue. Distortion, gas blow-by, and cracking of metal components result. To avoid such problems, designers have had to examine stronger alloys and employ alternate mechanical designs.

2. References

2.1 Applicable Publications—The following publications form a part of this specification to the extent specified herein.

Charles F. Walton, *Iron Casting Handbook*, Iron Casting Society, 1981
Stephen I. Karsay, *Ductile Iron I Production*, QIT – Fer et Titane, Inc., 1992
Michael F. Burditt, *Ductile Iron Handbook*, American Foundrymen's Society, Inc., 1992

3. Alloy Classes and General Properties—Before manifold design and use can be discussed in any detail, it is necessary to review some of the more basic issues regarding the material classes that are used to make them.

3.1 Cast Iron—Discussion of cast iron metallurgy will be brief, as excellent references are readily available.^{1,2,3} In very basic terms, cast irons are comprised of iron and large amounts (>1% by weight) of carbon (C), and contain two primary microstructural components, a free graphite phase and the surrounding matrix. "Gray" and "Ductile" iron, two of the most common types of cast iron in general, and certainly the most typical for exhaust manifolds, differ in the form of their free graphite. In gray cast iron, graphite is present in the form of clusters of thin, two-dimensional flakes, while in ductile (nodular) iron it is in the form of spheres, or nodules. A cast iron matrix can be ferritic, pearlitic, some combination of ferrite and pearlite, or, with addition of suitable amounts of austenitizing elements, entirely austenitic. Austenitic matrix irons are also known as Ni-Resist. The matrix of a cast iron can be varied independently of the graphite form, so both gray and ductile irons can be ferritic, pearlitic, or austenitic. The different graphite forms and matrix microstructures are created by using special alloying additions and inoculation practices. Silicon (Si) and carbon provide the primary influence on graphite type and amount. The combination of graphite form and matrix microstructure give each type of cast iron its characteristic mechanical and physical properties. For instance, flake graphite alloys (gray iron) typically exhibit the lowest toughness and resistance to crack growth of all the cast irons, but they are also the least expensive to make, and the graphite flakes very effectively dampen sound and conduct heat well. Nodular, or ductile irons exhibit better toughness, will conduct heat more sluggishly, and are more expensive to produce.

Tables 1 to 3 provide a summary of important properties associated with nodular cast irons used in manifold production. Gray iron properties are not included since they are not of current interest.

1. Charles F. Walton, *Iron Castings Handbook*, Iron Casting Society, 1981
2. Stephen I. Karsay, *Ductile Iron I Production*, QIT - Fer et Titane Inc., 1992
3. Michael F. Burditt, *Ductile Iron Handbook*, American Foundrymen's Society Inc., 1992

TABLE 1—COMPOSITIONAL AND MICROSTRUCTURAL CHARACTERISTICS OF DUCTILE CAST IRON

	Ferritic Ductile	Si-Mo Ductile Grade A⁽¹⁾	Si-Mo Ductile Grade B⁽¹⁾	Si-Mo Ductile Grade C⁽¹⁾
Carbon	3.80%	3.45%	3.45%	3.45%
Silicon	2.70-3.00%	4.00%	4.00%	4.00%
Sulfur	<0.015%	<0.02%	<0.02%	<0.02%
Magnesium	0.020% min	0.020% min	0.020% min	0.020% min
Molybdenum	N/A	0.80-1.0%	0.50-0.70%	0.40-0.60%
Copper	<0.10%	<0.10%	<0.10%	<0.10%
Manganese	0.20-0.40%	0.20-0.40%	0.20-0.40%	0.20-0.40%
Phosphorus	<0.04%	<0.04%	<0.04%	<0.04%
Chromium	0.10% max	0.10% max	0.10% max	0.10% max
Nickel	<0.10%	<0.10%	<0.10%	<0.10%
Ferrite	Balance	Balance	Balance	Balance
Pearlite ⁽²⁾⁽³⁾	10-15%	10-15%	10-15%	10-15%
Carbides	0-1%	2-3%	1-2%	0-1%
Graphite Nodularity	95% +	95% +	95% +	95% +

1. Difference in grades is primarily in the Molybdenum content.
2. Amounts vary depending on section size and presence of heat treating (process dependent), or as required by customer.
3. Area percent of matrix excluding graphite area; total matrix constituents = 100%, excluding graphite.

TABLE 2—ELEVATED TEMPERATURE MECHANICAL PROPERTIES OF DUCTILE CAST IRON

	Ferritic Ductile	Si-Mo Ductile Grade A (0.8-1.0% Mo)	Si-Mo Ductile Grade B (0.6-0.8% Mo)	Si-Mo Ductile Grade C (0.4-0.6% Mo)
Elongation	16-20%	10-14%	12-16%	14-18%
Tensile Strength	MPa	MPa	MPa	MPa
22 °C (72 °F)	565	601	592	588
316 °C (600 °F)	490	535	524	518
427 °C (800 °F)	386	414	407	404
538 °C (1000 °F)	248	293	282	276
649 °C (1200 °F)	90	123	115	111
704 °C (1300 °F)	61	83	78	75
Yield Strength	MPa	MPa	MPa	MPa
22 °C (72 °F)	331-365	468	462	459
316 °C (600 °F)		409	404	401
427 °C (800 °F)		379	370	366
538 °C (1000 °F)		263	253	249
649 °C (1200 °F)		92	83	79
704 °C (1300 °F)		71	66	63
Elongation				
22 °C (72 °F)	16-20%	8-12%	10-13%	11-14%
Compressive Strength (MPa)	234	356	354	353
Modulus Elasticity	170 GPa	145-170 GPa	145-170 GPa	145-170 GPa

TABLE 3—PHYSICAL PROPERTIES OF DUCTILE CAST IRON

	Ferritic Ductile	Si-Mo Ductile Grade A	Si-Mo Ductile Grade B	Si-Mo Ductile Grade C
Thermal Conductivity (W/K x cm)				
20 °C	0.33	N/A	N/A	N/A
100 °C	0.40	0.25	0.25	0.25
400 °C	0.33	0.27	0.27	0.27
1000 °C	0.24	0.25	0.25	0.25
Coefficient of Thermal Expansion Temp (°C)	x10 ⁻⁶ /°C			
20-100	11.2			
20-200	12.2			
20-300	12.8			
20-400	13.1			
20-500	13.5			
20-600	13.7			
20-760	14.8			
20-871	15.3			
Density (at 20 °C)	6.9 g/cc	6.9 g/cc	6.9 g/cc	6.9 g/cc
DBTT ⁽¹⁾ Charpy Impact Properties	At 22 °C notched 13.5–19.0 j	N/A	N/A	N/A
Notched: –10 °C to –65 °C as tensile increases	notched, ductile fracture: 16.3–21.7 j			
	un-notched, ductile fracture: 94.9–135.6 j			
Un-notched: –60 °C to –10 °C as tensile increases	un-notched, brittle fracture: 2.7–4.0 j			
Creep Strength Temp °C	MPa @ 0.0001%/h rate	N/A	N/A	N/A
427	96.5			
538	27.7			
649	3.09			
Hardness (HB)	143–217	192	192	192
Fatigue Strength Endurance Limit				
Un-notched	193 MPa	N/A	N/A	N/A
V-notched	117 MPa	N/A	N/A	N/A
Poisson's ratio	0.28	0.28	0.28	0.28

1. Ductile to Brittle Transition Temperature

3.2 Stainless Steel—Stainless Steels are selected for elevated temperature applications because of their excellent strength and resistance to oxidation and corrosion. Both cast and wrought versions are available. Additions of Chromium (Cr) to iron in amounts greater than approximately 12% will result in an alloy that will naturally form on its surface a tenacious chrome oxide passive film (chromia, Cr_2O_3). This film tightly adheres to the base alloy (in contrast to “red rust” on carbon steel which easily cracks and spalls) and protects the underlying metal from further oxidation at high temperature, or corrosion from other factors such as sulfur-bearing gases or chloride containing aqueous solutions.

Iron with the addition of 11% to 30% Cr comprises a host of ferritic stainless steels. These alloys are primarily characterized as having a BCC structure, are ferromagnetic, and are less expensive than their austenitic counterparts. High temperature oxidation resistance tends to be very good to excellent, partly because the thermal expansion coefficient of the alloys and chromia are similar, limiting scaling of the chromia during cyclic thermal conditions. While considering the ferritics for welded fabrications, it is important to maintain extremely low levels of carbon and nitrogen so that matrix chromium levels are not depleted by the formation of chromium carbonitrides. Improved weldability, formability, and corrosion resistance will result when these interstitial elements are controlled to low levels. Ferritic stainless steels are preferred in fabricated exhaust systems due to their cost advantage over the nickel (Ni) containing austenitics. Another important advantage is the low coefficient of thermal expansion (~40% less than austenitics) which minimizes stresses generated from thermal growth at operating temperatures.

Nickel, when added to stainless steels in percentages ranging from 6% to as high as 35%, will lead to an FCC or austenitic structure at room temperature. These austenitic stainless steels typically possess much better deep drawability, weldability, and elevated temperature strength than the ferritic grades. The austenitic alloys with moderate additions of other refractory elements, e.g., Molybdenum (Mo), Niobium (Nb), Titanium (Ti), exhibit even better corrosion resistance and further enhanced elevated temperature properties. Austenitic stainless steels exhibit superior elevated thermal mechanical properties in comparison to ferritic, pearlitic, and martensitic cast irons, as well as ferritic stainless steels.

Both ferritic and austenitic stainless steels are susceptible to the formation of internal chromium rich carbides at high temperature by a reaction between the chromium and carbon/nitrogen in the alloy. This is otherwise known as sensitization. Sensitization can lead to severely reduced corrosion resistance, because the local concentration of chromium near these carbide particles can be reduced to well below the nominal alloy level. If time and temperature are insufficient to allow back diffusion (or “healing”) into the area near the carbides, chromium-depleted regions will exist adjacent to the carbide network. If the network is continuous, a path of lower corrosion resistance will exist through the material. Sensitization can also lead to reduced strength and fracture resistance, particularly with the ferritic stainless grades. A common means of mitigating sensitization is by employing “stabilization” of the base alloy. This term refers to the addition of small levels of refractory elements, that are more reactive with carbon and nitrogen than chromium, e.g., Ti and Nb, to tie up the interstitial carbon/nitrogen, thus preventing further reaction with Cr. Thus, the chromium carbide formation that could occur during high temperature exposure is minimized. This is the primary method used to address the sensitization of ferritic stainless steels which are put into service in the as-welded condition.

The temperature ranges in which austenitic alloys become susceptible to sensitization are different than the ferritic counterparts. In the as-welded form, corrosion resistance in austenitics can be achieved through the use of low carbon chemistries (e.g., 304L) or by stabilization (e.g., 321 or 347). Applications in which austenitic stainless steels are put into service at sensitization temperatures require additional consideration.

Physical, chemical, and mechanical properties of some of the more commonly-used wrought stainless steels are shown in Tables 4 to 6. Additional elevated temperature properties are listed in Table 7.