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Supply chain readiness for HAYNES® nickel-based alloys in sCO2 applications

Brett M. Tossey
Emerging Markets Market Manager
Haynes International, Inc.
Kokomo, Indiana

Brett Tossey is a metallurgist at Haynes International, Inc. He has over 20 years of experience in high temperature alloy applications and environmental degradation, corrosion, electrochemistry, and failure analysis. He holds a M.S. in MSE from The Ohio State University.

ABSTRACT

Structural components in high temperature supercritical carbon dioxide and other emerging power generation and energy markets, such as advanced nuclear and ammonia production, require high resistance to creep and environmental degradation. Perhaps equally important, alloy products need to be commercially available and have representation in various codes and specifications. This paper discusses practical examples of wrought, extruded, and additively manufactured products and components that can be used for high temperature service in supercritical carbon dioxide. Alloy properties for wrought, welded, and additively manufactured products are presented and discussed. The data presented were generated on alloy specimens and components in air, air + water, and supercritical carbon dioxide and include HAYNES® 282®, HAYNES® 230®, and HAYNES® 233® alloys. 282 alloy is a classical gamma-prime strengthened superalloy. 233 alloy was originally developed as a solid-solution strengthened alloy but may also be strengthened by gamma-prime precipitation at intermediate temperatures. 230 alloy is a legacy solid solution strengthened alloy.

INTRODUCTION

The alloys discussed in this paper are used to fabricate structural components in high temperature, high pressure equipment. The applications of interest are in the power generation markets and the most common products supplied by Haynes International, Inc. (Haynes) are sheet, plate, wire, powder, and tubular products. Ingot, billet, slabs, and bar are also manufactured by Haynes. Plate and sheet are used to build heat exchanger shells, large diameter cylinders, and large welded fittings. Tubular products are often used in heat exchangers and power piping. Wire is used to join the alloys to themselves and adjoining dissimilar alloys. Powder and wire are used for additive manufacturing components such as heat exchangers, flanges, fittings, nozzles, adapters, and many other items.

The nominal compositions [1-3] of HAYNES® 233® alloy (UNS number forthcoming), HAYNES® 282® alloy (UNS N07208), and HAYNES® 230® alloy (UNS N06230) are in Table 1.

Table 1: Nominal composition (wt. %) of 233, 282, and 230 alloys.

Alloy	Ni	Co	Fe	Cr	Mo	W	Mn	Si	Al	Ti	C	Others
233	bal.	19	1.5*	19	7.5	0.3*	0.4*	0.20*	3.3	0.5	0.1	Ta-0.5, Y-0.025*
282	bal.	10	1.5*	20	8.5	–	0.3*	0.15*	1.5	2.1	0.06	–
230	bal.	5*	3*	22	2	14	0.5	0.4	0.3	0.1*	0.1	La-0.02

* maximum

230 alloy is included here to contrast its metallurgy, properties, and primary manufacturing processes against 282 and 233 alloys. 230 is a chromia-forming alloy [4] whose primary metal manufacturing process begins with air melting in an electric arc furnace (EAF) followed by argon oxygen decarburization (AOD). A typical Haynes' EAF-AOD heat is approximately 40,000 lbs. 282 and 233 alloys contain aluminum and titanium, which demands they are melted in a vacuum induction furnace (VIM). The maximum weight of a Haynes VIM heat of these alloys is 25,000 lbs. and expansion of this capacity is planned to increase to 75,000 lbs. (i.e. a 50,000-lb capacity second VIM furnace) by 2029 via an additional VIM furnace at Haynes primary production facility in Kokomo, Indiana. The products of EAF + AOD and VIM primary melting are cast electrodes that are remelted in the as-cast condition using electric slag reduction (ESR) remelting. The products of the ESR process are round and slab ingots that are homogenized by heat treatment and then further hot worked into various product forms. Maximum ingot weights range from 10,000 lbs. up to 13,000 lbs. per ingot depending on the alloy. Future capital investment at Haynes will allow melting and forging heavier and larger ingots to produce forgings that may weigh up to 15,000 lbs.

Round ingots continue through various manufacturing steps to make forged round and semi-round products, billet, bar, rod coil (wire-making feedstock), and tube hollows (tubular-making feedstock). Slab ingots are hot rolled into plate, sheet, coils, and foils. Both ingot shapes can also be forged to make heavy section components with the weight limitations mentioned prior.

The processes for making wrought products from the 282 and 230 alloys are well developed and have evolved over the past 20 and 40 years, respectively [5]. 233 alloy is a newer alloy; it was first introduced in 2017 and Haynes continues to produce new product forms as demanded by applications. Our key markets include emerging markets, high temperature chemical processing, aerospace, industrial gas turbines (IGT), and additive manufacturing. Aerospace and IGT markets dominate our annual mill production and, combined, account for 75% of our annual final product tonnage; about 20 million lbs.

WROUGHT PRODUCT MANUFACTURING

Table 2 contains product forms and product form sizes that have been commercially produced as of 2025 [6]. Note that product development trials in sizes other than those listed are possible and are a regular part of business in our mill. Bare wire welding consumables are produced by Haynes for the alloys in Table 2. The American Welding Society (AWS) designations for the wire products are ERNiCrWMo-1 (HAYNES® 230-W® alloy) and ERNiCrCoMo-2 (282 alloy). The welding wire for 233 alloy tradename is HAYNES® 233-W® alloy.

Table 2. Wrought product forms that are commercially available.

	230	282	233
ASME Tubulars	0.5” to 4" SCH80	0.5” to 8" SCH80	1” to 2" SCH40
Plate / Sheet	0.015 - 3"	0.015 - 2.25	0.015 - 2"
Foil	min. 0.002	min. 0.002	min 0.002
Bar / Billet	0.5 - 9"	0.5 - 9"	0.5 - 9"
Wire	0.49 - 0.025	0.49 - 0.025	0.49 - 0.025
Powder	yes	yes	yes
Forgings	up to 8,000 lbs	up to 8,000 lbs	up to 8,000 lbs

ASME CODE AND INDUSTRY SPECIFICATIONS

282 alloy is covered by Section I and Section VIII Division I ASME Code Case 3024 and the maximum use temperature is 1600°F (871°C). 230 alloy is covered by Section 1 and Section VIII Division I ASME by Code Cases 2063 and 2671, respectively [7]. Haynes is currently producing data for the 233 alloy Code Case and the data collection should be completed in 2028. Haynes began collecting ASME-specific data for 233 alloy in the fourth quarter of 2024 and the development of an ASME Code Case is supported by several industry partners.

Table 3 summarizes the various specifications for 282 and 230 alloys [8] and the specifications and standards for each alloy are also listed in active Code Cases. Haynes can produce 233 in all of the product forms listed below and we can reference the contents of the standards in the table to meet customers’ requirements. Efforts to include 233 alloy in various industry specifications will follow acceptance and publication of the Code Case.

Table 3. Specification for 282 and 230 alloys.

Alloy	HAYNES® 230® alloy N06230	HAYNES® 282® alloy N07208
Density lb./in3 (g/cm3)	0.324(8.97)	0.299 (8.27)
Sheet, Plate & Strip	AMS 5878 SB-435/B435 P=43	AMS 5951 **ASTM B670
Billet Rod/Bar	AMS 5891 SB 572/B 572 B 472 P=43	B637 AMS 5915
Coated Electrodes	SFA 5.11/ A 5.11 (ENiCrWMo-1) F= 43	–
Bare Welding Rods	SFA 5.14/ A 5.14 (ERNiCrWMo-1) AMS 5839 F= 43	–
Seamless Pipe & Tube	SB-622/B622P=43	**ASTM B983-16e1
Welded Pipe & Tube	SB-619/B619 SB 626/B626 P=43	** SB-619/B619 & B1007-17
Fittings	SB 366/B 366 P=43	**SB 366/B 366 P=43
Forgings	AMS 5891 SB-564/B564 P=43	B637 AMS 5915
DIN	17744 No. 2.4733 NiCr22W14Mo	–

** Haynes is working with standards organizations to include 282® alloy the listed specifications. Please refer to Code Case 3024 when necessary.

Careful examination of the ASME Code Case for 282 alloy will reveal that the alloy can be welded to create fabrications, welded cylinders, shells, etc. with the wrought material in the solution annealed condition or in the precipitation strengthened condition. It is likely bending and fabricating components while the wrought products are in the annealed condition will require much less effort due to the near doubling of the yield strength following precipitation strengthening heat treatment. After fabrication, the Code allows for the 282 alloy weldments to be post-weld heat treated for four hours at 800°C (1450°F) with or without the need for a post-weld solution anneal.

TENSILE AND CREEP STRENGTH

High temperature equipment requires alloys with excellent high temperature strength, creep resistance, and high thermal stability to retain ductility. The average tensile properties from room temperature to 982°C for 233, 282, and 230 alloys and selected data to 1093°C for 230 and 233 alloys are in Table 4 [1-3]. The data in Table 4 were collected from plate produced from at least three heats of each alloy. Tensile testing was conducted on alloy specimens machined from plates from three heats of each alloy. 233 and 282 alloys were tested in the precipitation strengthened condition. 230 was tested in the solution annealed condition.

Table 4. Typical tensile properties of 233, 282, and 230 alloys from room temperature to 1093°C.

	Alloy	**21°C**	**538 °C**	**649 °C**	**760 °C**	**871 °C**	**982 °C**	**1093 °C**
0.2% Yield Strength, MPa	233	807	737	722	692	400	84*	42*
	282	715	649	643	628	507	132	--
	230	383	263	267	260	234	116	63
Ultimate Tensile Strength, MPa	233	1230	1078	1139	832	471	125	63
	282	1147	991	1048	856	566	174	--
	230	852	706	677	533	311	168	91
Elongation, %	233	24.8	29.5	29.5	32.6	39.1	118	101
	282	30	34	31	22	31	71	--
	230	46	53.2	53	68	94	91.2	92.1

- 233 alloy tested in the solution annealed condition as the test temperature is above the gamma prime solvus.

High temperature tensile results represent the load bearing capability of a structural component operating for short periods of time in the creep temperature regime. For example, if a 230 alloy structural component was loaded to 50 MPa at 982°C, which is about 50 percent of its yield strength, it would rupture in less than one hour. Most alloy components that are in load-bearing service in the creep regime rely on accurate creep strain and creep rupture data to estimate the amount of strain that can expected at a certain load in a certain amount of time. Additional data can be found in literature [9].

The Larson-Miller plot [10] in Figure 1 contains creep data for one percent strain for the three alloys and Figure 2 contains a Larson-Miller plot [10] of the creep rupture strength for the three alloys from 649 to 982°C. The time in the Larson-Miller parameter was fixed at 10,000 hours in order to label the temperatures noted in Figure 1.

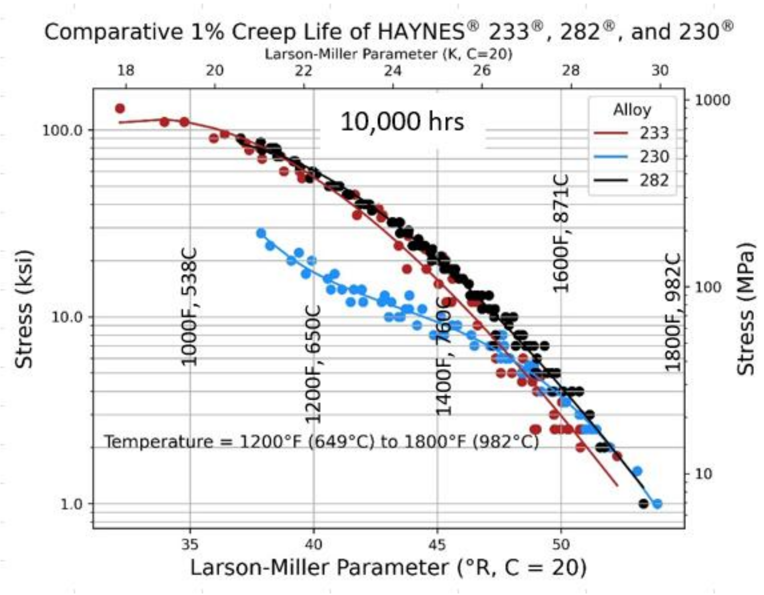

Figure 1. 1% creep strain Larson-Miller plot for 233, 282, and 230 alloys.

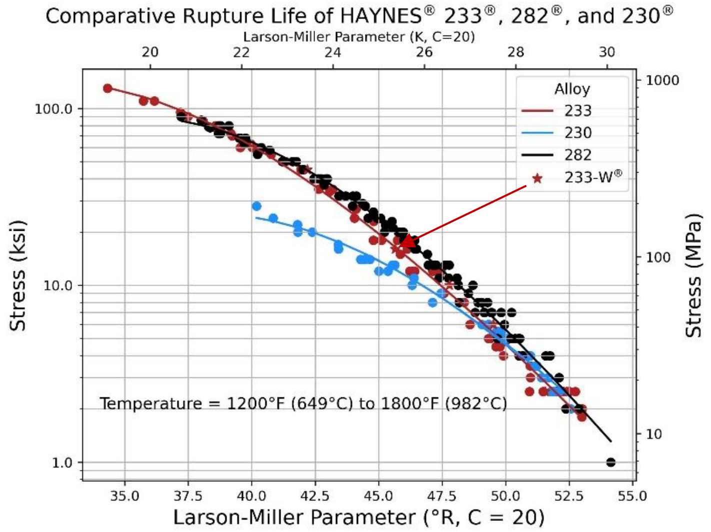

Figure 2. Creep-to-rupture Larson-Miller plot for 233, 233-W, 282, and 230 alloys.

The impact of precipitation strengthening on creep life, whether it is one percent creep strain or creep-to-rupture, is readily apparent in both figures. The creep life of the precipitation strengthened alloys can be higher than 230 alloy by a factor of approximately 2.5 to 3 depending on the temperature. This fact can have a significant impact on the pressure barrier thickness of structural components and possibly impact total wrought product cost for a project. Careful examination of Figure 2 reveals that the alloy used to weld 233 alloy, HAYNES® 233-W® alloy, has very similar creep resistance as the wrought 233 alloy plate and additional data will be produced in the future.

The creep performance of 282 alloy was studied extensively by Oak Ridge National Laboratory during the Advanced Ultra Supercritical (AUSC) steam power program that was funded for over two decades by the Department of Energy. ORNL and Haynes generated supporting data for the ASME code case and many other efforts [11, 12]

ENVIRONMENTAL RESISTANCE

Past work in the oxidation resistance of nickel-based alloy in supercritical carbon dioxide, steam, and air [4, 13-19] reveals that the oxidation rates can be similar to those in air.

The methodology and equations for measuring metal loss and average metal affected are described in Figure 3.

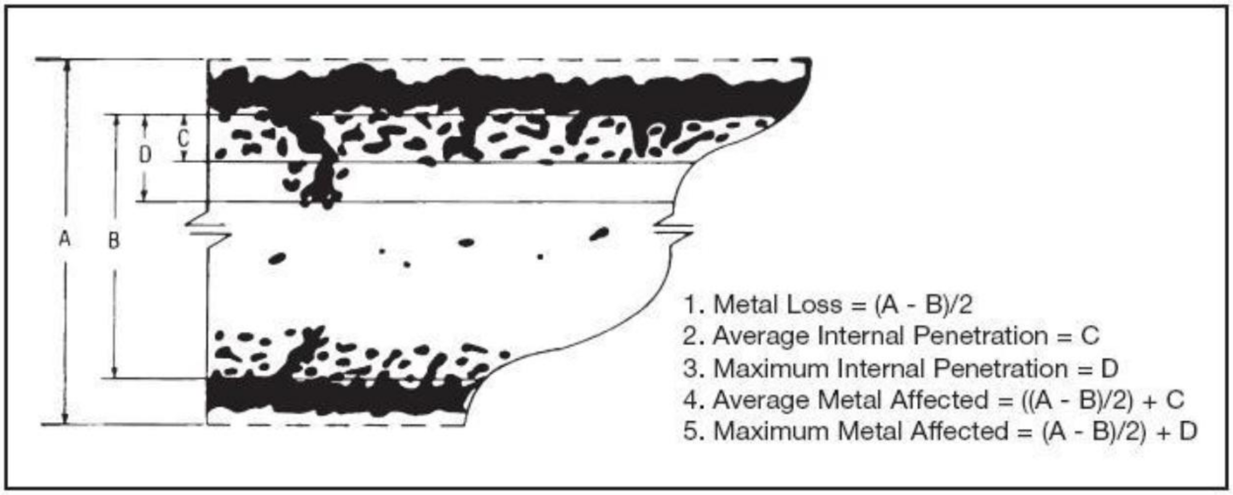

Figure 3. Sketch of the methodology to measure and calculate metal loss and average metal affected.

Haynes plans to collect oxidation data on 233 alloy in supercritical carbon dioxide in the future. Table 5 contains oxidation data for the three alloys in air at 871°C (1600°F) for 1008 hours [20].

Table 5. Air oxidation results of 233, 282, and 230 alloys at 871°C for 1008 hours in air.

	871°C / 1600°F, 1008 hours in air			
	Metal Loss		Average metal affected	
	mils	microns	mils	microns
233®	<0.1	<1	0.2	6
230®	0.1	1	0.6	14
282®	<0.1	<1	0.9	23

Table 5 shows that the oxidation resistance of 233 alloy is superior to 282 and 230 alloys at 871°C (1600°F), but 282 alloy and 230 alloy oxidation resistance is still excellent and adequate for most applications. The aluminum addition of 233 alloy is the key contributing factor to its improved oxidation resistance. To further improve oxidation resistance, Haynes developed and patented a pre-oxidation treatment for the alloy. The pre-oxidation treatment can be carried out by exposing the alloy to commercially-pure argon, which has trace amounts of oxygen, at 1000°C for approximately 12 hours. The result is a robust α-alumina layer on the surface and the layer is greatly reduces further oxidation of the substrate.

WELDING AND ADDITIVE MANUFACTURING

Welding 230 and 282 alloys are well developed in industry and the weld strength reduction factors (WSRF) for these alloys with and without matching-chemistry filler metal can be found in Section I of ASME Code. Above 677°C the WSRF for 230 alloy is 0.8. The WSRF for 282 alloy for service temperatures below 620°C is 0.99 and the WSRF between 621°C and 815°C is 0.93. Although the WSRF data for 233 alloy are under development, it is likely that the WSRF will be within the range of 0.99 and 0.8 for temperatures between 620°C and 815°C. As mentioned earlier, the filler alloy for 233 alloy is a welding-specific alloy; 233-W alloy, whose creep resistance is similar to 233 alloy.

Additive manufacturing is an important manufacturing technique for 282 alloy [21-24] and 233 alloy. Additive manufacturing development efforts continue for 233 alloy at the time of this writing and tensile testing results from laser powder direct energy deposition (LP-DED) specimens are offered below. Triplicate specimens were machined from the additive manufacturing build block perpendicular to the build direction and tested in in tension at the temperatures specified in the table. The thermal history for all LP-DED specimens was to perform the additive build without intermediate anneals, stress relieve the finished block at 2150°F / 1hr / furnace cool, hot isostatic press (HIP) at 2125°F and 100MPa for 3.5 hours and furnace cool, and then solution anneal at 2150°F for 1 hour followed by an argon quench (results in Table 6a) and all of the prior treatment plus age hardening in a two step process at 1650°F for four hours followed by eight hours at 1450°F and finally furnace cool (results in Table 6b). Further developments in printing parameters and more testing will likely reveal that 233 alloy can be annealed and aged from the as printed condition and retain sufficient creep and tensile strength for many industrial applications.

Table 6a: Tensile test results of LP-DED solution annealed 233 alloy specimens.

Temperature	0.2% Yield strength	Ultimate Strength	Elongation
°C	MPa	MPa	%
RT annealed sheet	362	818	57.3
RT	731	1074	22
538	657	901	23.6
871	463	469	20.2

Table 6b: Tensile test results of LP-DED age hardened 233 alloy specimens.

Temperature	0.2% Yield strength	Ultimate Strength	Elongation
°C	MPa	MPa	%
RT aged sheet	795	1198	25
RT	771	1131	18.3
538	706	987	16.5
871	441	445	19.2

The results in Tables 6a and 6b are not greatly differentiated due to the age hardening treatment, which is somewhat surprising. The tensile properties for solution annealed sheet and age hardened sheet are also included in each table for comparison. Characterization work for the specimens is ongoing at the time of this writing.

Cyclic oxidation testing was performed on specimens machined from a laser powder bed fusion build that was made using 233 alloy powder. The results are in Table 7. Wrought sheet results are also included in the table. The condition of the wrought sheet was solution anneal at 2150°F followed by the two-step age hardening heat treatment at 1650°F for four hours followed by eight hours at 1450°F and air cooling. The thermal history of the LPBF specimens was the same as the LP-DED specimens in the aged condition. The environment for the testing was 1600°F air and the temperature was cycled hourly for 1,000 hours by removing the specimens from the furnace, air colling, and reinserting for another hour of exposure.

Table 7. Cyclic oxidation testing results for LPBF 233 alloy specimens.

	Metal Loss	Average metal affected
Sample condition	microns	microns
Wrought sheet *	0.4	7
LPBF horizontal	1	19
LPBF vertical	1	29

Finally, Figure 4 is a photograph of a recently-produced wire arc additive manufactured test block using 233 alloy wire and the laser-wire direct energy deposition process. The blocks were manufactured in mid-2025. Creep, tensile strength, and oxidation testing are underway at Haynes International, and results will be presented in the future.

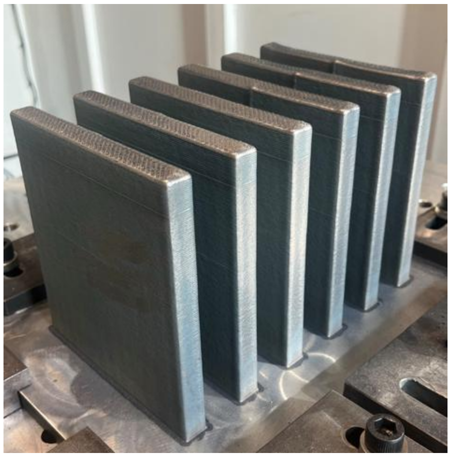

Figure 4. Wire arc additive manufactured test block using the laser wire direct energy deposition technique. 233 alloy. Block size is approximately 5.5” x 5.5” x 0.6”.

SUMMARY

The following list contains important information presented in this paper:

- The supply chain for wrought nickel alloy products in commercial applications is strong and many product forms are available.
- The tensile strength, creep resistance, and environmental resistance of 282 alloy and 233 alloy are suitable for sCO_2 service.
- Extensive research on 282 alloy is easily found in literature and ASME Code acceptance of 282 alloy shows that the alloy has been thoroughly vetted by Haynes, national laboratories, and industry.
- 233 alloy is a next-generation alumina forming alloy that will be a candidate for an ASME code case once the data has been generated. Code application is expected between 2028-2030.
- Additive manufacturing of 282 alloy using powder and wire products is widespread in academia and industry. 233 alloy additive manufacturing parameters and test data are being actively pursued due to its superior oxidation resistance and excellent creep strength.

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