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Electric Arc Deposition of Carbon Steel Coatings with Improved Mechanical Properties

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To achieve high deposition rate and efficiency, electric arc spraying has been routinely used to deposit carbon steel coatings. Although retention of carbon in these coatings is poor due to the use of compressed air during spraying, the coatings are sufficiently hardened by brittle iron oxide inclusions to be suitable for hardfacing mechanical components used in mild adhesive and abrasive wear environments. However, carbon steel coatings can be employed for hardfacing mechanical components used in more aggressive wear environments, provided they are hardened by the carbon retention rather than by iron oxide inclusions. Therefore, to increase retention of carbon, reduce inclusion of iron oxides, and improve hardness and wear properties of carbon steel coatings, deposition experiments were carried out using an inexpensive nitrogen, which is produced on-site by a pressure swing adsorption or a membrane separation system, instead of compressed air during spraying.

Keywords atomizing gases, electric arc process, nitrogen gas

1. Introduction

Carbon steel coatings are routinely used by the thermal spray industry for hardfacing automotive engine components and restoring worn machine parts such as shafts, journals, and rolls (Ref 1). These coatings, because of high deposition rate and efficiency, are deposited by the electric arc spraying technique using compressed air as a medium to atomize and propel droplets of molten metal. The use of compressed air during spraying, however, oxidizes molten metal droplets, thereby reducing the retention of carbon and increasing inclusion of brittle and porous iron oxides in the coatings. Both the reduction in retention of carbon and the increase in inclusion of porous oxides degrade mechanical properties such as wear resistance, limiting the use of carbon steel coatings to mechanical components used only in mild adhesive and abrasive wear environments.

The physical and mechanical properties of carbon steel coatings can be improved, and the mechanical components that are hardfaced or reclaimed can be used in more aggressive wear environments, if sufficient carbon is retained and oxide inclusions are minimized. This can partly be accomplished by spraying with an inert gas such as nitrogen or argon instead of compressed air (Ref 2). A further increase in carbon retention and decrease in oxide inclusions can be realized by spraying carbon steel coatings with an inert gas in a low-pressure chamber (Ref 3). Since the use of a low-pressure chamber is extremely expensive, it is not an economically attractive option for depositing carbon steel coatings. Likewise, the high cost of pure nitrogen and argon gas has limited their use for depositing these coatings.

This paper describes the physical and mechanical properties, including carbon and oxygen contents, hardness, microstructure, and abrasive wear resistance, of carbon steel coatings sprayed with nitrogen. It also compares and contrasts properties of carbon steel coatings deposited with inexpensive nitrogen produced on-site with those deposited with compressed air and with pure, more expensive nitrogen.

2. On-Site Production of Inexpensive Nitrogen

The nitrogen is produced on-site using a noncryogenic generation system such as a pressure swing adsorption (PSA) system or a membrane system (see Table 1 for relative costs of compressed air, pure nitrogen, and on-site-produced nitrogen). In a typical PSA nitrogen production system, clean, dry, compressed air is passed through one of the two carbon molecular sieve beds. The molecular sieve bed preferentially adsorbs oxygen, allowing nitrogen to pass through the bed to a storage vessel. After a preset time and before the bed is saturated with oxygen, the flow of compressed air is switched over to the second molecular sieve bed. Meanwhile, the first bed is regenerated and readied for the next cycle by depressurizing and venting it to the atmosphere. The cycle is repeated automatically, thereby producing a continuous stream of nitrogen.

Unlike nitrogen production in a PSA system, a membrane system produces a continuous stream of nitrogen by selective permeation. Compressed air is passed through a membrane module, which allows gases such as oxygen, carbon dioxide, and moisture to permeate through the membrane at a faster rate.

Table 1 Cost comparison of atomizing gases

Atomizing gas	Relative cost
Compressed air	1
Pure nitrogen	5
On-site-produced nitrogen (PSA/membrane)	2

Note: Costs are calculated based on 113 scmh (4000 scfh) flow rate of atomizing gas supplied at 690 kPa (100 psig) pressure

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These gases are generally rejected to the atmosphere. Nitrogen gas, which permeates at a much slower rate, is retained by the membrane and collected in a storage vessel.

The on-site nitrogen produced by these techniques contains 0.1 to 5 vol% residual oxygen, which is considerably lower than the amount present in compressed air. The physical and mechanical properties of carbon steel coatings can be tailored for specific applications by carefully selecting the level of residual oxygen present in the nitrogen produced on-site.

3. Experimental Method

Two sets of experiments were carried out to demonstrate the effectiveness of depositing carbon steel coatings with nitrogen produced on-site. In the first set of experiments, 0.5 to 0.65 mm (0.020 to 0.025 in.) thick electric-arc-sprayed carbon steel coatings were deposited on to 25.4 mm (1.0 in.) wide by 50.8 mm (2.0 in.) long by 6.4 mm (0.25 in.) thick test coupons using compressed air (~20.7% O_2) and pure nitrogen as atomizing gases. In the second set, on-site-produced nitrogen was used. The level of residual oxygen in the on-site-produced nitrogen was varied from 1 to 5% to determine the optimum oxygen level for depositing carbon steel coatings.

The carbon steel coatings were deposited on test coupons using a steel wire containing 0.83 wt% C and 0.01 wt% O_2. They were sprayed with an electric arc spray gun manufactured by TAFA (Concord, NH, USA), keeping the following spraying parameters constant: 140 mm (5.5 in.) standoff distance between the electric arc spraying gun nozzle and test coupon; 32 V and 200 A arc voltage and amperage, respectively; 7620 mm/min (300 in./min) linear traverse speed; approximately 550 kPa (80 psig) atomizing gas pressure; and approximately 116 scmh (4100 scfh) atomizing gas flow rate.

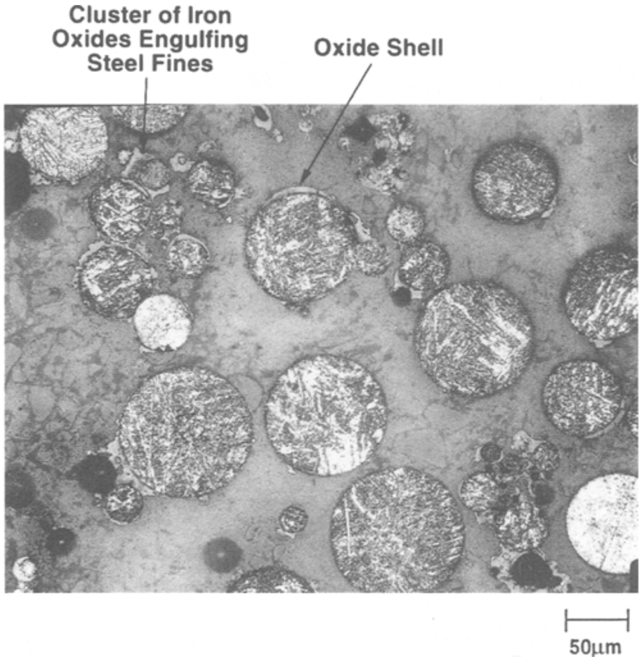

Fig. 1 Cross section of carbon steel molten droplets sprayed with compressed air and quenched in a bath of liquid nitrogen

The test coupons were analyzed for coating microhardness and microstructure using a Vickers microhardness tester and an optical microscope, respectively. The abrasive wear resistance of coatings was evaluated with a Falex (Aurora, IL, USA) dry-sand/rubber wheel tester following the procedure specified in ASTM G 65A. Finally, the coatings were analyzed for carbon and oxygen contents using Leco (St. Joseph, MI, USA) equipment.

4. Results and Discussion

4.1 *Carbon Retention*

The retention of carbon and the inclusion of oxides in coatings were determined. As summarized in Table 2, only 34% of the initial carbon was retained in the coating deposited using compressed air as an atomizing gas. This low level of carbon retention is due to oxidation of steel by oxygen present in the compressed air during the atomization of molten steel into droplets, the flight of molten droplets present in the spray plume toward the test coupon, and the subsequent deposition and solidification of molten droplets on the test coupon. A significant number of oxide inclusions are deposited in the coating, as evidenced by the presence of a high level of oxygen in the coating.

The use of pure nitrogen instead of compressed air as an atomizing gas increased the carbon retention to approximately 80% (Table 2). It also reduced the inclusion of oxides in the coating, as evidenced by lower oxygen content. The increase in carbon retention and decrease in oxide inclusions are due to elimination of oxidation during atomization and less oxidation in flight and during deposition and solidification of molten droplets on the test coupon. The elimination of oxidation of molten steel during atomization with nitrogen was confirmed by spraying carbon steel with air and nitrogen directly into a liquid nitrogen bath, thereby quenching molten droplets and preventing their consolidation. The droplets sprayed with air were found to be covered with thick and irregular oxide shells and mixed with clusters of iron oxides engulfing steel fines (Fig. 1). The droplets sprayed with nitrogen (Fig. 2), on the other hand, showed no evidence of oxide formation.

Although the oxidation of molten steel in flight is lessened by the use of pure nitrogen, it cannot be eliminated because of the entrainment of ambient air in the spray plume. Likewise, oxidation during deposition and solidification of molten droplets on the test coupon is reduced but not totally eliminated by the use of pure nitrogen because of the exposure of the freshly deposited and solidified coating surface to the ambient environment. The oxidation of steel during these stages can be eliminated by using a low-pressure chamber (Ref 3).

When nitrogen produced on-site was used, the retention of carbon in coatings varied from approximately 58 to 75%, depending on the level of residual oxygen present in the nitrogen (Table 2). The carbon retention in coatings, as expected, increased with a decrease in the level of residual oxygen present in the nitrogen. Likewise, the inclusion of oxides in the coatings decreased with a decrease in residual oxygen present in the nitrogen. More importantly, the carbon retention in the coating sprayed with the on-site-produced nitrogen containing 1% residual oxygen was very close to that noted with pure nitrogen. A further improvement in carbon retention in the coating could be achieved by selecting an on-site-produced nitrogen containing less than 1% residual oxygen. Thus, nitrogen produced on-site can be used to significantly improve carbon retention in carbon steel coatings.

4.2 *Coating Hardness*

The Vickers hardness of carbon steel coatings deposited with compressed air, pure nitrogen, and on-site-produced nitrogen was measured in cross section using a 300 gf load (Table 3). The carbon steel coating deposited with compressed air as an atomizing gas showed a relatively low hardness value of 367 HV. This low hardness value is due to low retention of carbon and high inclusion of porous oxides in the coating. The hardness of the carbon steel coating increased to 517 HV with the use of pure nitrogen as an atomizing gas. This is primarily due to increased retention of carbon in the coating.

With on-site-produced nitrogen, the hardness of carbon steel coatings varied from 406 to 508 HV, depending on the level of residual oxygen present in the nitrogen (Table 3). The hardness increased with a decrease in the level of residual oxygen present in the nitrogen. The coatings deposited with the on-site-produced nitrogen were considerably harder than those deposited with compressed air, primarily because of increased retention of carbon and decreased inclusion of oxides. Significantly, the hardness of the coating deposited with the on-site-produced nitrogen containing 1% residual oxygen was very close to that obtained with pure nitrogen. Further increases in hardness may be achievable using on-site-produced nitrogen containing less than 1% residual oxygen. Thus, nitrogen produced on-site can be used to deposit coatings with higher hardness than those deposited with compressed air, and with similar hardness to those deposited with pure nitrogen.

Table 2 Effect of atomizing gas on carbon and oxygen content in carbon steel coatings

Atomizing gas	Carbon, wt%	Oxygen, wt%	Carbon retention(a), %
Compressed air	0.28	5.55	33.7
Pure nitrogen	0.66	1.43	79.5
On-site-produced nitrogen			
1% residual O_2	0.62	2.17	74.7
3% residual O_2	0.55	2.18	66.3
5% residual O_2	0.48	2.63	57.8

Note: Original carbon steel wires contained 0.83% C and 0.01% O_2. (a) Carbon retention = [{1 – (original carbon – coating carbon)}/original carbon] × 100

Table 3 Effect of atomizing gas on hardness of carbon steel coatings

Atomizing gas	Microhardness, HV_{300}
Compressed air	367
Pure nitrogen	517
On-site-produced nitrogen	
1% residual O_2	508
3% residual O_2	458
5% residual O_2	406

Table 4 Effect of atomizing gas on abrasive wear resistance

Atomizing gas	Weight loss, g	Improvement in abrasive wear resistance, %
Compressed air	0.103	...
Pure nitrogen	0.077	25.2
On-site-produced nitrogen		
1% residual O_2	0.074	28.5
3% residual O_2	0.084	18.5
5% residual O_2	0.089	13.6

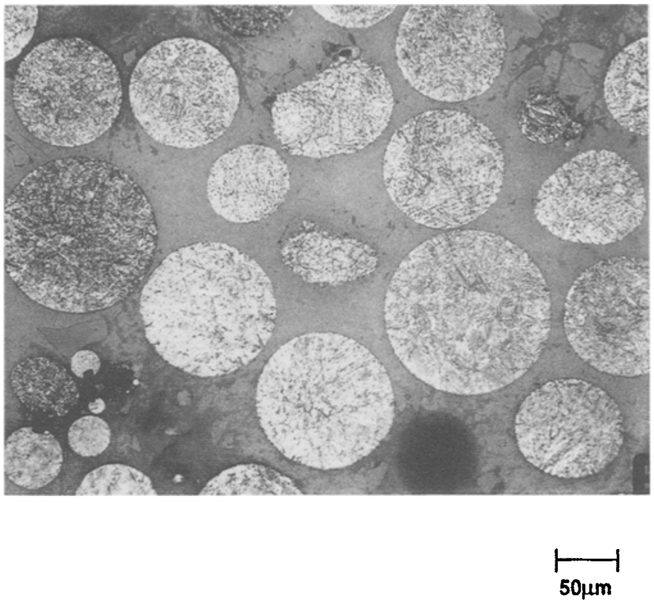

Fig. 2 Cross section of carbon steel molten droplets sprayed with pure nitrogen and quenched in a bath of liquid nitrogen

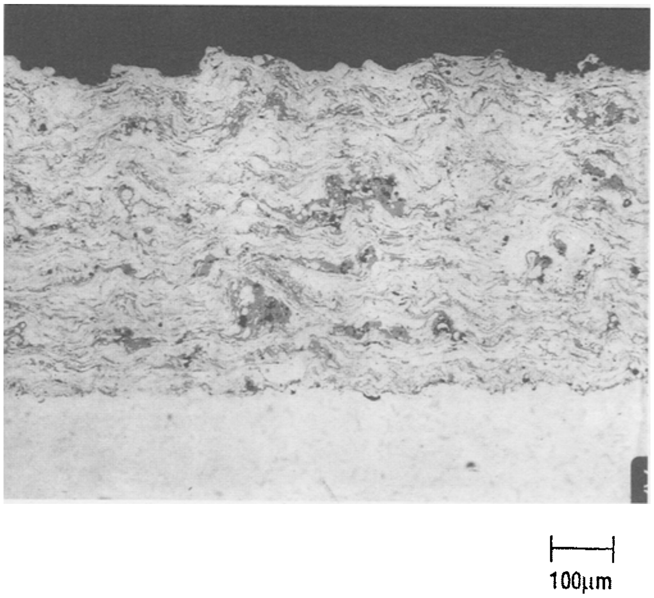

Fig. 3 Cross section of a carbon steel coating sprayed with compressed air

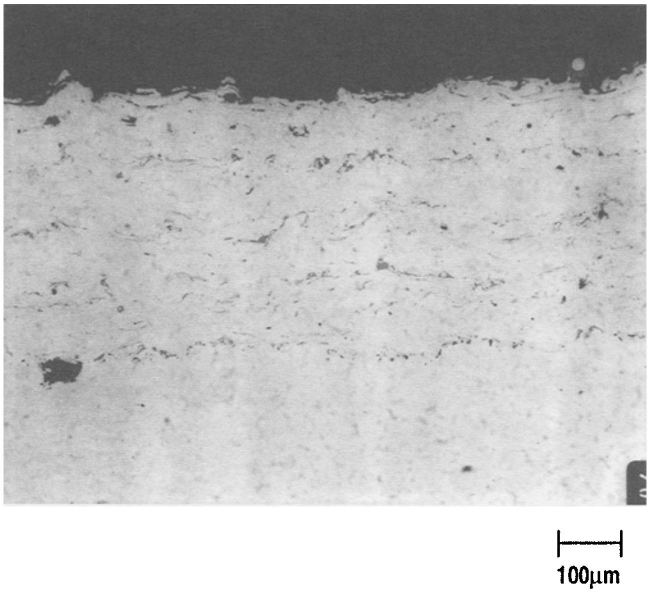

Fig. 4 Cross section of a carbon steel coating sprayed with pure nitrogen

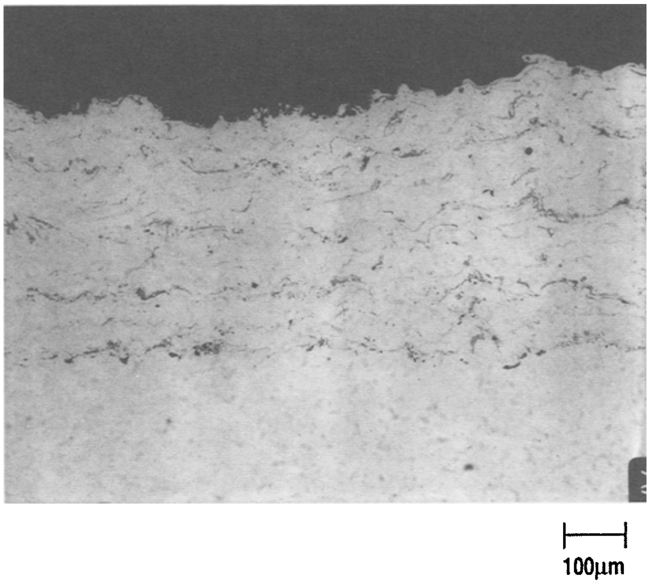

Fig. 5 Cross section of a carbon steel coating sprayed with on-site-produced nitrogen containing 1.0 vol% residual oxygen

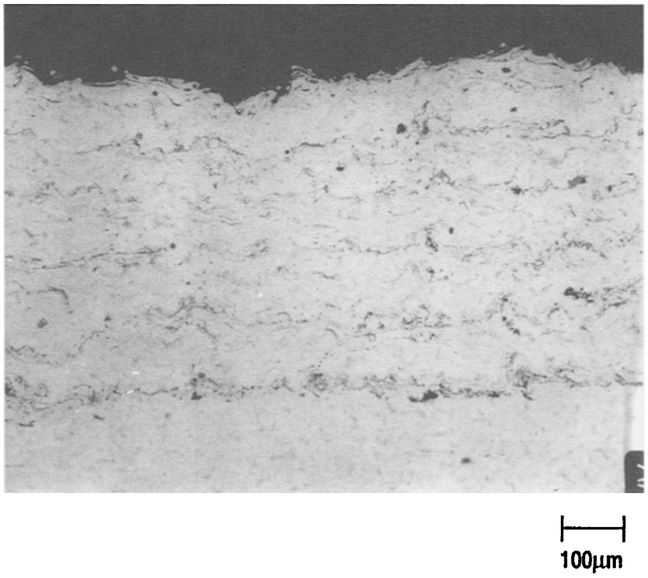

Fig. 6 Cross section of a carbon steel coating sprayed with on-site-produced nitrogen containing 3.0 vol% residual oxygen

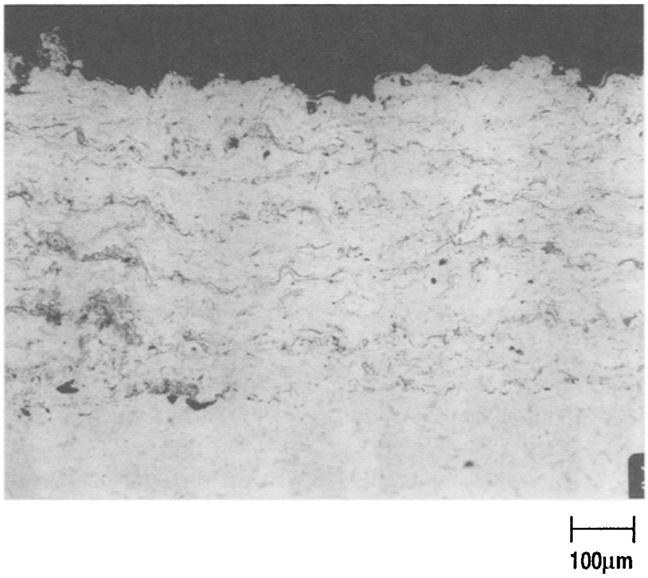

Fig. 7 Cross section of a carbon steel coating sprayed with on-site-produced nitrogen containing 5.0 vol% residual oxygen

4.3 *Coating Microstructure*

The photomicrograph in Fig. 3 of a carbon steel coating deposited with compressed air shows a highly oxidized, porous, and layered structure with nonuniform clusters of oxides (dark areas). The clusters of oxides are formed during atomization and spraying, as explained earlier and shown in Fig. 1. A few unmelted carbon steel particles frozen inside thick oxide shells are also visible. The use of pure nitrogen significantly reduced porosity and inclusion of oxides, as shown in Fig. 4. The oxides were present in this coating in the form of thin, dense horizontal layers, indicating oxidation of molten droplets during deposition and solidification on the test coupon.

The use of on-site-produced nitrogen also reduced porosity and inclusion of oxides (Fig. 5 to 7). On-site-produced nitrogen containing 1% residual oxygen resulted in a microstructure that is very similar to the one obtained with pure nitrogen (compare Fig. 5 with Fig. 4).

4.4 *Abrasive Wear Resistance of Coatings*

The relative abrasive wear resistance was evaluated according to the ASTM G 65A dry-sand/rubber wheel test method, by measuring weight loss of the coating. The carbon steel coating deposited with compressed air revealed a weight loss of approximately 0.103 g (Table 4). The use of pure nitrogen instead of compressed air reduced the weight loss to 0.077 g, an improvement of about 25%. This improvement may possibly be related to increased retention of carbon and decreased inclusion of oxides in the coating.

With on-site-produced nitrogen, the weight loss varied from 0.074 to 0.089 g, depending on the residual oxygen level in the nitrogen (Table 4). Importantly, the weight loss by the coating deposited with the on-site-produced nitrogen containing 1% residual oxygen was similar to that noted with the coating deposited with pure nitrogen (Table 4).

5. Conclusions

Nitrogen produced on-site by PSA or membrane separation systems can be used to deposit carbon steel coatings with improved physical and mechanical properties compared to those deposited with compressed air. The improvements in properties are related to the increased retention of carbon and decreased inclusion of oxides. The results also show that nitrogen produced on-site can be used to deposit carbon steel coatings with physical and mechanical properties that are similar to those deposited with pure nitrogen, but at a lower cost. Finally, carbon steel coatings sprayed with the on-site-produced nitrogen can be used in aggressive wear environments.

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