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Some Commercial Cobalt-Free Hardfacing Alloys

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Fracture Toughness Testing and Toughening Mechanisms of Some Commercial Cobalt-Free Hardfacing Alloys

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Abstract

Hardfacing alloys are weld deposited to provide a wear resistant surface for structural base materials. Commercial low cobalt hardfacing alloys are being evaluated to reduce plant activation levels. Since hardfacing alloys typically must be resistant to cracking to assure adequate in service performance, fracture toughness is a critical material property. Fracture toughness (K_{IC}) measurements of Fe-base, Ni-base, and Co-base hardfacings were performed in accordance with ASTM E399-90 procedure in an effort to identify a tough cobalt-free alternative. Reduced scatter in K_{IC} data was observed for the Fe-base hardfacings, and the 95% lower bound K_{IC} values were generally higher than the Ni-base hardfacing alloys. Preliminary crack growth data obtained during pre-cracking indicate that the Ni-base hardfacings possess better fatigue crack growth resistance. However, none of the Fe-base or Ni-base hardfacings have K_{IC} values that are comparable to the reference Co-base hardfacing. The test specimens were machined from thick (0.5") weld deposits, and the microstructures of the test specimens are compared with the more prototypic, thinner deposits. Microstructural and fractographic examinations are used to characterize the fracture mechanisms and delineate the operative toughening mechanisms. Crack deflection and crack bridging toughening mechanisms are shown to be relevant for most of the commercial hardfacings.

1. Introduction

Commercial low cobalt hardfacing alloys are being evaluated in efforts to reduce the costs associated with nuclear plant activation and expensive Co-base weld consumables [1]. Hardfacings are typically weld deposited (0.2 to 0.5 cm thick) on base metals that possess appropriate mechanical properties for provision of a stiff, wear resistant surface [2]. Ni-base and Fe-base alloys have been wear tested as potential replacements for the Co-base alloy Stellite 6, but none have demonstrated galling resistance comparable to Stellite 6 [1,3].

Differences in coefficients of thermal expansion between base metals and hardfacing deposits can produce large thermal stresses under thermal shock conditions resulting in potential cracking of the hardfacing. Fracture toughness (K_{IC}) testing in accordance with ASTM E399-90 was pursued as a guide to quantitatively rank the expected thermal shock resistance of several low cobalt hardfacing alloys, independent of base metal. The results of K_{IC} testing and microstructural examinations to characterize toughening mechanisms are presented.

2. Experimental Procedure and Materials

Descriptions of the Ni-base (Colmonoy 5, Nucalloy 453, and Nucalloy 488) and Fe-base (NOREM 02, NoCo-M2, and ELMAX) candidates and Stellite 6 have been previously presented [1]. Five-layered hardfacing deposits (20 cm X 5 cm X 1.27 cm thick) were made on AISI type 304 stainless steel plate (1.27 cm thick) using Plasma Transferred Arc Welding (PTAW) with a 371°C pre-heat. The compact tension (CT) K_{IC} specimen shown in Figure 1 was machined from the top 0.64 cm of the weld deposit to minimize base metal dilution. The CT notch was orientated perpendicular to the welding direction, which is thought to be the direction of maximum residual weld stresses. Five-layer deposits were needed to produce the required specimen thickness for a valid K_{IC} test with minimal base metal dilution, but 2-layer deposits ($\approx$ 0.5 cm thick) are the minimum used in service applications. Metallographic examinations showed that the 0.64 cm thick CT specimens consisted of the top three weld layers, but subsequent metallography indicated that the microstructures were comparable to 2-layer deposits.

The CT specimens were K_{IC} tested at room temperature (RT, $\approx$ 22°C (72°F)), 149°C (300°F), and 316°C (600°F) using ASTM E399-90 procedures [4]. All CT specimens were pre-cracked at RT. Rudimentary fatigue crack growth data obtained during pre-cracking were observed to be generally consistent with the ranking of K_{IC} values for the alloys shown in Table II. However, Nucalloy 453 and NoCo-M2 had better fatigue resistance than Stellite 6 over the narrow range of stress-intensities evaluated. Specific fatigue crack growth testing would be needed to fully define the fatigue resistance of these materials. As expected for PTAW processing [2], the

differences between the chemistry of the CT specimens (Table I) and weld consumables were generally less than 10%, indicating that base metal dilution was minimal. Larger increases in Fe content were observed for two of the Ni-base alloys, with a change from 0.45% Fe for the Colmonoy 5 (HT# 5792-1) weld consumable (WC) to 2.44% Fe for the weld deposit and 5.51% Fe WC to 7.18% Fe for Nucalloy 488, and changes of only 4.95% Fe WC to 5.35% Fe for Colmonoy 5 (HT# 1159) and 2.9% Fe WC to 2.87% Fe for Nucalloy 453 were observed (see Table I). These levels of dilution were not unexpected for Ni-base PTAW deposition on an Fe-base substrate. The CT specimens were sectioned along the transverse and longitudinal section to characterize the weld layer microstructures, see Figure 1. Scanning Electron Microscopy (SEM) with Energy Dispersive X-ray (EDX) analysis was used for fractography of tested CT specimens to identify the fracture mechanisms.

3. K_{IC} Test Results

The majority of the data given in Table II meets the requirements of ASTM E399-90 for valid K_{IC} data [4]. Invalid results usually violated the $K_{max}/K_Q \leq 0.6$, $P_{max}/P_Q \leq 1.1$, or $2.5(K_Q/\sigma_y)^2 \leq B$ criteria, where K_{max} is the stress intensity used for the final stage of pre-cracking, K_Q is the measured K_{IC} value, P_{max} is the maximum load applied during testing, P_Q is the load used to determine K_Q , σ_y is the yield stress, and B is the specimen thickness. Errors in the assumption of unknown, σ_y values may explain deviation from the $2.5(K_Q/\sigma_y)^2 \leq B$ criteria. Since hardfacing alloys possess little, if any, tensile ductility, these criteria are probably too conservative for hardfacings; thus, invalid results were judged to be conditionally valid (K_{CV}) and were used for the data analysis in Table II. The K_{IC} values for most of the hardfacing alloys exhibited no temperature dependence from RT to 316°C (Figure 2). Only Stellite 6 and NoCo-M2 showed statistically significant differences between RT and 316°C K_{IC} values to the 95% confidence interval, but only a limited temperature dependence was observed. A temperature dependent change in the kinetics of a martensitic, stress-induced phase transformation occurring in Stellite 6 (face-centered cubic (fcc) to hexagonal close-packed (hcp)) and NoCo-M2 (fcc to martensite or hcp) could explain the slight temperature dependence [2].

The low Weibul modulus values show the substantial scatter for the Ni-base hardfacings. K_{IC} values for the Ni-base alloys were generally lower than the Fe-base alloys and Stellite 6, with the exception of Nucalloy 453 which displayed some K_{IC} values at the low end of the range for Stellite 6. The significant difference in K_{IC} between the two heats of Colmonoy shows the potent influence of slight chemistry differences (higher Fe, Cr, C, and Si; lower Ni and B for Heat #1159) and source of weld consumable (see Table I). The Ni-base alloy deposits with higher Si:B ratios tend to have the higher K_{IC} values, but a more thorough understanding of the relationship between chemistry

and K_{IC} was not established. When the Si:B ratio is above 3.3, the formation of the brittle Ni_3B/Ni -solid solution (Ni-ss) binary eutectic constituent is avoided by changing the primary solidification path to form tougher binary Ni_3Si/Ni -ss eutectic or ternary $Ni_3Si/Ni_3B/Ni$ -ss eutectic constituents [5].

The K_{IC} values for the Fe-base hardfacings (Table II) exhibit less scatter and the Weibul modulus values are generally higher than the Ni-base alloys. Lower carbon and higher nickel contents result in higher K_{IC} values for the Fe-base hardfacings, but a clear relationship between chemistry and K_{IC} values is not obvious. Considering the wide scatter of Nucalloy 453 K_{IC} values, the 95% lower bound K_{IC} values 95% for NoCo-M2 and NOREM 02 are higher in Table II. Although Nucalloy 453, NoCo-M2, and NOREM 02 have K_{IC} values at the low end of the data range for Stellite 6, the average K_{IC} values for Stellite 6 are significantly higher than all the alloys.

4. Examinations of Fracture Toughness Specimens and Toughening Mechanisms

Transverse metallographic examinations showed that the CT specimens contained the top three weld layers of the 5-layer deposit. The microstructures of the top (5th) weld layer were similar in morphology, dimensional scale, and dendrite structure to the top weld layer of prototypic 2-layer deposits. The microstructures of the lower layers (3rd and 4th) of the CT specimens were also similar in morphology and scale to the top layer of the 2-layer deposits, consistent with the minimal base metal dilution noted in the CT specimens. Heat input from weld deposition of the top layer homogenized the dendrite regions of the lower weld layers and produced a higher density of precipitates in these dendrites. The high density of precipitates in the Ni phase dendrites of Nucalloy 453 in Figure 3a indicates that this is a lower (3rd) weld layer. Since the top (5th) weld layer comprised 40% to 55% of the CT specimens, since base metal dilution was minimal for the CT specimen, and since the hardness values and morphology and dimensional scale of microstructures of the CT specimens were similar to the top layer of the respective 2-layer deposits, the CT specimens are assumed to be a fair representation of a 2-layer deposit.

The microstructures of the Ni-base alloys essentially consisted of a brittle matrix of various carbide, boride, and silicide phases surrounding Ni-phase dendrites of varying sizes and volume fractions of occurrence with varying distributions of precipitates in the dendrites, see Table III. Metallographic and fractographic SEM examinations of the monotonic fracture regions showed that the matrices of brittle phases failed by cleavage, while the Ni-phase dendrites typically exhibited varying degrees of plastic stretching, necking and dimpling. For example, SEM/EDX analysis of a pultrusion showing necking and dimpling on the Nucalloy 453 fracture surface (Figure 3b) confirmed that this was a Ni-phase dendrite surrounded by a matrix of boride, carbide, and silicide phases exhibiting cleavage.

Microstructures of the Fe-base alloys basically consisted of Fe-phase dendrites surrounded by an interdendritic matrix of carbide/Fe-phase lamella, see Figure 4a. The sizes and volume fractions of the dendritic phases, presented in Table III, varied slightly, and were similar to Stellite 6 for NoCo-M2, and less similar for ELMAX and NOREM 02. Stellite 6 consists of Co phase dendrites in a matrix of carbide/Co phase interdendritic lamella [1,2]. The most significant differences between the microstructures of the various Fe-base alloys were the volume fraction and structure of the dendritic regions: (1) NoCo-M2 dendrites were mostly austenite with some δ -ferrite and the finest precipitate distribution noted in all the Fe-base materials, (2) NOREM 02 dendrites contained a higher fraction of δ -ferrite with a coarse precipitate distribution at the austenite/ δ -ferrite interfaces, and (3) ELMAX dendrites were fully ferrite with the highest precipitate density and coarsest precipitate sizes. The presence of δ -ferrite precipitates in the dendrites is believed to provide greater resistance to galling wear damage [1]. Metallographic and fractographic SEM images of the fracture surface in the monotonic loading region (Figure 4) show cleavage of the interdendritic regions, while the Fe phase dendrites display varying amounts of plastic stretching and necking with deformed dendrites bridging the crack. SEM/EDX analysis showed that the Fe phase regions exhibited necking and dimpling, while cleavage was observed in the interdendritic regions. Although not shown here, interdendrite regions in Stellite 6 were also observed to experience cleavage, while necking and dimpling were noted in the Co phase dendrites.

Crack bridging in the hardfacing alloys evaluated here is evidenced by stretching and necking failure of discrete ductile phase particles in the wake of a crack propagating through a brittle matrix [6,7]. The necking and dimple failure of dendrites observed in these hardfacing alloys indicates that crack bridging may be an important toughening mechanism. Crack bridging toughening (ΔK_{CB}) of a brittle matrix (K_m) has been quantified as [6,7],

$$\Delta K_{CB} = E_d \sqrt{\chi V_f \frac{\sigma_o}{E_d} a_o} \quad (1)$$

where E_d is the modulus of the ductile phase, χ is the work of rupture for the ductile phase, V_f is the volume fraction of ductile phase, σ_o is the yield strength of the ductile phase, and a_o is the ductile phase radius.

Crack deflection resulting in a local decrease in stress intensity at a crack tip in mode I loading (ΔK_I) produced by a kink of length D at an angle θ , with a distance (S) separating the kink, is the primary mechanism for increasing the inherent toughness of the brittle matrix (K_m) and is defined by [8],

$$\Delta K_I = \frac{K_m}{\left[\frac{D(\cos^2(\frac{\theta}{2})) + S}{D + S} \right]} \quad (2)$$

Using the assumed and measured parameters given in Table III, the toughness of the hardfacing alloys is calculated by addition of Eqs. (1) and (2).

The calculated toughness values generally overestimate the measured K_{IC} values shown in Figure 5 with the closest match observed for the Ni-base alloys. Crack bridging (Eq. (1)) was determined to provide a much larger contribution to toughening than crack deflection. The lower dendrite volume fraction and larger dendrite spacing for the Ni-base alloys likely results in the dominance of crack bridging and closer agreement between calculated and measured K_{IC} . However, given the possible errors in assumed material properties, the agreement between calculated and measured K_{IC} values as shown in Figure 5 is reasonable, which indicates that crack bridging and crack deflection are relevant monotonic toughening mechanisms. Good agreement between Eq. (1) and measured K_{IC} values has been observed for a variety of brittle matrix materials that are thought to exhibit crack bridging [6,9]. The agreement between calculated and measured K_{IC} for the hardfacing alloys in Figure 5 is comparable to the fit observed for other brittle materials [6,9].

Dendrite necking was absent in the fatigue pre-crack regions for all hardfacing alloys, which indicates that crack bridging was not an important toughening mechanism in fatigue. Fatigue failure of ductile phase particles prior to necking generally prevents crack bridging toughening in fatigue, as reported for other brittle matrix materials [6]. Further work would be needed to clarify toughening mechanisms active in fatigue.

Microstructural characterization summarized in Table III, and results of toughness calculations given in Figure 5 provide some insight into microstructure- K_{IC} relationships in the various hardfacing alloys. The measured dendrite volume fractions, values for work of rupture, and estimated dendrite yield strengths given in Table III were generally lowest for the Ni-base alloys, which would be expected to result in less crack bridging toughening. Relatively small contributions to toughening by crack bridging probably leads to the lower K_{IC} values measured for most of the Ni-base alloys. The lower volume fraction of dendritic phases and wide variation in dendrite sizes in the fracture path probably explain the wider scatter of K_{IC} values observed for the Ni-base alloys. The Ni-base alloys with the higher dendrite volume fractions and larger dendrite sizes (Nucalloy 453 and Colmonoy 5 (HT#1159))

exhibited the highest K_{IC} values, which is consistent with the crack bridging model (Eq. (1)). The higher density of fine precipitates observed in the dendrites of Nucalloy 453 and Colmonoy 5-HT#1159, which would be expected to result in higher dendrite yield strength (σ_0 in Eq. (1)), providing more potent crack bridging toughening, may produce the lower work of rupture values observed for Nucalloy 453 and Colmonoy 5-HT#1159 (Table III). The higher Si:B ratio in Nucalloy 453 and Colmonoy 5-HT#1159 (Table I) is also expected to produce higher K_{IC} values due to the formation of a tougher binary Ni_3Si/Ni -ss eutectic and ternary $Ni_3Si/Ni_3B/Ni$ -ss eutectic matrix constituents [5]; however, results for Nucalloy 488 are inconsistent with this relationship between Si:B ratio and K_{IC} . Thus, the crack bridging toughening mechanism provides the most accurate and consistent description of K_{IC} -microstructure.

The Fe-base alloys are observed in Table III to have higher volume fractions of dendrites, works of rupture, and assumed yield stresses, which are expected to provide more potent crack bridging toughening and higher K_{IC} values in comparison to the Ni-base alloys. Although the dendrite volume fraction for NOREM 02 is much lower than NoCo-M2, the higher fraction of δ -ferrite in the NOREM 02 dendrites likely increases the dendrite yield strength and work of rupture for improved crack bridging toughening, resulting in K_{IC} values almost comparable to NoCo-M2 (see Table III and Figure 5). The higher carbon content for ELMAX produces a lower dendrite volume fraction and a coarse precipitate distribution in the dendrites, which probably lessens crack bridging and results in the lower K_{IC} values. The high dendrite volume fraction and assumed high dendrite yield strength for Stellite 6 should result in vigorous crack bridging toughening consistent with the highest K_{IC} values being observed for Stellite 6. The Stellite 6 dendrites may also undergo a stress-induced martensitic fcc to hcp transformation to further assist toughening [2].

5. Summary

The ASTM E399-90 method was used to measure the K_{IC} of hardfacing CT specimens machined from thick (5-layer) PTAW deposits. Metallographic examination, hardness measurements, and chemical analysis results verified that the microstructure of the K_{IC} specimens was comparable to the top weld layer of more prototypic 2-layer deposits. The 95% lower bound K_{IC} values for the Ni-base alloys were generally the lowest with the widest scatter. The 95% lower bound K_{IC} values for the Fe-base alloys were generally higher than the Ni-base alloys with less scatter. None of the Fe- or Ni-base alloys had average K_{IC} values equivalent to the Co-base hardfacing Stellite 6, and only one Ni-base alloy (Nucalloy 453) and two Fe-base alloys (NoCo-M2 and NOREM 02) displayed individual K_{IC}

values at the low end of the range for Stellite 6. Fractographic examinations revealed evidence of crack bridging and crack deflection mechanisms. Reasonable agreement between calculated and measured fracture toughness values indicates that crack bridging and crack deflection are relevant toughening mechanism for the hardfacing alloys, with crack bridging providing the most significant contribution to toughening.

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TABLE I. Combustion and Inductively Coupled Plasma Chemistry Measurements of Tested K_{IC} Specimens,
with the exception of ELMAX.

Alloy	Fe	Ni	Cr	C	Si	Mn	Mo	W	Co	O	N	S	B	Sn	V	Nb
<u>Co-base Alloy</u>																
Stellite 6 ⁽¹⁾	2.04	2.16	29.27	1.24	1.62	0.33	0.03	4.27	58.41	.0040	.072	.006	--	--	--	.006
<u>Ni-base Alloys</u>																
Colmonoy 5 ⁽²⁾ HT# 5792-1 Si/B = 1.90 ⁽³⁾	2.44	80.05	11.53	0.44	4.74	--	--	--	--	.0015	.0039	.0003	2.49	--	--	<.02
Colmonoy 5 ⁽²⁾ HT# 1159 Si/B = 3.32 ⁽³⁾	5.35	72.77	15.05	0.73	5.88	--	--	--	--	.0029	.0057	.0020	1.77	--	--	<.02
Nucalloy 453 ⁽¹⁾ Si/B = 8.14 ⁽³⁾	2.87	79.26	10.20	0.69	5.62	--	--	2.25	--	.0037	.0030	<.000	0.69	--	--	--
Nucalloy 488 ⁽¹⁾ Si/B = 6.86 ⁽³⁾	7.18	65.25	18.22	0.31	6.93	--	--	1.03	--	.0037	.0093	<.000	1.01	0.75	--	--
<u>Fe-base Alloys</u>																
NoCo-M2 ⁽¹⁾	57.59	7.56	25.10	0.92	3.01	5.07	1.93	--	--	.0075	0.086	.0140	--	--	--	.007
NOREM 02 ⁽⁴⁾	60.38	4.20	25.36	1.23	3.78	4.26	1.95	--	--	.0082	0.171	.0130	--	--	--	.005
ELMAX ^(5,6)	BAL	0.13	18.2	1.71	0.88	0.32	1.10	0.34	--	--	0.091	.021	--	--	3.05	--

- Notes: 1. Tradename of Stoodly Deloro Stellite Div. Of Thermodyne Industries, Goshen, IN.
2. Tradename of Wall Colmonoy Corp., Madison Heights, MI.
3. The Si:B ratio was calculated for each Ni-base alloy by dividing the measured Si content by the boron content.
4. Trademark of Electric Power Research Institute, Palo Alto, CA.
5. Tradename of Uddeholm Corp., Rooling Meadows, IL.
6. Weld consumable chemistry reported in chemical certification.
7. The symbol "--" means the chemistry for this element was not measured.
8. Cobalt contents were not measured for the Ni-base and Fe-base alloys, as cobalt contents were reported to be at most <0.05% in all chemical certifications.
9. The two heats of Colmonoy 5 were procured from different producers of weld consumables.

Table II. Summary of K_{IC} Data Hardfacing Alloys.

Hardfacing Alloy	K_{IC} Fracture Toughness Data [MPa $\sqrt{m}$]			Average of All K_{IC} Data $\pm$ Standard Deviation [MPa $\sqrt{m}$]	Weibul Modulus ⁽⁸⁾ and 95% Lower Bound K_{IC} value ⁽⁹⁾ [MPa $\sqrt{m}$]
	Room Temperature	149°C	316°C		
Stellite 6	30.3, 34.1, 34.3, 34.7, 34.8, 36.9	34.7 ¹ , 35.7 ¹ , 38.2 ¹	37.0 ¹ , 40.1 ¹	RT = 34.2 $\pm$ 2.1 149°C = 36.3 $\pm$ 1.8 316°C = 38.5 All = 35.6 $\pm$ 2.5	m = 13.3 $K_{IC}(95\% \text{ LB}) = 29.5$
Colmonoy 5 HT# 5792-1	12.5 ² , 14.9 ^{2,4} , 15.4 ^{2,3,5,6} , 22.2	13.1 ^{2,5,6} , 17.5	15.1, 17.0	15.9 $\pm$ 3.0	m = 5.0 $K_{IC}(95\% \text{ LB}) = 9.6$
Colmonoy 5 HT# 1159	24.5, 24.6, 24.6, 24.8, 27.5	23.3, 32.1	26.0, 27.6	26.2 $\pm$ 2.7	m = 8.8 $K_{IC}(95\% \text{ LB}) = 19.7$
Nucalloy 453	27.3 ^{2,7} , 30.7, 31.3, 31.4, 36.9	25.8, 28.5, 30.0	29.3, 30.7	30.2 $\pm$ 3.0	m = 9.7 $K_{IC}(95\% \text{ LB}) = 23.4$
Nucalloy 488	20.3 ³ , 20.6 ² , 21.7, 22.1, 22.1, 22.6 ^{2,7} , 24.1	20.6 ² , 22.3, 24.8	22.0, 22.7	22.2 $\pm$ 1.4	m = 16.1 $K_{IC}(95\% \text{ LB}) = 19.1$
NoCo-M2	25.5, 28.6, 28.7, 28.7, 29.1, 29.1 ⁷ , 29.7, 29.7	29.7, 30.3, 30.8 ¹	29.6, 31.0 ¹	RT = 28.6 $\pm$ 1.3 149°C = 30.2 $\pm$ 0.6 316°C = 30.3 All = 29.3 $\pm$ 1.4	m = 19.6 $K_{IC}(95\% \text{ LB}) = 25.8$
NOREM 02	25.1, 25.1 ⁷ , 27.3, 27.5, 28.4, 29.6	26.8, 26.9, 27.7	26.9 ³ , 27.3 ³	27.1 $\pm$ 1.3	m = 20.1 $K_{IC}(95\% \text{ LB}) = 24.0$
ELMAX	20.3 ^{3,6} , 20.8 ³ , 21.1 ^{2,6} , 21.7 ^{3,6} , 24.0 ^{3,6} , 24.0 ^{3,6} , 27.9 ^{2,6,7}	19.5, 20.1, 20.5	22.3, 23.1	21.9 $\pm$ 2.3	m = 9.1 $K_{IC}(95\% \text{ LB}) = 16.8$

- Notes:
1. Conditionally Valid Test. Conditionally valid tests met the relaxed criteria: $(K_Q/\sigma)^2 \leq B$ in lieu of the $2.5(K_Q/\sigma)^2 \leq B$ criterion (with assumed yield stress values) of ASTM E399-90, section 9.1.3.
 2. Conditionally Valid Test. Conditionally valid tests met the following relaxed criteria: $0.6K_Q < K_{max} < 0.8K_Q$ in lieu of the $K_{max}/K_Q \leq 0.6$ criterion of ASTM E399-90, section A2.1.2.
 3. Conditionally Valid Test. Conditionally valid tests satisfied the relaxed criteria: $P_{max}/P_Q \leq 1.5$ in lieu of the $P_{max}/P_Q \leq 1.1$ criterion of ASTM E399-90 section 9.1.2.
 4. Invalid test criteria. Crack front was more than 10° out of plane per ASTM E399-90 section 8.2.4.
 5. Invalid test criteria. Surface pre-crack length differed more than 10%, per ASTM E399-90 section 8.2.2.
 6. Invalid test criteria. Variation of pre-crack length was greater than 10%, per ASTM E399-90 section 8.2.2.
 7. Invalid test criteria. Initial linear portion of load displacement curve was not between 0.7 and 1.5, per ASTM E399-90 section 8.4.
 8. Weibul modulus values were determined using the standard method.
 9. The 95% lower bound values were the 0.05 probability of failure values taken from the Weibul plot.

TABLE III. Measured and Assumed Values used to calculate fracture toughness using Eqs. (1) and (2).

Alloy	Measured Values for Eq. (1)					Measured Values for Eq. (2) Note 3			Assumed Values		
	$V_f \pm \text{St. Dev.}$	$(V_f) \times V_{f(\text{ductile})}$ Note 1	$a_0 \pm \text{St. Dev.}$ [μm]	Dendrite Neck Length $\pm$ St. Dev. [μm]	χ Note 2	D [μm]	S [μm]	θ	K_m [MPa $\sqrt{\text{m}}$] Note 4	E_d [GPa] Note 5	σ_o [MPa] Note 6
Stellite 6	$0.86 \pm .04$	0.68	9.1 ± 5.5	3.3 ± 1.7	1.71	17.8	32.0	56.2	10.6	213.7	413.7
<u>Ni-base Alloys</u>											
Colmonoy 5 ⁽⁷⁾	$0.51 \pm .02$	0.36	8.2 ± 4.2	3.8 ± 1.8	2.27	16.8	54.5	53.1	3.3	206.9	59.4
HT# 5792-1	$0.53 \pm .02$	0.46	8.9 ± 5.2	4.8 ± 2.2	2.81	19.6	28.5	58.6	3.3	206.9	59.4
Colmonoy 5 HT# 1159	$0.63 \pm .04$	0.42	17.1 ± 8.4	5.4 ± 3.4	1.50	22.9	34.7	43.4	3.3	206.9	258.6
Nucalloy 453	$0.66 \pm .05$	0.49	24.3 ± 11.5	7.4 ± 3.5	1.45	11.8	22.0	48.2	3.3	206.9	258.6
Nucalloy 488	$0.56 \pm .04$	0.33	11.4 ± 5.5	5.4 ± 2.6	2.36	42.2	71.2	57.6	3.3	206.9	258.6
<u>Fe-base Alloys</u>											
NoCo-M2	$0.87 \pm .03$	0.65	12.0 ± 5.2	7.2 ± 2.2	2.91	14.4	24.5	62.4	3.3	211.0	225.1
NOREM 02	$0.82 \pm .07$	0.57	8.3 ± 5.0	7.1 ± 2.1	4.05	13.9	24.7	57.9	3.3	211.0	296.5
ELMAX	$0.72 \pm .02$	0.40	20.1 ± 14.4	6.0 ± 3.0	3.07	53.8	59.0	51.6	3.3	211.0	344.8
Notes:											
1. $V_{f(\text{ductile})}$ was the fraction of dendrites on the fracture surface that were ductile. The product $(V_f) \times V_{f(\text{ductile})}$ was used in Eq. (1).											
2. The work of rupture (χ) was determined from a linear relationship in [7] using length of dendrite stretch divided by a_0 .											
3. These are averages from representative regions of the fracture surfaces.											
4. K_m values assumed for Stellite 6 ~WC/3%Co Cermet [9] and Ni-base and Fe-base alloys ~Al ₂ O ₃ [9].											
5. E_d values assumed for Stellite 6 ~Stellite [10], Ni-base alloys ~pure Ni [10], and Fe-base alloys ~NOREM [11].											
6. σ_o values assumed for Stellite 6 ~Haynes 25 [10], Colmonoy 5 HT# 5792 ~ pure Ni [10] and other Ni-base alloys ~72Ni-16Cr-8Fe-2Si-0.4C alloy [10]; and Fe-base alloys ~CF-8 with varying δ -ferrite [10].											
7. Two different specimens were analyzed for Colmonoy 5, HT#5792-1.

Fig. 1. Schematic of 5-layer hardfacing deposited on AISI type 304 stainless steel (304SS) base metal. The general CT specimen geometry and notch orientation are shown with respect to the direction of PTAW deposition, as are the transverse and longitudinal plane orientations used for metallography.

Fig. 2. Summary plot of measured K_{IC} [$\text{MPa}\sqrt{\text{m}}$] versus test temperature [$^{\circ}\text{C}$] for Stellite 6 (S6), Colmonoy 5-Heat# 5792-1 (Col5-1), Colmonoy 5-Heat# 1159 (Col5-2), Nucalloy 453 (N453), Nucalloy 488 (N488), NoCo-M2 (NoCoM2), NOREM 02 (NOREM), and ELMAX. The plotted K_{IC} data are given in Table II. The lines represent a linear regression fit of K_{IC} versus temperature.

Fig. 3. Post-test examination results from monotonic loading region of Nucalloy 453 K_{IC} specimens: (a) longitudinal metallography of polished and etched (electrolytic 10% chromic acid) section showing Nucalloy 453 microstructure with cleavage of brittle matrix regions and necking of Ni-phase dendrites, and (b) SEM fractograph of Ni phase dendrite showing necking and dimpling with cleavage of adjacent brittle matrix regions.

Fig. 4. Post test examination results from monotonic loading region of Fe-base alloys: (a) longitudinal metallography of polished and etched (electrolytic 40% nitric acid) section showing NoCo-M2 microstructure with cleavage of brittle matrix regions, necking of Fe-phase dendrites, and Fe-phase dendrites bridging a secondary crack, and (b) SEM fractograph of Fe-phase dendrite on NOREM 02 fracture surface showing necking and dimpling with cleavage of adjacent brittle, interdendritic regions.

Calculated K_{IC} [MPa $\sqrt{m}$]

Fig. 5. Plot of calculated K_{IC} values determined from the addition of Eqs. (1) and (2) using the input given in Table III versus measured K_{IC} values for Stellite 6 (Stellite, solid star), Colmonoy 5-Heat# 5792-1 (Col5-1, solid diamond), Colmonoy 5-Heat# 1159 (Col5-2, open diamond), Nucalloy 453 (N453, solid circle), Nucalloy 488 (N488, open circle), NoCo-M2 (solid dark square), NOREM 02 (open square), and ELMAX (solid grey square). Two Colmonoy 5-Heat# 5792-1 (Col5-1, solid diamond) specimens were examined, while only one specimen was examined for all other alloys. The line of exact match represents agreement between calculated and measured K_{IC} values.