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Selection of hardfacing material for components of the Indian Prototype Fast Breeder Reactor

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Abstract

Nickel-base hardfacing alloys have been chosen to replace cobalt-base alloys as hardfacing material for components of the Indian Prototype Fast Breeder Reactor, for minimising the dose rate to personnel during maintenance and decommissioning, and to reduce the shielding thickness required for component handling. Induced activity, dose rate and shielding computations showed that replacing cobalt-base alloys with nickel-base alloys for hardfacing of components would result in a marked reduction in both the dose rate from the components and the thickness of lead handling flasks. Long-term ageing studies on the nickel-base hardface deposits on austenitic stainless steel showed that the hardface deposit would retain adequate hardness at the end of the components' design service-life of 40 years of exposure at 823 K.

1. Introduction

The Indian Prototype Fast Breeder Reactor (PFBR) is a 'pool-type' 500 MWe sodium cooled reactor [1,2] having two separate sodium circuits with the intermediate heat exchanger (IHX) providing thermal contact between the primary pool and the secondary circuit. The secondary sodium circuits transfer heat from the IHX to the steam generator, the steam from which drives the conventional steam turbines. The minimum sodium temperature in the primary pool during normal operation will be about 673 K while the mean above-core temperature will be about 823 K. The minimum and maximum sodium temperatures in the secondary circuit will be 628 and 798 K, respectively. The steam temperature will be 763 K at a pressure of 16.6 MPa.

In PFBR, type 316L(N) austenitic stainless steel (SS) has been chosen as the structural material for components operating above 673 K. The liquid sodium coolant acts as a reducing agent and removes the protective oxide film present on the SS surface of the in-sodium components. Many of these components would be in contact with each other or would have relative motion during operation, and their exposure at high operating temperatures (typically 823 K) coupled with high contact stresses could result in self-welding of the clean metallic mating surfaces. In addition, the relative movement of the mating surfaces could lead to galling, a form of high-temperature wear, in which material transfer occurs from one mating surface to another due to repeated self-welding and breaking at the contact

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points of the mating surfaces. Further, the susceptibility to self-welding increases with temperature for 316 SS [3]. Hardfacing of the mating surfaces has been widely used in components of water-cooled and liquid-sodium cooled fast breeder reactors to avoid self-welding and galling [4,5].

Cobalt-base hardfacing alloys (e.g. Stellite©) have been traditionally used very extensively for high temperature application in many critical hardfacing applications due to their excellent wear-resistance properties [6]. However, when Co-base alloys were used in a nuclear reactor environment, the Co^{60} isotope formed due to (n, γ) reaction enhances the dose rate to operating personnel during handling, maintenance or decommissioning of the hardfaced components. Hence, there is an emerging trend of avoiding the use of Co-base alloys for hardfacing of nuclear power plant components. Nickel-base hardfacing alloys (e.g. Colmonoy©) were developed mainly to replace the Co-base alloys for avoiding induced activity problems in thermal and fast reactor applications. Accordingly, for PFBR, selection of suitable hardfacing materials for the various components was preceded by detailed induced activity, dose rate and shielding computations to ensure that induced activity from hardfaced components is kept to the minimum for maintenance and decommissioning purposes, and also to reduce the shielding thickness required for the component-handling flask, which in turn would reduce the flask weight, size of handling crane and loads on civil structures [7,8]. This paper reports the details of these computations based on which Ni-base Colmonoy was chosen for replacement of the Co-base Stellites for use as hardfacing material for components of the PFBR.

Ni-base Colmonoys have already been used in reactors with satisfactory results [9,10]. Tests on six liquid sodium pumps, with type 304 SS bearings hardfaced with Colmonoy 6 and shafts/journals hardfaced with Colmonoy 5, operating at 748–798 K, have accumulated 20 000 h each without failure of the bearing area [9]. The Rapsodie, Hallam, Fermi and EBR-II reactors have used Colmonoy-faced sleeves and shafts in their hydrostatic sodium-lubricated pumps [10], and bearing operation of the Hallam, Fermi and EBR-II pumps had been satisfactory, but all operations were below 813 K. However, seizure occurred in a Rapsodie intermediate (secondary) pump before attaining an operating temperature of 823 K. The cause of the failure is not reported in the open literature. Also, another Rapsodie primary pump seizure occurred sometime later, and its probable cause was lack of wear resistance in the bearing material. The temperature of the pumps was then limited to 723 K. All previous prototype bearings were made of Co-base Stellite, but for the Rapsodie pumps, a change to Ni-base Colmonoy was made. Hence it was surmised that the use of the proven material, the Co-base Stellites, might have eliminated the seizures [10]. This paper also discusses the evaluation of the suitability of using Ni-base Colmonoys as hardfacing material above 723 K, based on detailed investigations carried out to study the effect of long-term ageing on the hardness and microstructure of Ni-base Colmonoy deposits [11,12].

2. Computation and experiments

For induced activity computations of the hardfaced components of PFBR, replacement of Stellite 6 and Stellite 12 by the same amount of Colmonoy 5 was considered; the nominal compositions of the alloys used in activity computations are given in Table 1. The same geometrical configuration and operating conditions for the different components were used. As maintenance and handling operations are to be carried out at least one day after shutdown, only activation reactions with activation product of half-life longer than one day were considered. The activities were computed for all (n, γ), (n, p), (n, α) and (n, 2n) reactions. The activity and dose rate computations considered Colmonoy 5 with 0.25% Co in line with the maximum limit of 0.25% Co specified for the 316L(N) austenitic SS-base material to be used in PFBR. Saturation activity was considered for all components to be irradiated for at least 40 years, namely the in-vessel components, control and safety rod drive mechanism (CSRDM), diverse safety rod drive mechanism (DSRDM), failed fuel localisation module (FFLM) and primary sodium pumps (PSP). A cooling time of five years was considered for the grid plate components, as these would be handled only for decommissioning purposes. For the CSRDM, DSRDM, FFLM and PSP a cooling time of two days was considered. For the control and safety rod (CSR) and diverse safety rod (DSR), an irradiation time of two years and a cooling time of two days were considered.

Table 1
Nominal compositions (in wt%) of the hardfacing alloy deposits used in the induced activity computations

Alloy	B	C	Cr	Co	Fe	Mn	Ni	Si	W
Stellite 6	–	1.0	27.0	60.0	<2.5	1.0	<2.5	1.0	5
Stellite 12	–	1.8	30.0	52.2	<2.5	1.0	<2.5	1.0	9
Colmonoy 5	2.5	0.65	11.5	<0.25	4.25	–	77.10	3.75	–

In shielding computations, 1.3 MeV γ from Co^{60} is considered, as this forms the major source of γ dose rate. The tenth layer thickness of lead is about 35 mm for 1.3 MeV γ, i.e., the dose is reduced by a factor of 10 by a 35 mm thick lead shield. The 316L(N) SS-base material itself also becomes radioactive and requires shielding, and this was also considered in the computations.

For experimental investigations, a 316 SS plate of size $200\times50\times25$ mm^3 was hardfaced over a 150×75 mm^2 region with Ni-base Colmonoy 5 alloy rods of 4 mm diameter by the gas tungsten arc-welding process, with the hardface deposit thickness being about 2 mm. Samples of size $10\times10\times10$ mm^3, with a Colmonoy deposit thickness of 1.5 mm were cut from this hardfaced plate. These samples were then subjected to ageing at three different temperatures (823, 873 and 923 K) for five different durations (200, 500, 1000, 2000 and 5000 h) at each temperature. The Vickers hardness (HV) values of the as-deposited and all the aged Colmonoy 5 deposits were measured at room temperature (RT) using a load of 10 kg. These hardness values were then analysed to predict the hardness of the Colmonoy 5 after long-term ageing at the service temperatures of 673 and 773 K.

3. Results and discussion

3.1. Person–Sievert considerations during maintenance and decommissioning

The neutron flux under operating conditions, total mass of hardface deposit on the component, and dose rates for various components of PFBR from the hardfacing materials (Stellites and Colmonoy 5) and the 316L(N) SS substrate material are compared in Table 2. It is clear from the table that replacement of Co-base Stellites by Ni-base Colmonoy 5 will be beneficial from induced activity and dose rate considerations.

The reduction in shielding thickness, based on Person–Sievert (P–Sv) considerations, was considered with respect to the minimum shielding required for the 316L(N) SS components hardfaced with Co-base Stellite vis-à-vis that hardfaced with Ni-base Colmonoy 5 containing 0.25% Co as can be summarized as follows.

(1) As there is no maintenance requirement for the grid plate, only decommissioning requirement was considered. By replacing Stellite by Colmonoy 5, the P–Sv requirement comes down by a factor of 250 while handling the grid plate during decommissioning.
(2) For the anti-rotation lugs on grid plate, the dose rate would reduce from 60 Sv/h to 220 mSv/h on replacing Stellite. Hence, the P–Sv requirement during decommissioning can be reduced by a factor of about 270 by replacing Stellite by Colmonoy 5.
(3) For the IHX seal flanges in the inner vessel, the dose rate reduces from 3.7 Sv/h to 14 mSv/h and hence, during decommissioning, the P–Sv requirement would reduce by a factor of about 260 if Stellite is replaced by Colmonoy 5.
(4) For the CSRDM and DSRDM, the dose rate changes from 1.05 to 1.03 Sv/h on replacing Stellite. Hence, replacing Stellite by Colmonoy 5 practically does not change the lead shield thickness requirement for maintenance.
(5) For the FFLM, the dose rate decreases by a factor of 250, if Colmonoy 5 replaces Stellite.
(6) For the PSP, the dose rate reduces from 10 mSv/h to 1 mSv/h on replacing Stellite by Colmonoy 5. The maintenance of PSP is to be carried out after decontamination of 99% of the corrosion product and fission product deposits. Hence, Stellite has to be replaced by Colmonoy 5.
(7) For the pump-to-pipe connection (PPC) of PSP, the dose rate from Stellite is comparable to that from the 316L(N) SS. However, Stellite can be replaced by Colmonoy 5 to reduce the dose rate locally.
(8) No maintenance of the DSR and CSR is presently envisaged. However, in case they have to be removed for maintenance, it would be beneficial to replace Stellite by Colmonoy 5, as this reduces the shielding requirement by 40–50 mm of lead.

3.2. Shielding in flasks – considerations during handling and removal

An approximate estimate of the shielding requirement, assuming a dose rate of 1 mSv/h on contact, is also given in Table 2.

The DSR and CSR will take the same route as the spent fuel sub-assemblies for their removal. For the DSR, the dose rate reduces from 4.6 Sv/h to 98 mSv/h on replacing Stellite by Colmonoy 5. However, as it will follow the same route as that of the CSR during removal, the dose rate from the DSR will not be the deciding factor for shielding. It is estimated that the 240-day cooled fuel sub-assembly (corresponding to 5 kW decay power) gives a dose rate of 10^5 Sv/h.

For the CSR, on replacing Stellite by Colmonoy 5 the dose rate reduces from 1×10^4 to 5×10^2 Sv/h. For the guide-cum labyrinth of the CSR, the dose rate reduces from 6.3×10^6 to 2.7×10^4 Sv/h on replacing Stellite by Colmonoy 5.

If Stellite is used in the CSR's guide-cum labyrinth, the shield thickness would also increase by 60 mm of lead. If Colmonoy 5 replaces Stellite for this component of the CSR, the weight of the lead handling flask would be reduced by approximately 25 tonnes. Hence, replacing Stellite by Colmonoy 5 for the CSR and DSR would be highly beneficial.

Table 2
Dose rates and shielding requirement with or without hardfacing for the various components of PFBR

Component	Flux ($n\ cm^{-2}\ s^{-1}$)	Total mass of hardface deposit (kg)	Dose rate (in Sv/h) from			Lead shield thickness (mm)		
			316L(N) SS substrate	Stellite 6/12	Colmonoy 5 (with 0.25% Co)	Without hardfacing	With Stellite 6/12	With Colmonoy 5 (0.25% Co)
Grid plate – top plate	5×10^{13}	9	3.5×10^{4}	7.5×10^{7}	2.8×10^{5}	250	380	280
Grid plate sleeves	2×10^{12}	41	2.5×10^{3}	2.5×10^{6}	9.2×10^{3}	210	320	250
Grid plate anti-rotation lugs	1×10^{7}	8.2	4.4×10^{-2}	60.0	0.22	70	150	100
Intermediate heat exchanger inner-vessel seal	1×10^{7}	37	2.9×10^{-3}	3.7	1.4×10^{-2}	20	120	40
Intermediate heat exchanger valves	1×10^{7}	32	9.0×10^{-4}	3.1	1.1×10^{-2}	20	120	40
Control and safety rod drive mechanism	1×10^{7}	17.6	3.5×10^{-2}	1.05	1.03	130	170	130
Diverse safety rod drive mechanism	1×10^{8}	2	0.18	1.05	1.03	140	180	140
Failed fuel localisation module	5×10^{6}	8	0.47	0.50	2.0×10^{-3}	90	130	90
Primary sodium pump bearing	1×10^{7}	11.8	9.0×10^{-4}	1.0×10^{-2}	1.0×10^{-3}	20	40	20
Pump-to-pipe connection of primary sodium pump	5×10^{7}	17.4	40.0	0.15	5.0×10^{-4}	140	180	140
Control and safety rod – bottom coolant passage tube	2×10^{15}	14	3.4×10^{2}	2.1×10^{4}	90.0	180	250	180
Control and safety rod – guide-cum labyrinth	2×10^{15}	13	0.12	6.3×10^{6}	2.7×10^{4}	200	280	200
Control and safety rod – guide	2×10^{12}	1	0.47	2.7×10^{2}	1.0	90	180	100
Diverse safety rod	1×10^{10}	0.06	0.44	4.6	9.8×10^{-2}	90	130	90
Transfer arm	1×10^{6}	1.3	1.0×10^{-5}	1.3×10^{-2}	1.0×10^{-4}	40	50	40
Inclined fuel transfer machine	3×10^{6}	3	2.0×10^{-4}	0.11	2.0×10^{-3}	40	80	40

3.3. Effect of long-term ageing on hardness of Colmonoy deposits

The hardness of as-deposited and all aged Colmonoy 5 deposits, measured at RT using a 10 kg load, are presented in Fig. 1. The time–temperature correlation for these hardness values were obtained using the Larson–Miller parametric approach, given by LMP $= T(C + \log t)$, where LMP is the Larson–Miller parameter, T is the temperature in Kelvin, t is the time in hours, and C is a constant. The constant C was determined as 14.4 for Colmonoy 5 by least-square fitting with R^2 of the fit being about 0.97. Using C as 14.4, the RT hardness of Colmonoy 5 after ageing at 823 K for the service-life of the various PFBR components was estimated. Fig. 2 shows the estimated hardness after simulated service exposure of the Colmonoy 5 deposit for 2, 3, 5, 10, 15, 20, 25, 30, 35 and 40 years.

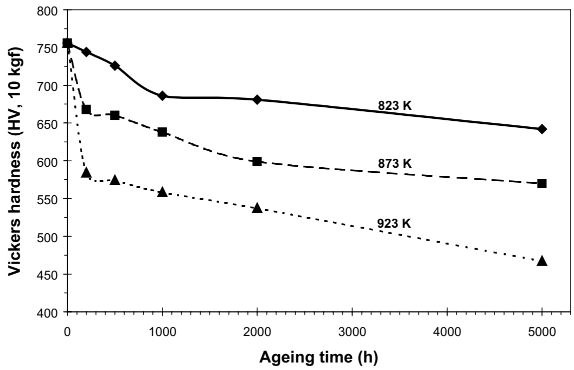

Fig. 1. Variation of room-temperature (300 K) hardness of Ni-base Colmonoy 5 hardface deposit with duration of ageing at 823, 873 and 923 K.

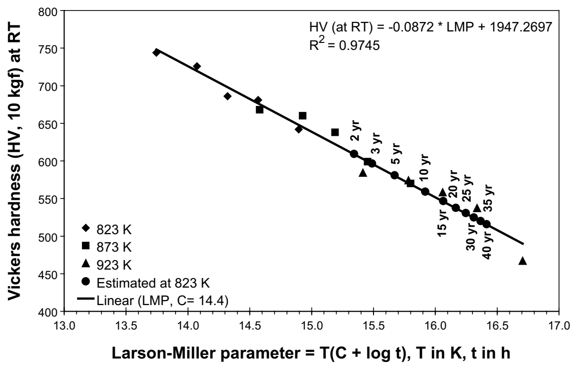

Fig. 2. Variation in hardness of Ni-base Colmonoy 5 hardface deposit at room temperature (RT = 300 K) with Larson–Miller Parameter.

To estimate the hot-hardness of the Colmonoy 5 on prolonged exposure at the different operating temperature of the various PFBR components, namely 673 and 823 K, the average hot-hardness values of unaged Colmonoy 5 and Stellite 6, as shown in Fig. 3 [13], were used. The temperature dependence of the hardness of these hardface deposits was determined by an Arrhenius-type plot of ln (hardness at RT/hardness at temperature) vs. $1/T$ (K^{-1}), as given in Fig. 4.

Using the relationships for both the hardfacing alloys over the specific temperature ranges as in Fig. 4, the hardness of Colmonoy 5 at 673 and 823 K was estimated for prolonged exposure at 823 K, as presented in Fig. 5.

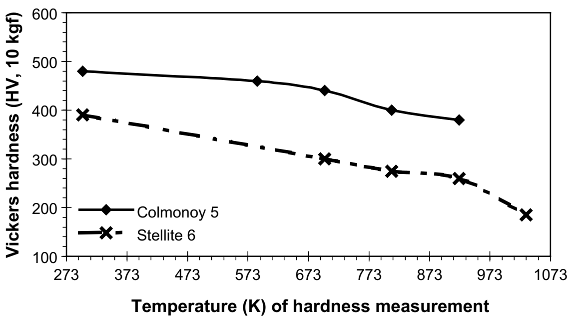

Fig. 3. Variation of average hot-hardness of unaged (as-deposited) hardfacing alloy deposits of Co-base Stellite, Ni-base Colmonoys and Ni-base Deloro 60 (equivalent to Colmonoy 6) [13].

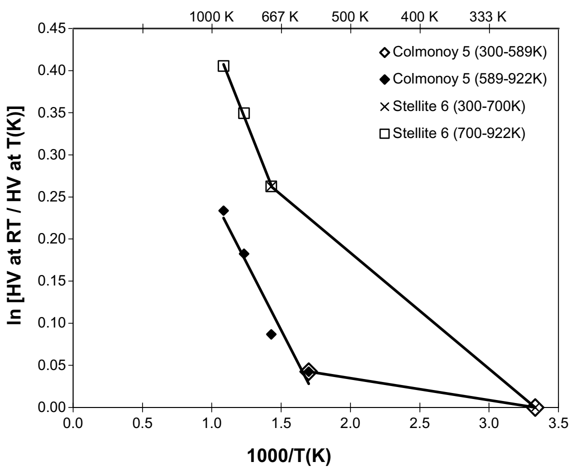

Fig. 4. Arrhenius-type plot showing the temperature dependence of average hot-hardness values of Co-base Stellite 6 and Ni-base Colmonoy 5 hardface deposits. For Colmonoy 5 (300–589 K): $y = -26.042x + 0.0868$, $R^2 = 1$; for Colmonoy 5 (589–922 K): $y = -320.54x + 0.5728$, $R^2 = 0.9532$; for Stellite 6 (300–700 K): $y = -137.79x + 0.4593$, $R^2 = 1$; and for Stellite 6 (700–922 K): $y = -416.85x + 0.8598$, $R^2 = 0.998$.

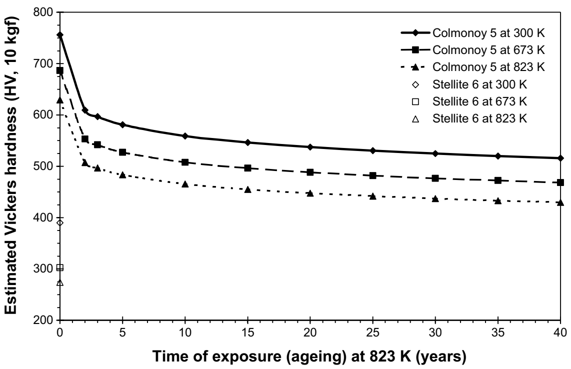

Fig. 5. Estimated hot-hardness of Ni-base Colmonoy 5 hardface deposit on exposure (ageing) at 823 K.

The hardness values of as-deposited Stellite 6 at 300, 673 and 823 K are also presented in Fig. 5 for comparison.

Figs. 2 and 5 show that although there is expected to be about 43% reduction in the hardness of Colmonoy 5 after 40 years of exposure at 823 K, the hardness of Colmonoy 5 is expected to remain sufficiently higher than the hardness of as-deposited Stellite 6. Hence, Colmonoy 5 deposits are expected to retain adequate hardness of about 516 VHN at RT and about 430 VHN at 823 K after 40 years of exposure (ageing) at 823 K. It needs to be pointed out here that the above discussion is based on 'estimated' hot-hardness calculated from room-temperature hardness measurements and the temperature dependence of hardness of the hardface deposit. These hot-hardness values are to be verified with actual hot-hardness measurements.

4. Conclusions

Replacement of Co-base Stellites by Ni-base Colmonoy as the hardfacing material will be beneficial for reducing the dose rate to personnel and shielding requirement during maintenance and decommissioning as also with respect to shielding in flasks during handling and removal. Colmonoy 5 hardface deposits would retain adequate hardness after 40 years of service exposure, its hardness would remain sufficiently higher than the hardness of as-deposited Stellite in spite of an expected reduction of about 43% in the hardness of Colmonoy 5. Hence, nickel-base Colmonoy 5 has been chosen as the hardfacing material for all the austenitic stainless steel components of PFBR.

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