Low-Stress Sliding Abrasion Resistance of Cobalt-Based Surfacing Deposits Welded with Different Processes

The influence of the welding process on the microstructure and subsequent wear resistance of the deposit is observed

BY J. C. CASSINA AND I. G. MACHADO

ABSTRACT. The main aim of this work was to study the low-stress sliding abrasion resistance and to compare the microstructures of surfacing deposits of the cobalt-based Alloy ERCoCr-A (Stellite® 6)[1] welded by three processes: gas tungsten arc, shielded metal arc, and oxyacetylene. To carry out this research, a test apparatus for simulating low-stress sliding abrasion conditions was constructed, following the recommended procedures of the ASTM G65-85 standard.

Other important characteristics of the deposits were analyzed, such as chemical composition and hardness.

A large process influence on the microstructure was observed, especially with regard to the thickness of the interdendritic network of carbides, which was observed by optical and scanning electronic microscopy.

The low-stress sliding abrasion resistances of the deposits appear to be strongly related to their microstructures, in particular to the amount and distribution of the carbides. Concerning the influence of hardness, its general importance was established, though in this case, where the microstructures are similar, its influence is greater than when they are dissimilar.

Introduction

There are four main ways in which inanimate objects lose their usefulness: obsolescence, breakage, corrosion and wear.

For complicated objects, the latter is almost always the most important mechanism (Ref. 1).

Nevertheless, there has been insufficient interest in wear phenomena and a lack of appreciation of the importance of wear. This situation is the result of the historically late growth of tribology (the science of wear) and the recent elucidation of the laws of wear.

The probable reason is that wear phenomena are so complicated that systematic investigation is very difficult.

Methods of reducing wear have been under development throughout the industrial age, but in the last few decades, with the growing realization of the high cost of wear, the pace of development has accelerated. These developments include changes in design, improved lubrication and the use of more resistant materials. These may be bulk materials, but they can also be surface layers on softer and tougher substrates (Ref. 2).

Many different wear resistant coatings are now available so that it is quite a task for the design engineer to select the optimum material and coating process for a given application.

Particularly, the deposition of protective surfaces by welding is widely used in the repair of worn components, as well as in the manufacture of new equipment, where the construction of whole components from a wear resistant alloy would be impractical or too costly. These coatings are generally applied only to those areas for which maximum exposure to wear is encountered.

KEY WORDS

Abrasion Resistance
ERCoCr-A
Cobalt-Based Alloy
Microstructure
Surfacing Deposits
Chemical Composition
Hardness
Low-Stress Sliding
GTAW
SMAW

Types of Wear

It is very important to establish the nature of the wear taking place in a given situation, because the action taken and the materials selected to reduce wear will depend critically on the nature of the wear process.

Rather than classifying wear in terms of the operative wear mechanisms, common practice (Refs. 1, 9) is to group together these mechanisms and identify major wear types. Even with this grouping, disagreement still prevails over the classification of wear types.

Rabinowicz (Ref. 1) has identified four major types of wear: adhesive, abrasive, corrosive and surface fatigue. Davies and Bolton (Ref. 9), however, listed six wear types: adhesive, abrasive, erosion, contact fatigue, cavitation, and corrosive wear. The staff of researchers of International Research and Development (IRD) (Ref. 2) have identified the following principal wear types: adhesive, abrasive, fatigue wear and combined wear types. These points illustrate the complexity of wear and the difficulty encountered in classification.

Eyre noted that abrasion is the most frequently encountered wear type in industry, contributing some 50% toward the total wear experienced. Adhesive wear is seen as the second most prevalent, but accounting for only 15% of industry's wear problems (Ref. 4).

Abrasive Wear

Rabinowicz (Ref. 1) has established that this kind of wear occurs when a

---

J. C. CASSINA is a Mechanical Engineer in the Materials Science Dept., and I. V. MACHADO is a Metallurgical Engineer and the Head of Welding Laboratory, Center of Technology, Federal University of Rio Grande do Sul, Porto Allegre, Brazil.

[1] *Stellite is a registered trademark of Thermadyne, Inc.*

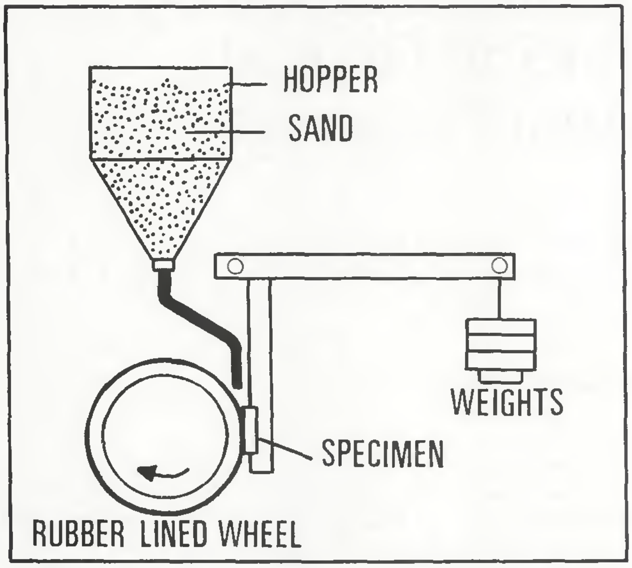

Fig. 1 — Schematic view of an abrasive test machine.

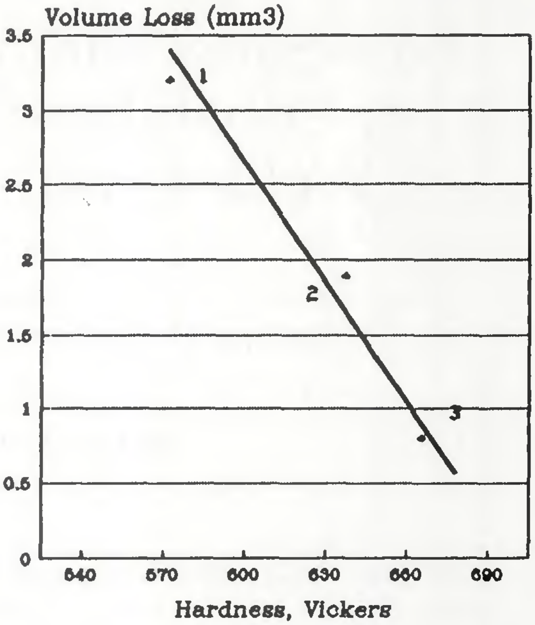

Fig. 2 — Abrasive wear resistance vs. hardness for each welding process.

rough hard surface, or a soft surface containing hard particles, slides on a softer surface and ploughs a series of grooves in it. The material from the grooves is displaced in the form of wear particles, generally loose ones.

The IRD (Ref. 2) has described abrasive wear as the removal of material from a surface by a harder material impinging on, or moving along, the surface under load. The hard material indents the surface and, depending on the properties of the materials and the type of motion or loading, may remove material by various mechanisms. Wear by materials of similar hardness can occur as well.

Low-Stress Sliding Abrasion

When abrasive material slides over a surface without significant impact, the wear produced by the cutting or ploughing action is termed low-stress abrasion.

It is also defined as wear resulting from a cutting action by sliding abrasives at stresses below their crushing strength (Ref. 5). Usually, the resulting wear pattern shows scratches, and the amount of subsurface deformation is minimal.

A wide range of materials is used to resist low-stress abrasion, the choice being determined by the hardness of the abrasive and the prevailing operating and environmental conditions.

Cobalt-Based Alloys

There are two allotropic forms of cobalt: a hexagonal close-packed (hcp) form, ε, stable at temperatures below 417°C (783°F); and a face-centered-cubic (fcc) form, α, stable at higher temperatures up to the melting point 1495°C (2723°F) (Ref. 6).

The $\varepsilon \leftrightarrow \alpha$ transformation is sluggish and the fundamental reason for this fact is to be found in the very low free-energy change associated with the transformation. The application of even low stresses has a significant influence on this allotropic transformation. Cobalt is typically found (as are its alloys) in a metastable fcc form at room temperature because of the sluggishness of the transformation.

The question of the influence of plastic deformation on the allotropic transformation of cobalt has been extensively studied. By moderate deformation at room temperature, (metastable) fcc cobalt is altered wholly or in part into the hcp form, which is then very stable and persists even after heating for 200 h at 800° to 1000°C (1472° to 1832°F) (Ref. 6).

Cobalt alloys with a large number of alloying components have been investigated, with particular reference to the existence of solid solutions and intermediate phases and to the change of transformation temperature on alloying. The available data are most conveniently presented in the form of equilibrium diagrams.

The occurrence of the hcp $\leftrightarrow$ fcc transformation in cobalt-based alloys is a potential source of wear property improvement, *i.e.*, the hcp phase may, either alone or intimately mixed with the fcc form, offer a more resistant material.

The microstructure of the cobalt-based wear-resisting alloys has been described by Sharp (Ref. 7), Avery (Ref. 8), and more recently, by the ASM committee on hardfacing (Ref. 5). ERCoCr-A typically exhibits a cobalt-rich dendritic structure (fcc crystal structure) with a surrounding constituent consisting of chromium-rich eutectic carbides of the M_7C_3 type. The probable composition is $(Cr\ 0.85, Co\ 0.14, W\ 0.01)_7C_3$, which has a hexagonal crystal structure.

High-carbon-content alloys are hypereutectic and contain primary M_7C_3 carbides, which are hexagonal in shape and are considerably larger than the eutectic carbides. High-carbon-content alloys also contain M_6C-type carbides, the probable composition of which may vary from $(Co,W)_6C$ to $(Co_{0.66},W_{0.34})_6C$.

Wear Tests

It must be emphasized that the order of merit of different coatings, established in a particular type of test, may only be applicable to a limited range of service conditions (Refs. 2, 9). In consideration of a service application using laboratory data, great care should be taken in assessing whether a particular test method effectively simulates the application. Even in cases in which laboratory simulation is representative, prototype testing is recommended prior to the adoption of a coating in production.

Dry Sand/Rubber Wheel Abrasion Test

Figure 1 shows a rubber wheel abrasive wear test unit, constructed in accordance with the ASTM G65-85 standard (Refs. 10–12). The test used abrasive

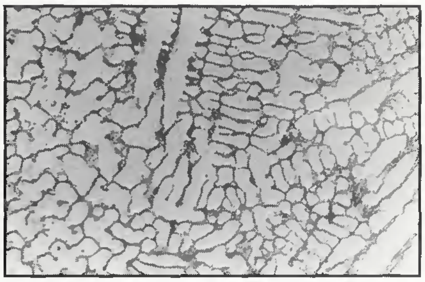

Fig. 3 — GTAW process, second layer. 200X.

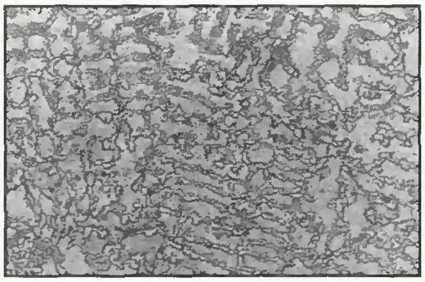

Fig. 4 — OAW process, second layer. 200X.

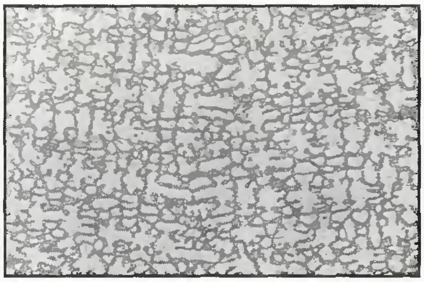

Fig. 5 — SMAW process, second layer. 200X.

powder of silica sand AFS 50/70, and it was performed by feeding abrasive particles down into the rubber wheel/test piece interface from a hopper at a rate of between 250 g/min (8 oz/min) and 350 g/min (11 oz/min). The weld surfaced portion of the test specimen was pressed at a load of 130 N (29 lb-ft) against the neoprene rubber wheel rotating at 200 ±10 rpm, with the abrasive particles in between, for 2000 revolutions (Procedure B). The indicator of abrasion is the wear loss of the specimen. To carry out the tests, a test apparatus was constructed at the welding laboratory of the Centre of Technology, Federal University of Rio Grande do Sul, following the recommended procedures of the mentioned standard.

Relations between Microstructure, Hardness and Wear Resistance

Even the hardest alloy in the cobalt-based group has a room-temperature hardness (as measured on the Rockwell scale) no greater than that which can be attained by quenching a plain high-carbon steel, yet most of these surfacing alloys will outwear high-carbon steel from two to twenty times (Ref. 7). This indicates that for dissimilar classes of alloys, bulk hardness (*i.e.*, Rockwell scale) is not the controlling factor when determining relative wear resistance.

A microstructural study, however, can provide the means to explain the superior wearing characteristics of cobalt-based surfacing deposits over other alloys. For example, it is impossible to obtain an accurate Rockwell hardness reading on a piece of carbide because it shatters under the relatively heavy load. A microhardness test is necessary to obtain an accurate hardness reading.

Moreover, the cobalt-based alloy deposits are heterogeneous in nature, being made up of uniformly distributed carbide particles held in a softer matrix. Under the heavy load of the Rockwell test, the hard carbides are pushed down into the matrix, so that the softer material is really supporting all the weight. It is the microhardness of the hard constituents in the structures, and their distribution and size, which account for their greatly increased resistance to low-stress abrasion over plain carbon steels (Refs. 7, 13).

Within the same alloy system, and for similar structural conditions, hardness can, however, be a useful indication of abrasive wear resistance (Ref. 14).

Experimental Details

The two-layer weld surfacings were deposited over low-carbon steel (SAE 1020), to a thickness of 12.7 mm (0.5 in.), obtaining five specimens for each process. All of them were longitudinally restrained before welding to avoid difficulty in the subsequent machining. The respective welding variables were the following:

1) Gas tungsten arc welding (GTAW) process; welding rod, ⅛ in. (3.2 mm); 100 A; electrode negative.

2) Oxyacetylene welding (OAW) process; welding rod, ⅛ in. (3.2 mm); size welding tip, No. 6; 3X flame.

3) Shielded metal arc welding (SMAW) process; electrode, ⅛-in. (3.2 mm); 90 A; 23 V; electrode positive. The electrodes were dried for 2 h at 200°C (392°F).

In all cases, the preheating and interpass temperatures were 150°C (302°F), and the cooling rate was controlled to avoid cracks.

Furthermore, additional one- and

Table 1—Chemical Compositions of the Deposits

	GTAW	OAW	SMAW
Cr	27.94	26.96	28.34
Ni	0.50	0.55	1.69
W	3.00	1.48	1.60
Fe	1.50	2.92	4.80
Mn	0.32	0.36	0.20
Si	n.d.[a]	n.d.[a]	n.d.[a]
Mo	n.d.[a]	n.d.[a]	n.d.[a]
C	1.11	1.61	1.15
Co	balance	balance	balance

(a) n.d.: nondetected.

Table 2—Hardness Test Results (Transverse Section)

		GTAW[c]		OAW[c]		SMAW[c]	
		A	B	A	B	A	B
1 L[a]	VHN	360	—	522	—	401	—
	HRC	37	—	51	—	41	—
1 L[b]	VHN	375	441	527	527	418	472
	HRC	38	45	51	51	43	47

(a) 1 L: Specimens with one layer.
(b) 2 L: Specimens with two layers.
(c) A, B: Points belonging to the first and second layer, respectively (mean values of three groups of measures).

Table 3—Hardness Test Results (Specimens for Wear Tests)

Specimen	1		2		3		4		5		Average[c]	
No.	HVN	HRC	HVN	HRC	HVN	HRC	HVN	HRC	HVN	HRC	HVN	HRC
GTAW	570	54	584	54	566	53	552	53	579	54	570	54
SMAW	575	54	645	58	645	58	629	57	661	58	631	57
OAW	685	59	669	59	651	58	662	58	668	59	667	59

(a) HVN: Hardness Vickers, 30 kg.
(b) HRC: Hardness Rockwell C.
(c) Mean values of four measurements in each specimen.

Table 4—Wear Test Results (GTAW Process)

Test No.	1	2	3	4	5
Sand Flow (g/min)	295.2	296.2	293.6	295.4	294.9
Mass Loss (mg)	25	29	22	23	27
Volume Loss (mm^3)	3.0	3.5	2.6	2.8	3.2

Table 5—Wear Test Results (OAW Process)

Test No.	1	2	3	4	5
Sand Flow (g/min)	293.4	294.7	288.3	287.1	294.2
Mass Loss (mg)	5	4	6	4	4
Volume Loss (mm^3)	0.6	0.5	0.7	0.5	0.5

Table 6 — Wear Test Results (SMAW Process)

Test No.	1	2	3	4	5
Sand Flow (g/min)	277.3	293.1	292.4	289.3	291.2
Mass Loss (mg)	17	13	14	13	13
Volume Loss (mm^3)	2.0	1.6	1.7	1.6	1.6

Table 7 — Comparison with other Abrasive Wear Data for ERCoCr-A

	Stoody			
	HRC	Volume Loss (mm^3)	HRC	Volume Loss (mm^3)
GTAW	40	64	54	3.02
OAW	42	29	59	0.56

two-layer specimens were obtained for metallography and transverse hardness analysis, using the same welding variables.

Results and Discussion

Table 1 shows chemical analysis of the deposits. There is a larger carbon content in the oxyacetylene deposits than in the arc welded deposits. This is due to the carburizing flame used (it forms an intermediate zone containing white-hot carbon particles). These carbon particles partially dissolve in the molten deposit, thereby, increasing carbon content, hence, carbide volume fraction, and, indirectly, resistance to low-stress abrasion.

Tables 2 and 3, respectively, show the results of hardness tests on transversely sectioned specimens and on wear test specimen surfaces after machining. With regard to the former, some authors have investigated the secondary precipitation of carbides in cobalt-based wear alloys when heated above 700°C (1292°F) (Ref. 6). Such precipitation could result in increased hardnesses. However, for the three welding processes used in this work, the mean hardness values for the first layers of the coatings were not affected by the deposition of the second layers (*i.e.*, it appears that there was not sufficient heating time for significant secondary precipitation).

Higher hardness values were obtained on the oxyacetylene deposits, these being consistent with higher carbide volume fraction. There were no differences between the mean values for the first and second layer in the case of oxyacetylene, confirming the negligible influence of dilution for that particular welding process.

Table 3 shows for all processes higher hardness levels than those in Table 2. Although the measurements were performed on longitudinal samples, this fact does not explain the differences. Previously, the importance of $\varepsilon \leftrightarrow \alpha$ phase allotropic transformation in cobalt-based alloys was discussed. The higher hardness values recorded for the wear test specimens could be attributed to the presence of ε hcp phase platelets, induced by the strain developed during the machining process. It is a matter of fact that the stress-rupture life of some cobalt-based alloys has been increased by even low values of cold reduction (Ref. 15).

Tables 4–6 show the results of the low-stress scratching abrasion tests for each welding process. In all cases, the sand flow was controlled within an extremely narrow band of values. Table 7 compares the former with other wear data, obtained under the same test conditions (Ref. 15).

In terms of performance, the oxyacetylene deposits were the most resistant, followed by the shielded metal arc and gas tungsten arc deposits.

The choice of welding process is normally made on the basis of component geometry and required deposition rate, rather than on particular compositional or microstructural advantage. Avery and Chapin, referring to abrasive wear resistance of austenitic and hardenable high-chromium irons, state that the difference

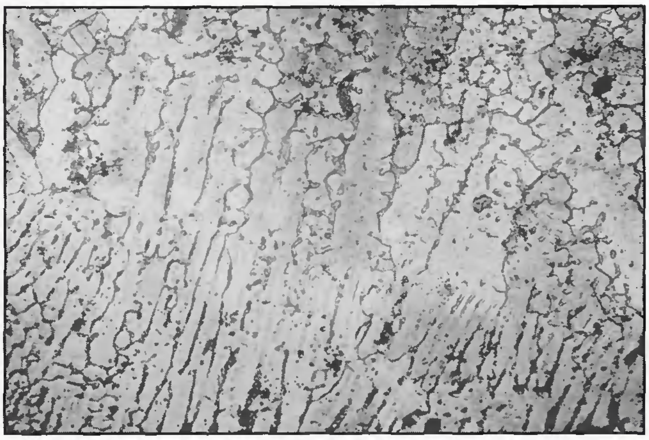

Fig. 6 — GTAW process, interface between first and second layers. 300X.

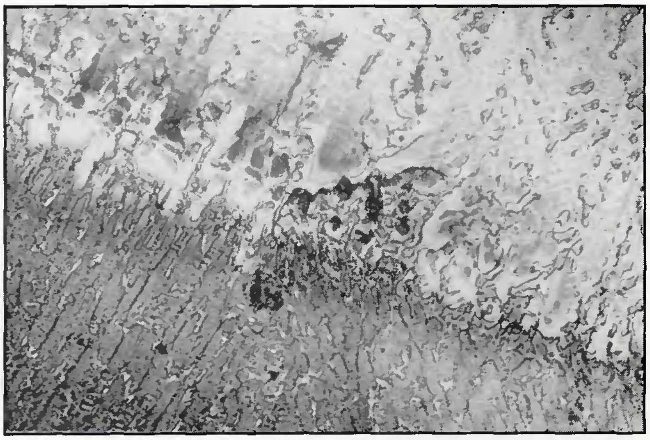

Fig. 7 — GTAW process, interface between first and second layers. 300X.

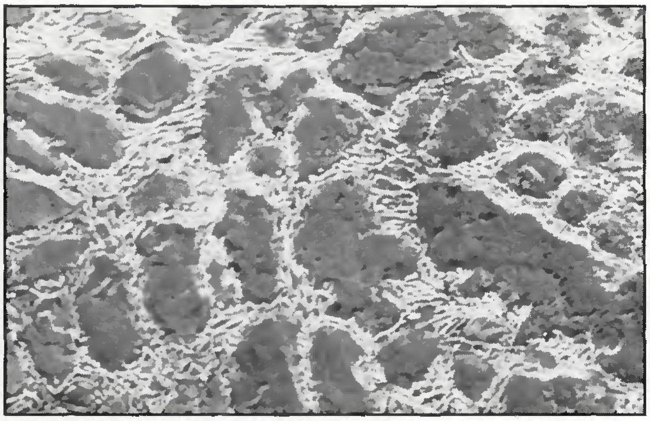

Fig. 8 — OAW process, zone of second layer. 1000X.

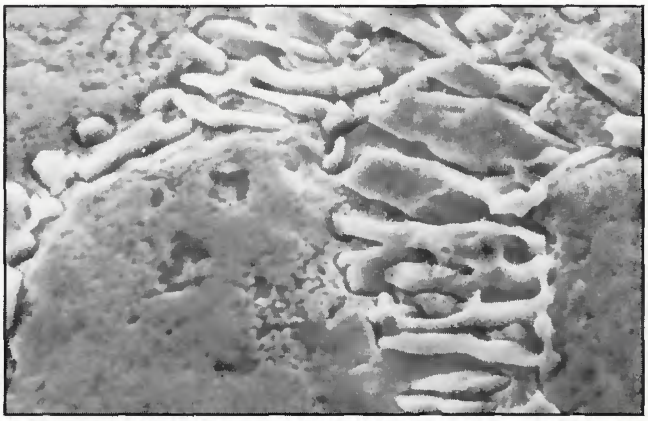

Fig. 9 — OAW process, zone of second layer. 5000X.

in performance due to welding technique is as great or greater than variations that can be assigned to composition.

Several authors (Refs. 14, 17–19) suggested that abrasive wear resistance increases directly with the volume of the hard constituent, particularly for structures with coarse hard phase morphologies, associated with weld deposition under high heat input conditions (gas welding). Probably, the scratches or grooves that are formed during abrasion by the abrading media are large enough in many cases to "plow" out small carbides in a single phase, while larger carbides will withstand several passes before being worn down and pulled out (Ref. 14).

Figure 2 shows the correlated relationship between average values of abrasion wear resistance and hardness on wear test specimens for each welding process. It confirms that within a given class of material similar in composition, wear resistance can be related to hardness.

The microstructures of the different weld surfacings are depicted in Figs. 3–5. The carbide morphology varied, with deposition technique being coarser in the oxyacetylene than the arc deposits. Longer solidification times for oxyacetylene deposits, as compared to other deposition methods, and carbon pickup from the acetylene flame, produce larger carbides, thereby increasing wear resistance. The microstructures were recorded by electrolytic etching in 100 mL of hydrochloric acid (HCl) and 5 mL of hydrogen peroxide (H_2O_2) at 4 VDC, 4 s, stainless steel cathode.

The microstructures of some deposits (GTAW) are illustrated in Figs. 6 and 7.

Figures 8 and 9 show scanning electron micrographs (SEM) of oxyacetylene deposits. Due to the relatively high carbon content, a grain-boundary skeletal network may actually form, which can support some of the load as well as hinder sliding.

Specimens for SEM were electropolished in 74% acetic acid ($HC_2H_3O_2$), 24% perchloric acid ($HClO_4$) and 2% distilled water at 6 V, and 20°C for 80 s.

Conclusions

1) The oxyacetylene deposits contained higher carbon levels than the arc deposits, due to carbon pickup during welding. They also exhibited higher hardnesses.

2) The hardness was highest in the machined specimens for wear test. This is probably due to the existence of ε phase, with a hcp crystal structure. This phase was probably induced by the strain developed in the machining process.

3) The ranking of samples for wear resistance from highest to lowest is as follows: oxyacetylene process samples, shielded metal arc process samples, and gas tungsten arc process samples.

4) The microstructures consisted of a continuous network of complex carbides within the cobalt-rich matrix. The thickness of this network was strongly related to the carbon content of each deposit.

References

1. Rabinowicz, E. 1965. *Friction and Wear of Materials.* New York, John Wiley & Sons., p. 244.

2. International Research & Development. 1985. *Wear Resistant Surfaces in Engineering.* The Welding Institute, London, England, p. 171.

3. Davies, V. H., and Bolton, L. A. 1980. The mechanism of wear. *Weld Surfacing and Hardfacing.* The Welding Institute, London, England, pp. 4–10.

4. Noble, D. N. 1985. Abrasive wear resistance of hardfacing weld deposits. *Metal Construction,* Sept., pp. 605-611.

5. Hardfacing. *Metals Handbook. Welding, Brazing and Soldering.* 9th Edition, Vol. 6, ASM International, Materials Park, Ohio.

6. Centre d'Information du Cobalt. 1960. Cobalt Monograph. Brussels, Belgium, p. 515.

7. Sharp, H. W. 1946. Microstructure of hardfacing alloys. *Welding Journal* 25(10): 936-941.

8. Avery, H. S., and Chapin, H. J. 1952. Hardfacing alloys of the chromium carbide type. *Welding Journal* 31(10): 917-930.

9. Torrance, A. R. 1980. The correlation of abrasive wear tests. *Wear,* Lausanne 63 (2): 359-370.

10. Rodrigues, J. R., *et al.* 1985. Equipamento para ensaios de desgaste abrasivo por riscamento. Anais do XI Encontro Nacional de Tecnologia de Soldagem. Rio de Janeiro.

11. Fujimura, H., *et al.* 1988. *Development of Hard Overlay Welding for High Wear Resistance.* Mitsubishi Heavy Industries, Nagasaki, Japan.

12. ASTM. 1985. *Standard Practice for Conducting Dry Sand/Rubber Wheel Abrasion Tests.* Designation G65-85. Philadelphia, Pa., p. 19.

13. Clemow, A. J. T., and Daniell, B. L. 1980. The influence of microstructure on the adhesive wear resistance of a Co-Cr-Mo alloy. *Wear,* Lausanne 61(2): 219-231.

14. Silence, W. L. 1977. Effect of structure on wear resistance of Co-, Fe-, and Ni-base alloys. Proceedings from the Wear of Materials Conferences, ASME, p. 77.

15. Centre d'Information du Cobalt. 1970. Cobalt-base superalloys. Brussels, Belgium, p. 72.

16. Stoody Deloro Stellite, Inc. 1987. *Cobalt and Nickel Base Rods and Electrodes, Bulletin* 2112.

17. Alcoforado, J.M., et al. 1987. Resistencia ao desgaste por abrasao, dureza ε microestrutura de revestimentos duros depositados por arco submerso. Anais do XIII Encontro Nacional de Tecnologia de Soldagem. Guaruja, pp. 87-100.

18. Shetty, H. R., Kosel, T. H., and Fiore, N. F. 1983. A study of abrasive wear mechanisms in cobalt-base alloys. *Wear,* Lausanne 84(3):327-343.

19. Moore, M. A. 1975. The abrasive wear resistance of surface coatings. *J. of Agricultural Eng. Res.,* 20, pp.167-179.

WRC Bulletin 341
February 1989

A Preliminary Evaluation of the Elevated Temperature Behavior of a Bolted Flanged Connection
By J. H. Bickford, K. Hayashi, A. T. Chang and J. R. Winter

This Bulletin consists of four Sections that present a preliminary evaluation of the current knowledge of the elevated temperature behavior of a bolted flanged connection.

Section I—Introduction and Overview, by J. H. Bickford; Section II—Historical Review of a Problem Heat Exchanger, by J. R. Winter; Section III—Development of a Simple Finite Element Model of an Elevated Temperature Bolted Flanged Joint, by K. Hayashi and A. T. Chang; and Section IV—Discussion of the ABACUS Finite Element Analysis Results Relative to In-the-Field Observations and Classical Analysis, by J. R. Winter.

Publication of this report was sponsored by the Subcommittee on Bolted Flanged Connections of the Pressure Vessel Research Committee of the Welding Research Committee. The price of WRC Bulletin 341 is $20.00 per copy, plus $5.00 for postage and handling. Orders should be sent with payment to the Welding Research Council, Suite 1301, 345 E. 47th St., New York, NY 10017.

WRC Bulletin 349
December 1989

This bulletin contains two reports that evaluate the PWHT cracking susceptibility of several Cr-Mo steels and several HSLA pressure vessel and structural steels.

Postweld Heat Treatment Cracking in Chromium-Molybdenum Steels
By C. D. Lundin, J. A. Henning, R. Menon and J. A. Todd

Postweld Heat Treatment Cracking in High-Strength Low-Alloy Steels
By R. Menon, C. D. Lundin and Z. Chen

Publication of this report was sponsored by the University Research Committee of the Welding Research Council. The price of WRC Bulletin 349 is $35.00 per copy, plus $5.00 for U.S., or $10.00 for overseas, postage and handling. Orders should be sent with payment to the Welding Research Council, 345 E. 47th St., Room 1301, New York, NY 10017.

WRC Bulletin 353
May 1990

Position Paper on Nuclear Plant Pipe Supports

This position paper recommends design methods which represent the collective "best methods" of the industry. These enhanced design methods are developed by reviewing the issues that have added to the complexity of design and fabrication of piping systems.

Publication of this report was sponsored by the Task Group on Nuclear Plant Pipe Supports of the Technical Committee on Piping Systems of the Pressure Vessel Research Council of the Welding Research Council. The price of WRC Bulletin 353 is $25.00 per copy, plus $5.00 for U.S., or $10.00 for overseas, postage and handling. Orders should be sent with payment to the Welding Research Council, 345 E. 47th St., Room 1301, New York, NY 10017.