Experience of various materials for design and manufacture of bellows for nuclear industry

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Abstract

Bellows find wide applications in reactor systems such as in bellows sealed valves as primary leak tight barriers and in piping systems to absorb differential thermal expansions. Reliable operation of bellows is strongly dependent of proper material selection. Various candidates for material of the bellows are austenitic stainless steels (such as SS316, SS304, SS316Ti, SS304L etc.), precipitation hardened stainless steels (such as AM350) and Nickel base alloys such as Inconel-718 and Inconel-625. This paper presents the review of the operating experience, mechanical & neutronic properties of various materials for bellows in nuclear industry. In this work, it is observed that Inconel alloys have superior mechanical properties than austenitic stainless steels but exhibit neutron embrittlement. Hence, use of Inconel bellows is limited to low neutron fluence applications. Precipitation hardened steels such as AM350 have high mechanical strength but lesser ductility. Though AM350 is not suitable for formed bellows, it has excellent operating experience for welded disc bellows in nuclear applications. Austenitic stainless steels have large operating experience. Variants of SS316 are used for high temperature and variants of SS304 are used for temperatures below creep range. 'L' grades or stabilized grades are used for resistance to sensitization during welding. Based on the present review work, guidelines for selection of material for bellows are drawn, satisfying the selection criterion. Copyright © 2017 VBRI Press.

Keywords: Material of construction of bellows, austenitic stainless steels, Inconel 718, Inconel 625, AM350.

Introduction

Bellows find wide range of applications in nuclear industry. Bellows are highly engineered components. Reliable operation of the bellows in severe conditions such as in high temperature or high pressure systems as in nuclear industry is strongly dependent on proper material selection, design and manufacturing.

Bellow sealed valves are widely used in nuclear industry especially in sodium cooled fast reactors. Bellows are used as primary leak tight barriers in Bellows-sealed valves as shown in **Fig. 1**. Bellows are used in piping systems for flexibility as shown in **Fig. 2**. Bellows are used to absorb the differential thermal movements in piping systems without need of pipe bends thus optimizing the material inventory as well as simple layouts are possible. Bellows are used for isolating one medium from the other medium in many reactor systems. Based on the construction, the bellows are classified in to formed bellows and nested ripple type welded disc bellows. Welded disc bellows are flexible compared to formed bellows. Generally formed bellows are used in applications where the stroke to the length ratio is less than 0.3 and welded disc bellows are used to when the stroke to length ratio is high.

Bellows are commonly manufactured of austenitic stainless steels. For bellows, pressure capability and flexibility are contradictory requirements. In high pressure systems, thickness required is large and results in reduction in flexibility of the bellows. A multi ply construction gives high pressure capacity with better flexibility. Bellows are used in hot shutdown passive valves of advanced heavy water reactor **[2]**, which need more than 5 plies to meet both pressure capacity and flexibility requirements and results in manufacturing difficulties. Similarly, in sodium cooled fast reactors, typical operating temperatures are above creep range. The stresses in the bellows plies need to be controlled to reduce the effect of creep. The bending stresses in the bellows plies can be reduced by reducing the ply thickness, however, this result larger membrane stresses. In this case also, a multi ply construction is needed to address membrane and bending stresses in the bellows plies. However, there is a limit on number of plies of bellows. Standards of Expansion Joint Manufacturers association (EJMA) recommend a maximum of 5 plies **[1]**. Such problems can be addressed by selecting an alternative material for manufacturing the bellows with higher yield stress and young's modulus comparable with that of austenitic stainless steels. Hence, there is a large need and scope to study the alternate materials for manufacture of bellows in the nuclear industry.

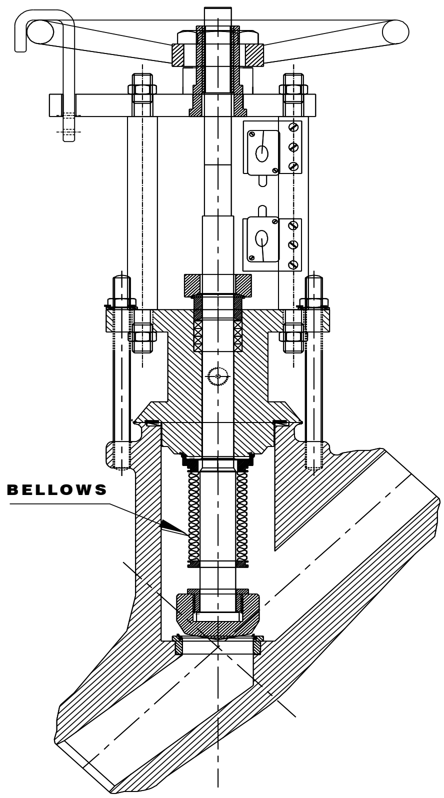

Fig. 1. Schematic of typical bellows sealed sodium valve.

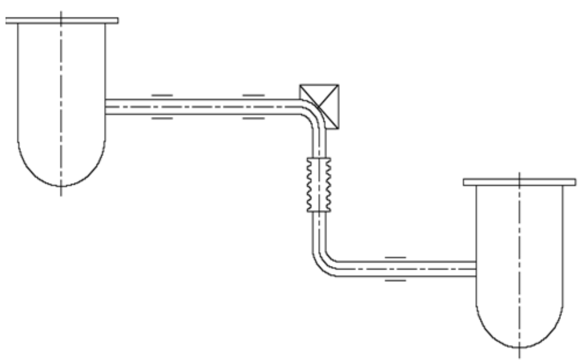

Fig. 2. Use of bellows in piping system to absorb thermal expansions.

Criteria for selection of the material for bellows

The basis for selection material of construction for bellows consists of the following considerations.

i. Type of the bellows: Formed bellows require materials with good ductility, weldability and good mechanical strength. Nested ripple type welded disc bellows can be manufactured with materials of relatively lesser ductility with higher yield stress material are preferred.
ii. Operating conditions: The operating medium (for example in LMFBRs, compatibility with sodium and sodium aerosols), operating temperatures influence the selection of the material.
iii. Manufacturing considerations: Manufacturing considerations such as weldability, requirements of preheating and post weld heat treatment, heat treatment of bellows and the capability of the Indian industry to handle the material need to be considered in selection of the material.
iv. Operating experience
v. Cost

Review of operating experience, mechanical and neutronic properties of various materials of bellows in nuclear industry

In France, the operating experiences of the bellows used in bellow-sealed valves and in control rod drive mechanisms (CRDMs) of Rapsodie and Phenix rectors was reported. Formed bellows were used in bellow-sealed valves and the material of construction of the bellows was SS316L material. The operating temperatures of this material is up to 400^{o}C is satisfactory. The material used in welded disc bellows of CRDMs was AM350. It is a precipitation hardenable stainless steel. French experience of AM350 for welded disc bellows was satisfactory, though a lot of scatter in the bellows performance is observed **[3, 4]**.

The gripper bellows of CRDM were of SS316L. Though stabilized steels such as SS347 and SS321 were also tried. Nickel based alloys such as Inconel 718 and Inconel 625 were tested for nested ripple type bellows. The results of the testing were encouraging. The bellows of Inconel material survived 2500 fast drop tests without failure. Consistency in the behavior of the bellows was also reported. In spite of their better mechanical properties, AM350 was selected over the Inconels due to their neutron embrittlement. However, use of Inconel bellows for high temperature applications as in LMFBRs in low neutron fluence environment was recommended. Compatibility of the Inconel 625 and Inconel 718 with sodium and inn sodium aerosol applications was well proven. In gas cooled fast reactors in France, main material used in bellows was SS304, where the operating temperatures were limited to 365^{o}C.

The material used in sodium systems of SNR 300 in Germany was SS304H (up to 500^{o}C) and SS 316H up to 530^{o}C **[5]**. SS304 and SS 316 were added Boron for creep resistance. However, it is reported that these steels show helium embrittlement due to (n, α) reaction in boron resulting premature failure of the bellows.

The parts in contact with sodium in bellow-sealed valves are made up of SS316 in PFR reactor, UK **[6]**. Six years of operating experience was reported and it was satisfactory.

In Japan, the sodium systems of Joyo and Monju reactors used bellows made up of austenitic stainless steels. SS304L was used when the temperature of the system was less than creep range. SS316 and SS347 were used as bellows material for high temperatures

Table 1. Operating experience of austenitic stainless steel as bellows material.

S. No.	Property	SS304	SS316	SS304L	SS316L	SS321/ 347	SS316Ti	SS304LN	SS316LN
1	0.2% Yield strength & UTS	YS: Around 220 MPa, at 20^{o}C ; UTS: 540 MPa							
2	Ductility	35%							
3	Temperature of application for long duration	475^{o}C	550^{o}C	475^{o}C	530^{o}C	475^{o}C	475^{o}C	475^{o}C	550^{o}C
4	Weldability	High and comparable to each other							
5	IGSCC resistance	X	X						
6	Knife-line attack	X	X	X	X			X	X
7	Pre-heating/ PWHT	Not required							
8	Heat treatment	Solution annealing to avoid sensitization		Not required with respect to bellows manufacturing					
9	Capability of industry	High, austenitic Stainless steel are the most widely used bellows materials.							
10	Operating experience	High (Sensitization Problems)	High (Sensitization Problems)	High and satisfactory upto 475^{o}C	High and satisfactory upto 530^{o}C	Less		High	Not much available due to non availability of thin sheets of this material
11	Cost	Less expensive and readily available in market as thin sheets						More expensive	

(530^{o}C) applications. The operating experience of the bellows manufactured of austenitic stainless steels used in small bellows test facility (SBTL), Japan was also satisfactory **[7].**

The operating experience of bellows in sodium systems of Fast Breeder Test Reactor (FBTR) and various experimental sodium loops in shows that various grades of austenitic stainless steels were used for bellows. Failures due to intergranular stress corrosion cracking in bellows of SS 316/304 were reported. Failure of bellows manufactured of 321 due to knife line attack is also reported. Certain failures due to improper storage of SS304 bellows (due to pitting) were observed. The performance of the bellows made up of SS316L/SS304L in low temperature systems such as in fuel handling machines is satisfactory. However, pre-matured failures of certain bellows made up of austenitic SS at temperatures around 550^{o}C were observed. Data from various indigenous suppliers of bellows shown that stabilized stainless steel grade 316Ti is one of the most commonly used material for bellows.

In many cases L grades of the austenitic stainless steels were selected for their IGSCC resistance **[8]**. Stabilized stainless steels such as SS 321 and SS 316Ti were also tried though issues related to knife-line attack were reported in literature. Though SS316LN is the most suited for bellows, non-availability of thin sheets in this material makes the material as very expensive for bellows. Based on reported operating experience and literature on material properties, suitability of various grades of austenitic stainless steels for bellows in nuclear applications is compiled in **Table 1**.

AM350 is precipitation hardened stainless steel. The mechanical strength of the AM350 is superior to conventional austenitic stainless steels. In solution annealed condition (H), the material possesses an austenitic structure, although it has several percent delta ferrite. As an austenitic material, the AM350 precipitation hardening alloy possesses a relatively low strength. This is the condition in which formability is easiest. To develop the high precipitation hardened strength, from condition H, heat treatments are done to accomplish two necessary steps. The first is a heat treatment which allows the relatively stable austenite of Condition H to transform to martensite (Austenite Conditioning and Transformation). The second is a precipitation hardening heat treatment to further strengthen the material. Based on the heat treatment process, AM350 is designated as DA or SCT condition. The other method to produce martensitic structure in AM350 is by cold working and designated as CRT condition. Based on relatively higher ductility, AM350 in SCT condition is widely used. Typical room temperature properties of AM350 for different grades are given in **Table 5** and high temperature properties of SCT (850) are given in **Table 2**. Variation of the mechanical properties with temperature is given in **Fig. 6**.

Inconel materials are having superior mechanical properties even at elevated temperatures. Thin sheets of Inconel material are readily available. Welding of the Inconel materials is also well understood and experienced. Thus, for the following applications, Inconel 718 & Inconel 625 are better choices for both high pressure and high temperature systems.

Table 2. Room temperature properties of various grades of AM350.

	Cond-ition H	Cond-ition DA	Condition SCT (850°F)	Condition SCT (1000°F)
0.2% Yield Strength (MPa)	480	1100	1380	1020
UTS (MPa)	1035	1310	1520	1165
% Elongation	30 to 35	13.5	13.5	15
HRC	20	42	45	38

(Courtesy: Allegheny Ludlum Steel corporation)

Inconel 718 is highly suitable material for manufacturing bellows. Inconel alloys have good high temperature strength, formable and wieldable. Inconel 718 is chemically inert and compatible with the operating medium such as coolant/ moderator in the reactor systems. Inconel 718 is suitable to manufacture both welded disc and formed bellows.

Mechanical strength of Inconel 718 is given in the following **Fig. 3**. Inconel 718 has good high temperature strength, with a rupture life of 3×10^5 hrs is reported at 537 MPa and 560°C. The welding and heat treatment of the material also standardized.

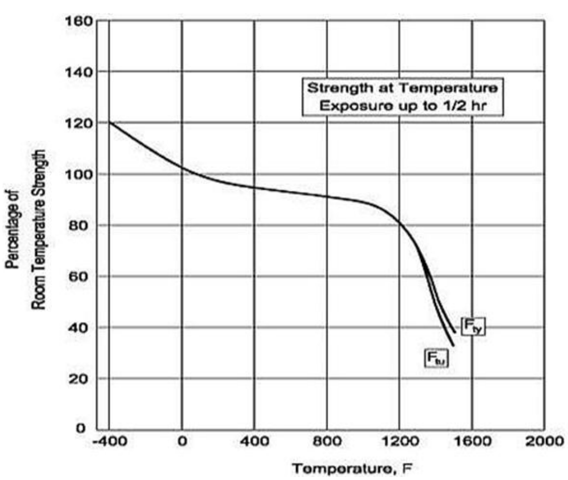

Fig. 3. High temperature strength of inconel 718.

However, the Inconel materials show neutron embrittlement as shown by T.S. Byun, et.al, (2003) **[9]**. Irradiation on Inconel alloys results in drastic reduction of their toughness and other mechanical properties. Following **Fig. 4** gives the reduction in the mechanical properties of Inconel 718 with irradiation.

For applications other than in primary components or in components such as bellow seals valves where neutron fluence is less, inconel alloys for a good choice as bellows material. In such cases, there will be a dissimilar weld between the bellows collar to the parts of the bellow-sealed valves. Dissimilar welding between Inconel alloys and austenitic stainless steels was established was established in nuclear applications both at room temperature and at elevated temperatures. One of such examples is welding of austenitic stainless steels to ferritic steels in Steam generator systems in FBRs with Inconel welding consumables. Operating experience of the Inconel bellows for CRDM bellows is satisfactory. Bellows with Inconel 718 were manufactured indigenously and used in FFLM DC conduction pump.

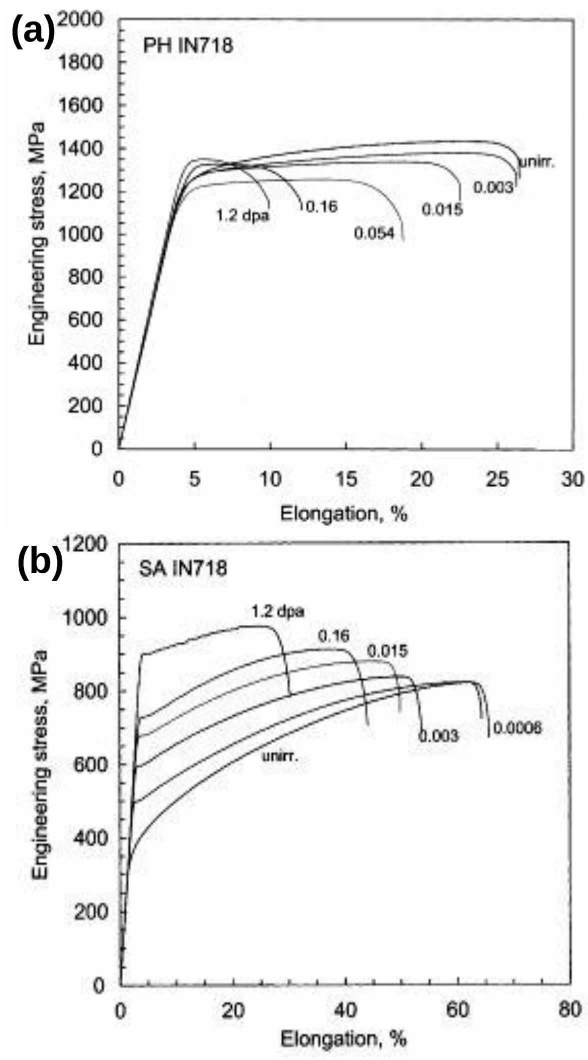

Fig. 4. Change in mechanical properties of Inconel 718 with irradiation. (a) Stress-strain curve of Inconel 718 (hardened) at various doses and (b) stress-strain curve of Inconel 718 (solution annealed) at various doses.

Mechanical strength of Inconel 625 is high compared to austenitic stainless steels and lesser compared to alloy 718. It has superior corrosion resistance. The ductility of Inconel 625 is as high and comparable with that of austenitic stainless steels. It is easily formable compared to Inconel 718. The cost of Inconel 625 is less compared to Inconel 718. The mechanical properties of Inconel 625 material are given in **Fig. 5 [10]**.

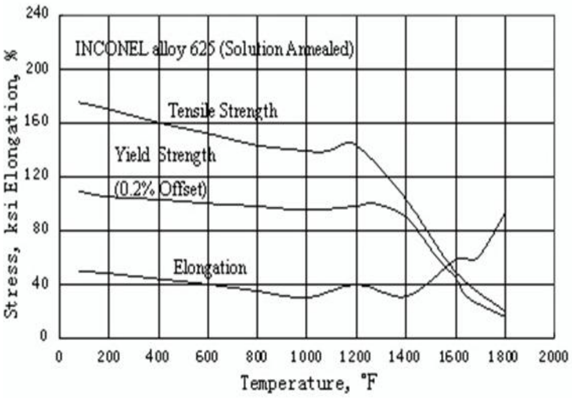

Fig. 5. Mechanical properties of Inconel 625.

Results and Discussion

Austenitic stainless steels as material of construction for bellows is the simplest and most common choice based on chemical inertness, formability, weldability, no need for preheating and PWHT and less expensive. Issues regarding sensitization and SCC are addressed by low carbon grades such as 304L and 316L or by selecting stabilized stainless steels such as SS347 and SS321. In stabilized stainless steels, failures due to knife-line attack are present. Though SS316LN is a good choice of material up to 550^{o}C, thin sheets of SS 316LN are commercially not feasible as this material in the form of thin sheets is not readily available in market. For high temperature applications, SS316Ti is one of the most widely used among the austenitic stainless steels.

Certain duplex stainless steels such as AM350 can be used for welded disc bellows. The mechanical strength of AM350 is far superior compared to austenitic steels. These steels are formable and weldable in their solution annealed condition. After precipitation hardening, it shows significant reduction in ductility. Hence, it is not suitable for formed bellows but extensively used in welded disc bellows.

Inconel 718 & Inconel 625 show excellent mechanical strength compared to the other materials. Inconel 625 is softer compared to Inconel 718 and easy to form. Except in high fluence ambience, these materials can be used for high temperature application up to 650^{o}C. The choice of Inconel 625 or 718 depends upon the strength requirement.

A comparison of the material properties of bellows materials is presented in the following **Fig. 6(a)** and **Fig. 6(b) [11]**. The selection of material for bellows considering various criterions is summarized in the following **Table 3**.

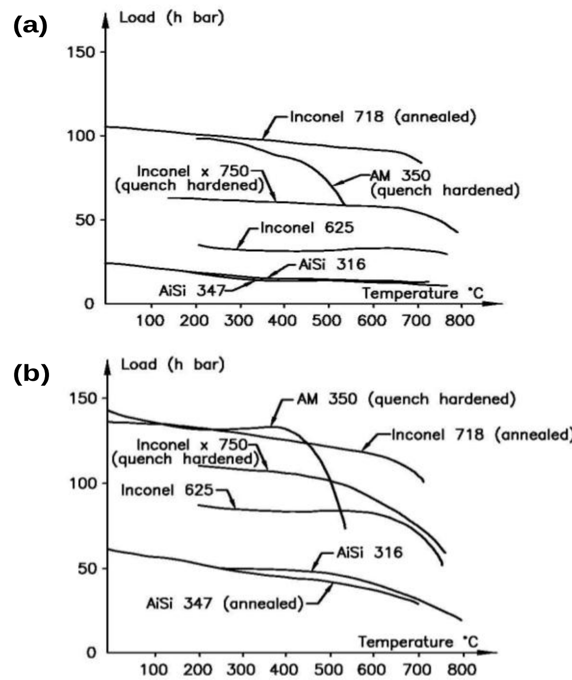

Fig. 6. (a) YS of the candidate materials of bellows and (b) UTS of the candidate materials of bellows

Table 3. Choice of material selection for bellows.

S. No	Property	Austenitic stainless steels	Duplex stainless steels	Inconel alloys
1	Mechanical strength	Relatively lesser	Good	Good
2	Ductility	Good	Good in solution annealed condition	Good
3	Temperature of application for long duration	550^{o}C	500^{o}C	650-700^{o}C
4	Weldability	Good	Good only in solution annealed condition	Good
5	SCC resistance	Good in ‘L’ grade or in stabilized grades	Poor, comparable with 304 or 316	Good
6	Pre-heating/ PWHT	Not required	Not required	Required
7	Heat treatment	Not required	Required	Required
8	Capability of industry	Good	Less	Good
9	Suitability for formed bellows/ Welded disc bellows	Yes	NO, Suitable to make welded disc bellows	Yes
10	Operating experience	High	Moderate	High
11	Cost	Cheaper(except ‘LN’ grades)	Costlier	Costlier

Conclusion

For formed bellows with less operating pressure and less stroke to length ratio, austenitic stainless steels are best choice. SS316LN is the best choice among the austenitic stainless steels but not economical. SS316Ti is another good choice of bellows material. For formed bellows with higher operating pressure, high stoke to length ratio, and less neutron exposure, Inconel alloys form good choice of bellows material.

For welded disc bellows, with stroke to length ratio varies from 0.5 to 0.75, precipitation hardenable stainless steels are preferred in presence of neutron fluence and Inconel alloys are preferred when neutron fluence is less. For welded disc bellows with less pressure and length to stroke ratio less than 0.5, the stresses induced in the bellows are less and austenitic stainless steels are the better choice due to their less cost.

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