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WELD OVERLAY COATINGS FOR
EROSION CONTROL

Progress Report Prepared for
Department of Energy

Task A: Literature Review

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I. Introduction

Hardfacing is the deposition of wear resistant material to new or worn surfaces of a component by weld overlay processes [1]. There are two main areas where hardfacing is used: 1) The rebuilding of worn metal parts to their original dimensions and 2) The protection of base metal against the loss of material. Usually, deposited hardfacing material has a different chemical composition from base metal. The deposition of weld overlay increases the life time of the material up to two or more times [2]. Protective weld overlay coatings are particularly advantageous in terms of coating quality. Weld overlays are applied by a fusion process which achieves a strong metallurgical bond with the substrate. The weld overlay coating is essentially immune to spallation [3,4]. By using powder mixtures, multiple alloys can be mixed in weld overlay coating systems to provide unique coating characteristics in order to achieve the best performance in corrosive and erosive environments.

This literature search revealed a lack of information about weld overlay coatings performance in erosive environment (e.g. boiler tubes, waterwalls on power plants). Although there has been a large amount of research that has been carried out in order to understand wear resistance of weld overlay coatings, few investigations evaluated the erosion aspects of wear. Nevertheless, weld overlay coatings show great promise for developing metallurgically bonded erosion and corrosion resistant coatings [5]. Given the many similarities between erosion and abrasion [6], highly abrasion-resistant material might expected to exhibit high erosion resistance.

The objective of this project is to determine the effect of composition and microstructure of weld overlay coatings on their erosion resistance. Several different coating groups can be used as weld overlays for erosion and erosion-corrosion protection. They can be separated into five groups: 1) Cobalt base/carbide-type alloys, 2) Nickel base/boride-type alloys, 3) Nickel base superalloys, 4) Iron base alloys, 5) Tungsten carbide alloys [1,7].

II. Cobalt-Base/Carbide Type Alloys

II.I. Abrasion and Erosion Resistance.

Cobalt base alloys are extensively used in many industries for components which require high resistance to wear of all kinds [8]. The main difference between the various cobalt base/carbide type alloys is in carbon content [1]. It was found that carbide volume fraction has a significant effect on erosion, abrasion and corrosion resistance of cobalt base alloys [1,9]. Table 1 lists typical compositions of the cobalt base/carbide type alloys. Chromium rich M_7C_3 is the predominant carbide in these alloys. Tungsten-rich M_6C carbide was also found in cobalt base alloys that had a high tungsten content. Chromium-rich $M_{23}C_6$ carbide is common in cobalt base alloys that have a low carbon concentration [1]. Photomicrographs of plasma transferred arc deposits of three cobalt base carbide/type alloys are shown in Figures 1a, 1b, and 1c [1]. It can be seen that tungsten and carbon contents have a strong influence on carbide formation. Both

elements increase the volume fraction of carbides [2]. The microstructure of cobalt base/carbide hardfacing alloys consists of primary- solidified hard phases such as M_7C_3 or other type of carbides that were listed above, depending on chemical composition. These carbides are embedded in a eutectic that consists of a metal matrix (Co-Cr-W solid solution) and eutectic hard phases. The structure of the eutectic hard phases consists of carbides (M_6C , M_7C_3 , $M_{23}C_6$) and intermetallic compounds [9]. It was documented by Berns et. al. [9] that hardness of the primary solidified phases in cobalt base alloys was much greater than the hardness of the eutectic. It was also found that coarse primary solidified carbides are responsible for excellent abrasion resistance of cobalt base alloys [2,9]. The eutectic hard phases also significantly contribute to the abrasion resistance of this alloy by covering the areas between primary carbides [1,9]. However, Ninham [10] found that the morphology of the carbides in cobalt base/carbide alloys has a much smaller effect on erosion performance than the composition of the matrix. The author also concluded that the hard coarse carbides which provide good abrasion resistance to cobalt base alloys cause a disruption of plastic flow during erosion. It is believed [10] that inhomogeneous nature of the plastic flow results in very high strain gradients, and consequently to void formation and cracking of the carbides. These processes facilitate material removal when the erodent particles strike a surface of the material and increases erosion rate [10]. Therefore, a hard coarse carbides in cobalt base/carbide alloys may be responsible for high erosion damage. However, it is still unclear how the

composition, size and shape of primary and secondary carbides in cobalt base alloys affect erosion rate.

The cobalt base matrix provides excellent strength of the material at high temperature, and chromium additions contribute to corrosion resistance of cobalt base/carbide type alloys [2]. For the past few years, a significant amount of research has been conducted in order to modify cobalt base/carbide alloys by additions of alloying elements that provide better abrasion, erosion and corrosion resistance [1,2,7-9]. Berns et.al [9], have found that by alloying additional Nb, Mo, and B the volume fraction of coarse, hard phases is raised. With respect to the base material certain amounts of Ni, W, Si, Cr, B and C that remain after the primary solidification of the hard phases bring fine eutectic phases (carbides, borides, intermetallic phases) together with the metal matrix [8,9]. For example, with addition of niobium in cobalt base alloys, primary carbide (MC) solidified from the melt an additional intermetallic phases dissolved in Co-Cr matrix [9].

II.II. Oxidation and Wet Corrosion.

The primary solidified carbides as well as the eutectic hard phases in Co base/carbide alloys show nearly no oxidative attack [9]. Therefore, the oxidation resistance of the entire material depends on the properties of the metal matrix [9]. It was documented that for Co base alloys Cr, Mo, Ni, and Si may have a positive effect on oxidation resistance, while Fe decreases the oxidation resistance [11].

The corrosion behavior of Co base alloys in acid

environments depends on the content of dissolved metallic elements in the metal matrix. Chromium is primarily responsible for corrosion protection in Co base hardfacing alloys. It was found that with a chromium content over 20 % the metal matrix is protected by Cr-oxide layers and thus, the wet corrosion resistance is greatly improved [9]. However, the mechanism of corrosion resistance of Co base hardfacing alloys in various environments has not been investigated. Therefore, further research needs to be done.

Because of the relatively high cost of cobalt, use of this coating for power plant applications may not be feasible. Therefore, alternate materials should be evaluated, with iron and nickel as potential cost effective substitutes.

III. Nickel-Base/Boride Hardfacing Alloys

Of all the hardfacing materials, the nickel-base/boride type alloys exhibit most complex microstructure [1]. The typical alloys compositions are shown in Table 2. Together with nickel, the other elements such as chromium, boron and carbon determine the level and type of hard phases within the structure of nickel-base/boride hardfacing alloys upon solidification [1]. The actual phases that form in the nickel base/boride type alloys are listed in Table 3. The microstructure of a commercial Ni-Cr-B-Si hardfacing alloy is shown in Figure 2 [11]. The microstructure shows initially solidified coarse chromium borides of MB type, which are embedded in a $\text{Ni}_3\text{B}/\text{Ni}$ -eutectic and Ni metal matrix

hardened by the dissolved Cr and Si. This alloy has good resistance against abrasive wear and good corrosion resistance [11]. It appears that abrasion resistance of Ni-Cr-B alloys is controlled by the amount of coarse hard phases in the microstructure [11]. This mechanism is very similar to that in cobalt base alloys. It was found that additions of Nb, Mo, W, and Si can increase the volume fraction of hard phases and therefore improve the abrasion resistance of these types of alloys [11-13]. Berns et.al. found that for hardfaced alloys the best abrasion wear resistance at a given volume fraction of coarse hard phases occurs in alloys having the lowest amount of metal matrix [9].

III.I Nickel-Base Superalloys.

Nickel-base superalloys can be defined as alloys that consists of Ni-Cr matrix, hardened by γ' phase $[\text{Ni}_3(\text{Al}, \text{Ti})]$, with further optional additions of cobalt, iron, tungsten, molybdenum, vanadium, niobium, tantalum, boron, zirconium, carbon, and magnesium [14]. It is well known that nickel-base superalloys are widely used for high temperature applications. Typical chemical compositions of nickel-base superalloys are shown in Table 4 [14]. Carbon concentration in Ni-base superalloys is lower than carbon concentration in Ni-base/boron alloys. Therefore, one can expect that the amount of carbide phases in Ni-base superalloys is lower than the amount of carbide phases in Ni-base/boride alloys.

Nickel-base superalloys may exhibit high erosion resistance due to their unique hardening mechanism. It was established that Ni-base superalloys have two major microstructural characteristics: 1) Solid-solution hardening of γ phase matrix and 2) Precipitation of γ' phase, Ni₃(Al,Ti) [14]. Tungsten, molybdenum, chromium, and aluminum contribute strongly to solid solution hardening. The precipitation of γ' phase is a phenomenon that separates the Ni-base superalloys from Ni-base/boride alloys. γ' phase is a unique intermetallic phase. Remarkably, the strength of γ' phase increases as temperature increases [14]. Moreover, the ductility of γ' phase prevents severe embrittlement of the microstructure [14]. The chemical composition of γ' phase can vary depending upon the amount of alloying elements in Ni-base superalloys.

This literature search revealed no information in the subject literature about resistance of weld overlays nickel base/boride alloys and nickel base superalloys against solid particle erosion. However, it seems necessary to conduct research in order to evaluate the erosion resistance of nickel base/boron and nickel superalloy weld overlays. Nickel base/boride type alloys and nickel base superalloys have a different chemical compositions of intermetallic phases in their microstructures. The effect of intermetallic compounds on erosion resistance of these alloys has to be determined.

IV. Iron-Base Hardfacing Alloys

It is believed that most hardfacing alloys develop their wear resistance from hard carbides [15]. In iron-base hardfacing alloys intermetallic compounds are responsible for wear protection of the material. The development of iron- base hardfacing alloys is based on two criteria: 1) limited use of strategically important and expensive materials (e.g. cobalt), 2) use of intermetallic compounds as the primary hard phase [15]. A wide range of compositions exist for iron-base hardfacing alloys [16]. Chemical compositions of some of the iron-base hardfacing alloys are shown in Table 5. The lack of information on erosion resistance of these alloys makes material selection very difficult. However, iron-base alloys have a great potential as an erosion resistant weld overlay coating [17]. For example, new Fe-Cr-Ni and Fe-Cr-Ni-Mo alloys have been developed for erosion protection of base metals [17]. It was found that these alloys have an amorphous structure that provides unique abrasion and erosion resistance. Recently, several new high silicon stainless steels have been developed for abrasion protection of bulk materials [1]. The high-silicon hardfacing alloys differ from other hardfacing materials in terms of their corrosion resistance, their mechanical properties at high temperature and their thermal stability. Silicon is an important matrix element and is a potential promoter of intermetallic precipitates. It has a powerful influence on the wear properties of a material [1]. However, the effect of silicon on erosion resistance of hardfacing alloys has not been determined. Scholl et.al. [15]

have found that Fe-Mo-Ni-Si-C hardfacing alloys, which had a microstructure of austenite/martensite matrix plus austenite/carbide eutectic, showed good abrasion resistance [15]. Apparently, the primary intermetallic compounds and carbides provided high abrasion resistance of this alloy [15]. These results suggest that the effect of chemical composition and microstructure of iron-base hardfacing alloys on their erosion resistance has to be studied.

Erosion behavior of iron-aluminide weld overlay alloy (14.8 wt% Al) has been studied by Baron [5]. It was found that Fe-Al weld overlays exhibit high erosion resistance at room and elevated (400⁰C) temperature. Erosion rates of Fe-Al weld overlay alloy versus erosion rates of plain carbon steel (1080) are shown in Figure 3. It was suggested that FeAl intermetallic compounds provide high erosion resistance of this alloy. The exact role of the FeAl intermetallic compounds in erosion requires further evaluation.

V. Tungsten-Carbide-Cobalt Base Alloys

Erosion of WC-Co based materials has been studied extensively [18,19,20] because of their very high erosion resistance relative to other alloys [1]. The erosion rates of WC-Co-base alloys compared with erosion rates of others materials are shown in Tables 6 and 7 [18]. These alloys have very high volume fractions (63-90%) of fine (1-3 um) carbides [18]. The carbides are located so close to each other that an impacting

particle often contacts more than one carbide [1]. Also, this material has a high matrix yield strength due to constraint of adjusted carbides, and cobalt that provide high yield strength of matrix due to solid solution strengthening [1,7]. Apparently, the combination of high volume fraction of carbides (more than 60%), their small size and matrix strength provides high erosion resistance of WC-Co based materials. Anand and Conrad [20,21] found that for angles of impact lower than 90^0 (Al_2O_3 erodent), the erosion rate of WC-Co based alloys decreases with increasing carbide volume fraction. All erosion tests were conducted at room temperature. However, the high temperature erosion behavior of WC-Co based alloys has not been studied. Also, application of this alloy as weld overlays did not receive attention in subject literature. Further research will be necessary to evaluate erosion resistance of weld overlays WC-Co alloys.

VI. Summary

- 1) In spite of similarities between abrasive wear and solid particle erosion, weld overlay hardfacing alloys that exhibit high abrasion resistance may not necessarily have good erosion resistance. The performance of weld overlay hardfacing alloys in erosive environments has not been studied in detail.
- 2) It is believed that primary-solidified hard phases such as carbides and intermetallic compounds have a strong influence on erosion resistance of weld overlay hardfacing alloys. However, relationships between size, shape, and volume fraction of hard phases in a hardfacing alloys and erosion resistance were not established.
- 3) Almost all hardfacing alloys can be separated into two major groups based upon chemical compositions of the primary solidified hard phases: a) carbide hardening alloys (Co-base/carbide, WC-Co and some Fe base superalloys) and b) intermetallic hardening alloys (Ni-base alloys, austenitic steels, iron-aluminides).

VII. Future research

Six types of weld overlays hardfacing alloys are being prepared for preliminary testing. They are follows: 2) Co-base/carbide alloys (stellites), 2) WC-Co base alloys (cermets), 3) Nickel base superalloys (Inconel), 4) Nickel-base/boron alloys (Deloro), 5) Fe-base superalloys (Tristelle), 6) Fe-base alloys (austenitic and martensitic stainless steels, iron-aluminide). These alloys will be separated into three major groups: 1) Cobalt containing alloys hardening alloys (Co-base/carbide, WC-Co, Fe-base/Co), 2) Nickel-base alloys (Ni-base superalloys, Ni-base/boride alloys) and 3) Iron-base alloys (Delcrome types, austenitic stainless and martensitic stainless steels). Erosion rates of alloys in a third group will be compared with erosion rate of iron-aluminide alloy (14.6 wt% Al). Two alloys will be selected for future research based upon results of the preliminary erosion tests. These two alloys will be studied in greater detail order to determine the relationship between microstructure of weld overlays alloys and their erosion resistance. These relationship will establish necessary criteria for providing best erosion resistance of weld overlay alloys.

VIII. Alloys Selected for Preliminary Erosion Testing

I. Cobalt Containing Alloys.

- a) Stellite 6 (Cobalt-base/carbide type alloy)
- b) K701-cermet type alloy (WC-Co base alloy)
- c) Tristelle TS-2 (Iron-base alloy)

II. Nickel-Base Alloys.

- a) Deloro 50 (nickel-base/boron alloy)
- b) Incoloy 800 (nickel-base superalloy)
- c) Inconel 625 (nickel-base superalloy)

III. Iron-Base Alloys.

- a) Delcrome 90
- b) Delcrome 92
- c) 316 austenitic stainless steel
- d) 420 martensitic stainless steel
- e) Cr-Mo White Iron

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Figure 1. Microstructure of Plasma-Transferred-Arc deposited hardfacing cobalt-base/carbide-type alloys. a) Stellite-20, b) Stellite-12, c) Stellite-6 [1].

Figure 2. Microstructure of nickel-base/boride hardfacing alloy (13 wt%-Ni, 2.4 wt%-B, 4 wt%-Ni).

Figure 3. Weight loss due to solid particle erosion vs. time for iron-aluminide weld overlay alloy (14.6 wt%-Al) and low carbon steel (0.18 wt%-C, 1080). Tests temperature-20°C and 400°C. Erodent- Al_2O_3 . Angles of impingement-30° and 90. [5].

Table 1. Nominal Chemical Composition (wt %) of Cobalt Base Hardfacing Alloys [7].

ALLOY	B	C	Co	Cr	Fe	Mn	Mo	Ni	Si	W
<u>Stellite 6</u>		1.1	Bal	27.7	3.0	1.0	1.0	3.0	1.1	4.5
<u>Stellite 12</u>	--	1.4	Bal	29.5	3.0	1.0	1.0	3.0	1.4	8.3
<u>Stellite 20</u>	--	2.5	Bal	32.5	3.0	1.0	1.0	3.0	1.0	17.3

Table 2. Nominal Chemical Compositions (wt %) of Nickel-base/Boride-Type Hardfacing Alloys [7].

Alloy	B	C	Co	Cr	Fe	Mn	Mo	Ni	Si	W
<u>Deloro 50</u>	2.4	0.4	--	11.0	3.0	--	--	Bal	4.0	--
<u>Deloro 60</u>	3.1	0.6	--	15.0	4.0	--	--	Bal	4.3	--

Table 3. Phases Formed in Nickel-Base/Boride-Type Hardfacing Alloys [1].

Chromium content	Secondary phases formed	Required conditions for secondary phase formation	Dominant hard phase
Low (5 wt%)	Ni_3Si	$\geq 3 \text{ wt\% Si}$	Ni_3B , complex carbides of M_{23}C_6 and M_7C_3 types.
Medium (15 wt%)	Ni_3Si	$\geq 2.5 \text{ wt\% Si}$	Ni_3B and chromium boride (usually CrB , although Cr_2B and Cr_3B_2 may also be present). Complex carbides of M_{23}C_6 and M_7C_3 types.
High (25 wt%)	Ni_3Si	$\geq 3.0 \text{ wt\% Si}$	CrB and Cr_5B_3 . Complex carbides of M_{23}C_6 and M_7C_3 types.

Table 4. Nominal Chemical Compositions of Nickel Base Superalloys [14].

Alloy Designation	Composition																C†
	C	Mn	Si	Cr	Ni	Co	Mo	W	Nb	Fe	Ti	Al	B	Zr	Other		
Cast Alloys																	
MC-102	* 0.04 **0.20	—	—	20.0 23.4	bal 67.4	—	6.0 3.8	2.5 0.8	6.5 4.3	—	—	—	—	—	—	850	
GMR 235-D	* 0.15 **0.69	—	—	15.5 16.5	bal 65.0	—	5.0 2.9	—	—	4.5 4.5	2.5 2.9	3.5 7.2	0.050 0.256	—	—	927	
MAR-M 421	* 0.15 **0.70	—	—	16.0 17.4	bal 58.5	9.0 8.6	2.0 0.08	3.8 1.2	2.0 1.2	—	1.8 2.1	4.3 9.0	0.015 0.078	0.05 0.03	—	975	
Alloy 713LC	* 0.05 **0.23	—	—	12.0 12.7	bal 70.4	—	4.5 2.6	—	2.0 1.2	—	0.6 0.7	5.9 12.1	0.010 0.050	0.10 0.06	—	980	
Alloy 713C	* 0.12 **0.55	—	—	12.5 13.2	bal 69.3	—	4.2 2.4	—	2.0 1.2	—	0.8 0.9	6.1 12.4	0.012 0.060	0.10 0.06	—	985	
IN-738	* 0.17 **0.80	—	—	16.0 17.5	bal 59.4	8.5 8.2	1.7 1.0	2.6 0.8	0.9 0.5	—	3.4 4.0	3.4 7.1	0.010 0.052	0.10 0.06	1.8Ta 0.6Ta	901	
B-1900	* 0.10 **0.47	—	—	8.0 8.7	bal 62.5	10.0 9.6	6.0 3.5	—	—	—	1.0 1.2	6.0 12.6	0.015 0.078	0.10 0.06	4.0Ta 1.3Ta	1000	
IN-100	* 0.18 **0.81	—	—	10.0 10.4	bal 55.8	15.0 13.8	3.0 1.7	—	—	—	4.7 5.3	5.5 11.0	0.014 0.070	0.06 0.04	1.0V 1.1V	1000	
IN-731	* 0.15 **0.67	—	—	10.0 10.4	bal 60.9	10.0 9.2	2.5 1.4	—	—	—	4.5 5.1	5.6 11.3	0.014 0.069	0.06 0.04	1.0V 1.1V	1000	
MAR-M 200	* 0.15 **0.74	—	—	9.0 10.2	bal 60.8	10.0 10.0	— 4.0	12.5 4.0	1.0 0.7	—	2.0 2.5	5.0 11.0	0.015 0.082	0.05 0.03	—	1020	
Wrought Alloys																	
A-286	* 0.05 **0.23	1.35 1.36	0.50 0.99	15.0 16.0	26.0 24.6	—	1.3 0.8	—	—	bal 53.3	2.0 2.3	0.2 0.4	0.015 0.076	—	—	780	
Inconel alloy 718	* 0.04 **0.19	0.20 0.21	0.30 0.62	18.6 20.7	bal 52.2	—	3.1 1.9	—	5.0 3.1	18.5 19.2	0.9 1.1	0.4 0.9	—	—	—	802	
IN-120	* 0.04 **0.19	—	—	21.0 23.4	bal 55.4	14.0 13.8	4.0 2.4	—	2.0 1.3	—	2.5 3.0	0.25 0.54	0.005 0.026	0.05 0.03	—	802	
Incoloy alloy 901	* 0.05 **0.24	0.10 0.11	0.10 0.21	12.5 14.0	42.5 78.0	—	5.7 3.5	—	—	bal —	2.8 3.4	0.2 0.4	0.015 0.080	—	—	826	
Nimonic 80A	* 0.06 **0.28	0.10 0.10	0.70 1.39	19.5 20.8	bal 70.8	1.1 1.1	—	—	—	—	2.5 2.9	1.3 2.7	—	—	—	826	
Inconel alloy X-750	* 0.04 **0.19	0.70 0.26	0.30 0.60	15.0 16.3	bal 70.7	—	—	—	0.9 0.5	6.8 6.9	2.5 2.9	0.8 1.7	—	—	—	835	
D-979	* 0.05 **0.24	0.25 0.53	0.20 0.41	15.0 16.7	bal 44.6	—	4.0 2.4	4.0 1.3	—	27.0 28.0	3.0 3.6	1.0 2.1	0.010 0.053	—	—	843	
Nimonic 90	* 0.07 **0.32	0.50 0.50	0.70 1.38	19.5 20.9	bal 54.3	18.0 17.0	—	—	—	—	2.4 2.8	1.4 2.9	—	—	—	848	
René 41	* 0.09 **0.43	—	—	19.0 21.2	bal 54.6	11.0 10.1	10.0 6.0	—	—	—	3.1 3.8	1.5 3.0	0.005 0.026	—	—	881	
M-252	* 0.15 **0.72	0.50 0.53	0.50 1.03	20.0 22.2	bal 54.4	10.0 9.8	10.0 6.0	—	—	—	2.6 3.1	1.0 2.1	0.005 0.026	—	—	884	
Waspaloy	* 0.08 **0.38	—	—	19.5 21.3	bal 56.3	13.5 13.1	4.3 2.5	—	—	—	3.0 3.6	1.3 2.8	0.006 0.031	0.06 0.04	—	894	
Inconel alloy 700	* 0.12 **0.57	0.10 0.10	0.30 0.61	15.0 16.6	bal 48.1	28.5 27.8	3.7 2.2	—	—	0.7 0.7	2.2 2.6	3.0 0.6	—	—	—	905	
Nimonic alloy 105	* 0.20† **0.91	1.0† 0.99	1.0† 1.9	14.6 15.3	bal 46.7	20.0 18.5	5.0 2.8	—	—	2.0† 2.0	1.2 1.4	4.7 9.5	—	—	—	925	
Udimet 500	* 0.08 **0.37	—	—	18.0 19.4	bal 51.0	18.5 17.6	4.0 2.3	—	—	—	2.9 3.4	2.9 6.0	0.006 0.030	0.05 0.03	—	927	
Nimonic alloy 115	* 0.15 **0.68	—	—	15.0 15.7	bal 53.2	15.0 13.8	3.5 2.0	—	—	—	4.0 4.5	5.0 10.1	—	—	—	950	
Udimet 700	* 0.08 **0.37	—	—	15.0 16.0	bal 50.3	18.5 17.4	5.2 3.0	—	—	—	3.5 4.0	4.3 8.8	0.030 0.153	—	—	960	

* Weight percent.

**Atomic percent.

† Temperature capability (temperature for 100 h life at 14 kgf/mm²). : Maximum.

Table 5. Nominal Chemical Compositions (wt. %) of Iron-Base Alloys for Hardfacing [1,7,16].

ALLOYS	C	Co	Cr	Fe	Mn	Mo	Ni	Si
Tristelle-2	2.0	12.0	35.0	Bal.	1.0	--	10.0	4.9
Delcrome-90	2.7	--	27.0	Bal.	1.0	--	1.0	1.0
Delcrome-92	3.7	--	1.5	Bal.	1.0	10.0	2.0	1.0
316 stainless steel	0.1	--	17.0	Bal.	2.0	2.5	12.0	3.5
430 stainless steel	0.1	--	17.0	Bal.	1.0	--	--	1.0
Low alloy steel	0.1	--	0.2	Bal.	1.0	--	--	

Table 6. Nominal chemical compositions of abrasion resistant alloys [18].

Alloy	Nominal Composition(wt%)	Vol. % Carbide
Pure Iron	Ingot Iron	0
Spheroidized 1020	Fe-0.2C	3.1
Spheroidized 1080	Fe-0.8C	12.0
Stellite No6	Co-30Cr-4W-1.1C	10.4
Haynes 6B	Co-30Cr-4W-1.1C	10.4
Tristelle TS-1	Fe-30Cr-10Ni-12Co-5Si-1C	8.3
Tristelle TS-2	Fe-35Cr-10Ni-12Co-5Si-2C	16.8
Tristelle TS-3	Fe-35Cr-10Ni-12Co-5Si-3C	21.4
Cr-Mo White Iron	Fe-20Cr-2.5Mo-2.6C	23.1
K90	WC-25Co	63.1
K3520	WC-20Co	69.5
K3055	WC-10Co	83.7
K701	WC-10Co-4Cr	76.2
K801	WC-5.7Ni-0.4Co	89.9
K162B	TiC-6NbC-2WC-25Ni-7Mo	78.5
K165	TiC-7WC-2.5NbC-9Ni-9Mo	88.8

Table 7. Erosion rates and volume percent of carbides for various alloys [18].

Alloy	Vol% Carbide	Volume Erosion Rate ($\text{m}^3\text{g}^{-1}\times 10^{-12}$)		
		30°	60°	90°
Pure Iron	0	9.70	7.76	5.77
1020	3.1	10.05	7.88	5.67
1080	12.0	9.99	8.19	6.22
Stellite No6	10.4	10.8	14.8	13.4
Haynes 6B	10.4	11.4	12.8	12.9
Tristelle TS-1	8.3	11.78	12.18	11.51
Tristelle TS-2	16.8	14.43	20.87	18.54
Tristelle TS-3	21.4	15.94	24.37	19.02
White Iron	23.1	10.61	13.33	12.27
K90	63.1	7.04	11.47	12.12
K3520	69.5	4.83	10.21	10.73
K3055	83.7	2.21	4.70	4.10
K701	76.2	0.11	0.10	0.20
K801	89.9	0.46	0.77	0.61
K162B	78.5	5.33	10.29	12.59
K165	88.8	1.23	2.51	1.95

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