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Peening Effect of Thermal Spray Coating Process

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The present study investigated the influence of grit blasting, feedstock powder, and thermal spraying technology on performance near the surface on the substrate's side. The experimental results show that both the grit-blasting process and thermal spraying process harden the substrate, and microhardness on or near the surface was noticeably increased. Grit blasting created deformed regions next to the surface of the substrate and interface between entrapped grits and substrate. Initial equiaxed grains in the deformed regions were elongated and spirally oriented surrounding impact spots. There were no visible changes in microstructure caused by thermal spraying, and the elongated grain regions remained in the coated substrate. Substrate hardening was attributed to grit blasting and associated heating due to flame rather than powder particle impacting during thermal spraying, thus feedstock powder and individual thermal spray technology had no influence on the hardening.

Keywords HVOF process, production/preparation technology, properties of coatings

1. Introduction

Thermal sprayed cermet coatings provide a component with wear, corrosion, or heat resistance which is associated with the performance of the coated component on surface or near surface. Grit blasting is commonly conducted to prepare substrates prior to coating by removing contaminates and roughing the surface to provide sufficient adhesion of thermal spray coating to the substrate. Several studies have been conducted on the effect of grit blasting on coating adhesion, and removability of residual grit (Ref 1-5). Impact effect of grit blasting on substrate was observed near surface (Ref 6). It is also assumed that an effect of particle impacting on the substrate occurred during spray (Ref 7), especially in the case of cold spray (Ref 8, 9). This article will investigate the influence of grit blasting and thermal spraying on hardness near the surface on the substrate's side.

2. Experimental Procedure

2.1 Materials

All substrates used were $40 \times 40 \times 6$ mm flat plate of 1010 carbon steel. Commercially available SX178 manufactured by Osram Sylvania with nominal chemical composition of 86%WC-10%Co-4%Cr was used as feedstock powder. This spherical powder was processed to two hall densities of 4.44 and 5.28 g/cm^3 before thermal spraying. SiC grit with sizes of No. 36 and No. 54 were used during grit blasting.

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2.2 Thermal Spray Facility and Process

Grit blasting was conducted under the condition listed in Table 1. HVOF Diamond Jet (Sulzer Metco DJ-2600), HP/HVOF JP (Praxair/TAFA JP-5000) and Praxair SG-100 air plasma spray systems were used in the present study. Diamond Jet (DJ) and JP-5000 (JP) employed hydrogen and kerosene as fuel, respectively. Standard parameters for WC-10Co-4Cr selected by the manufacturers of each spray system were used for coating. Table 2 shows feed rates and spray distances for each system. Air was applied to cool specimen during spraying. An X-Y traverse, on which spray guns were attached, moved at a velocity of 600 mm/s and 10 passes were sprayed for each coating. After sectioning and polishing, microhardness (Vickers) of the specimens was tested on cross section using a conventional microhardness tester with a monitor at a load of 50 g and a dwell time of 15 s, each data comes from an average value of three readings. Two percent of Nital was used to etch substrates after microhardness being tested for optical microscope and SEM observations. SEM examinations were conducted with Hitachi S-3000N scanning electron microscope.

3. Results and Discussion

3.1 Hardness Profile of Substrate

The thermal spray coating process affects the hardness of the substrate. The primary influence on the substrate hardness results from grit blasting and thermal spraying.

Table 1 Condition of grit blasting

Air pressure	Shooting distance	Shooting angle	Shooting pass
65 psi	115 mm	60°	3

Table 2 Feed rate and spray distance

	DJ	JP	Plasma
Feed rate	10 lb/h (76 g/min)	10 lb/h (76 g/min)	3.5 lb/h (26.5 g/min)
Spray distance	9 in. (230 mm)	15 in. (380 mm)	3.5 in. (90 mm)

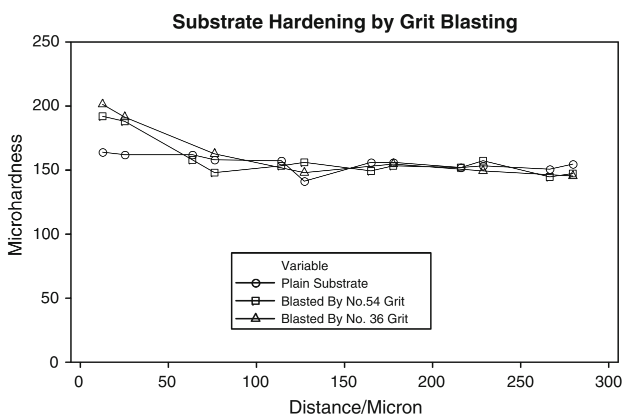

Fig. 1 Hardness profiles of untreated and grit-blasted substrates

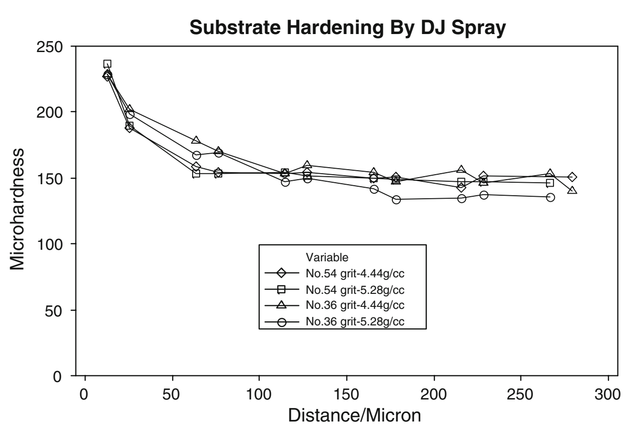

Fig. 2 Hardness profiles of the substrates with coatings sprayed by DJ

In order to identify the influence of individual process procedure, the hardness profiles of three substrate groups [(a) untreated plain, (b) grit-blasted, and (c) grit-blasted and coated] have been measured on cross sections. Figure 1, where the X axis represents the distance between the center of indentation and surface of the specimens in microns, and the Y axis is the average value of HV_{50}, shows the hardness profiles of untreated and grit-blasted substrates. It can be seen that the untreated

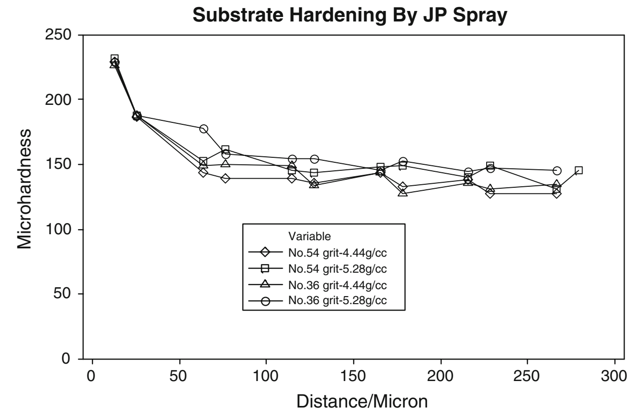

Fig. 3 Hardness profiles of the substrates with coatings sprayed by JP

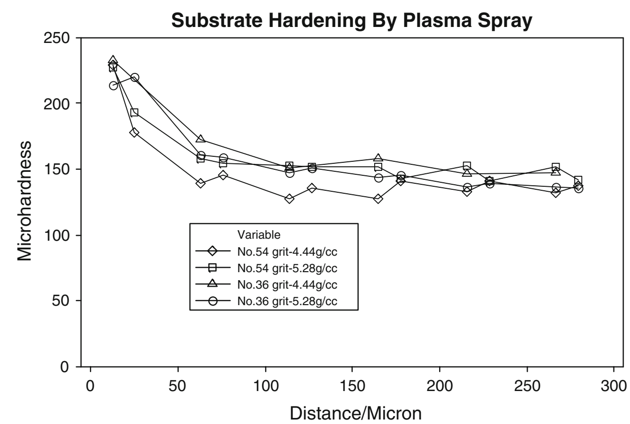

Fig. 4 Hardness profiles of the substrates with coatings sprayed by plasma

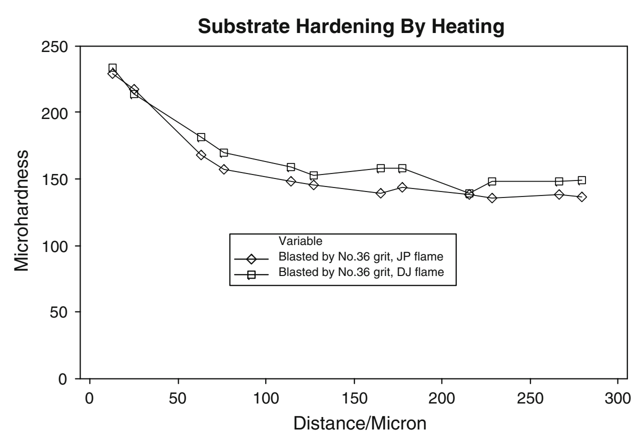

Fig. 5 Hardness profiles of the substrates heated by JP and DJ flame

plain substrate has invariant hardness with distance, except for the fluctuation which will be explained in the next section. Grit blasting increases hardness from 160 to 190

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on the surface or near surface as expected. The increase in hardness is limited within a range of around 50 μm; however, the size of grit (No. 36 and No. 54) had no influence on hardness profile.

Figures 2-4 indicate hardness profiles of the substrates which were grit-blasted and thermally coated by Diamond Jet (DJ), JP-5000 (JP), and air plasma (plasma) spraying, respectively. In each figure, there are four hardness profiles, which were produced by different grit sizes and

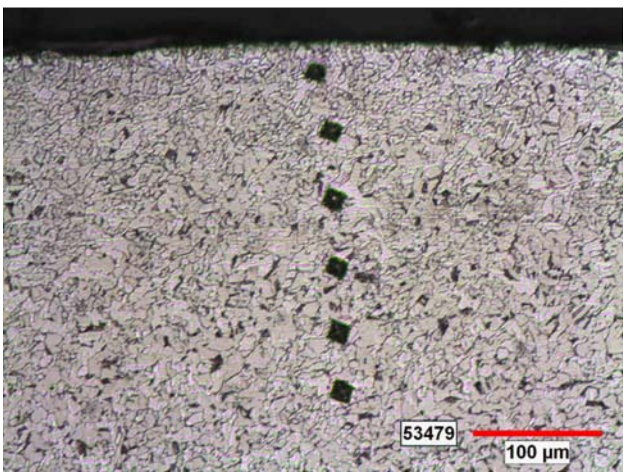

Fig. 6 Microstructure of untreated plain substrate (optical metallograph)

powder hall densities. These four hardness profiles are very close, which demonstrates grit size and powder hall density have no visible influence on the hardness of the substrate. It should be noted that all three spray technologies have created almost identical hardness profiles in the substrates, that is, the hardness near the surface increased from around 190, which resulted from grit blasting, to approximately 230, independent of which spray technology was applied. In comparing the results of grit blasting, influences on hardness are limited within 50 μm. DJ and JP are HVOF technologies; they have lower temperatures and higher velocities of the flame and particle than plasma technologies. (It is estimated that the DJ system created a particle temperature range from 1650 to 2170 K, and particle velocity of 300-500 m/s, dependent of particle size (Ref 10). The JP has slight higher temperatures and velocities than the DJ system.) It was theorized that a higher velocity impact on the substrate would result in a hardening similar to the peening process. However, plasma spray with much lower velocities also created the same magnitude of hardening of the substrate as did HVOF. Moreover, powder density did not make a difference in hardness of the substrate, either.

Thermal spray processing simultaneously creates mass transfer and heat exchange. Substrate hardening could be resulted from both mass transfer and heat exchange or one of these two processes. In order to identify the influence of mass impact and heat exchange on substrate hardening, heat exchange of thermal spray was simulated by spraying with the same parameters used as in Fig. 2 and 3 but

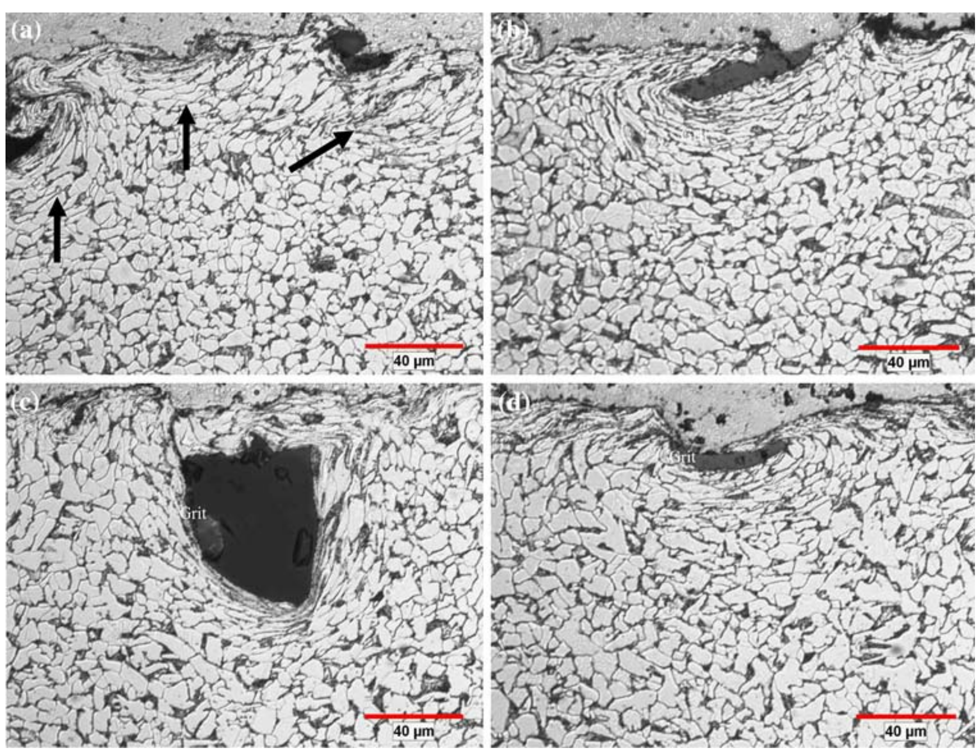

Fig. 7 (a) Arrows indicate areas in which grains are spirally oriented. (b) An entrapped grit particle next to interface of coating and substrate. (c) An entrapped grit particle inside substrate. (d) An entrapped grit particle next to interface of coating and substrate

without powder feeding, although an exact heat exchange process of thermal spray could not be created because the mass transferring could interfere with heat exchanging. Figure 5 shows results of DJ and JP ‘‘spray’’(without powder feeding). It can be seen that hardness profiles of substrate resulted from grit blasting and heating are almost identical to ones of grit blasting and coating process shown in Fig. 2-4, which means substrate hardening was attributed to grit blasting and heating accompanied by thermal spraying, and the role of particle impact on substrate can be ignored.

3.2 Microstructure of Substrate

The substrate used in this study is 1010 carbon steel. Figure 6 shows the cross section microstructure of untreated substrate. It consists of around 87% of ferrite (α) phase (light phase in the picture) and 13% of pearlite (P) phase (dark phase in the picture). Grain size of the ferrite phase varies from 5 to 20 μm. When fine ferrite grain regions or pearlite phase were indented, higher hardness were obtained. While coarse ferrite grains created lower hardness value. Therefore, a fluctuation of hardness was observed in the hardness profiles. There are always fine grain zones near the surface because of higher cooling rates after hot rolling of the plate.

Grit blasting resulted in plastic deformation and the general characteristics of this plastic deformation can be seen in Fig. 7. The middle and lower parts of the microstructure shown in Fig. 7(a) are undeformed, equiaxed grains, and the top part is coating. Deformed regions located in the upper part of the picture show a deformed region created by grit blasting, in which the grains are spirally oriented surrounding an impact spot. Grains next to the impact spot are extensively elongated, and each deeper layer contains grains that are slightly less elongated. However, all are spirally oriented; see the areas indicated by the arrows in Fig. 7(a). A deformed region has a total dimension of around 50 μm [excluding the deformed regions surrounding entrapped grit which is shown in Fig. 7(b)-(d)]. This dimension is comparable to the hardening scope in hardness profiles in Fig. 1-4. Figure 7(b)-(d) shows the deformed regions created by entrapped grit particles with different shapes. The entrapped grit particle is spirally surrounded by a number of elongated grains, inner layer consisted of extensively elongated grains and outer layer consisted of slightly elongated grains. This result concludes that a deformed region could be formed by single impact of a grit particle, although a large number of grit particles are impacting the substrate during grit blasting. The deformed region associated with an entrapped grit particle, whose morphology is an extension from 180 to 360° of one formed beneath the surface of the substrate, was formed by single impact of the entrapped grit particle. Figure 8(a) and (b) show the microstructure of grit-blasted substrate. The highly deformed layer is 5-15 μm in depth with extensively elongated grains (distorted disc-shaped grains should be observed in a three-dimensional space). Arrows D and P in Fig. 8(b) indicate the highly deformed layer and the pearlite phase, respectively. Apparently, the increase in hardness in the grit-blasted substrate was attributed to this deformed microstructure. Cracks, propagating spirally along the direction of the elongated grains, can be seen in the highly deformed layer, see Fig. 8(a). Cracks were usually observed in the highly deformed layer next to the surface of the substrate rather than at the interface between the entrapped grit and the substrate, although the latter has a more severe stress-strain status. Therefore, it is easy to assume that the cracks were formed by multiple grit impacts, and multiple impacts could also remove material fragments from the substrate, see Fig. 8(a) and 10(a).

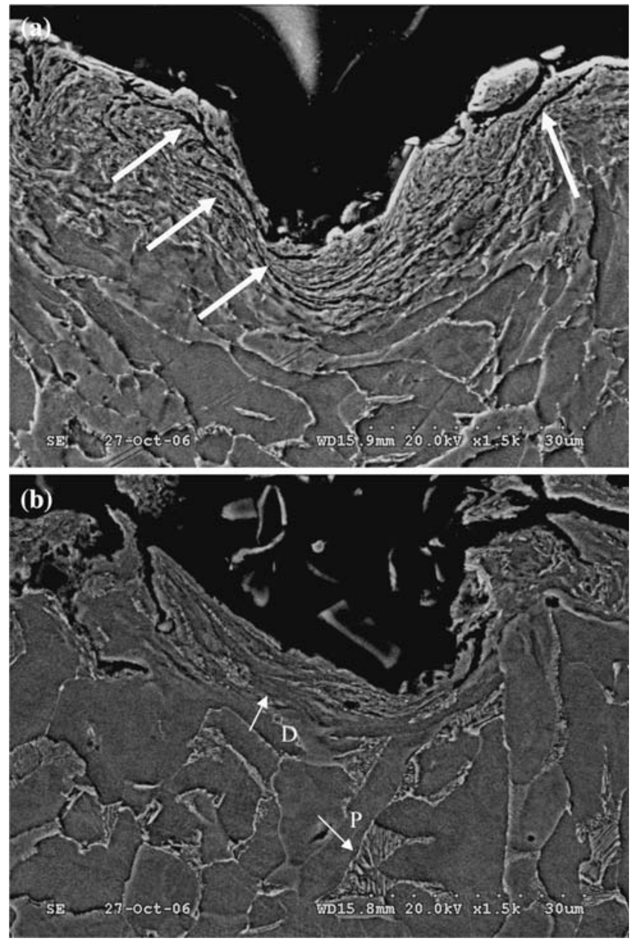

Fig. 8 Microstructure of grit-blasted substrate (SEM images). (a) Grit-blasted by No. 36 grit, and arrows indicate cracks. (b) Grit-blasted by No. 54 grit

Figure 9(a) shows the microstructure in a grit-blasted and then thermal coated substrate, indicating that the surface roughness created by grit blasting plays a role of mechanical interlock and increases the bond strength between the substrate and coating. Figure 9(b) is a detailed view of an indentation. It can be seen that the deformed microstructure remained in the coated substrate. There was no evidence of recrystallization in the

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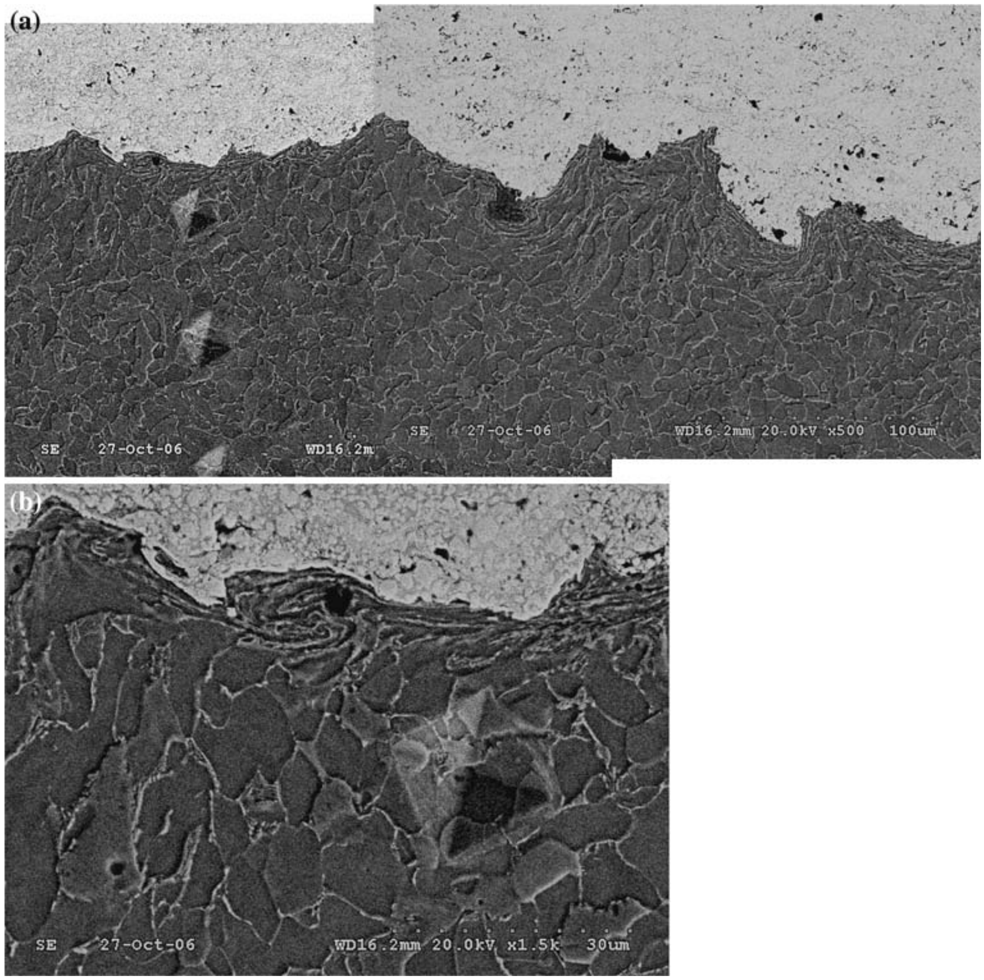

Fig. 9 Microstructure of substrate (SEM images) grit-blasted by No. 36 and coated by JP using SX178 powder with hall density of 5.28 g/cm^3. (a) Microstructure of substrate coated by JP using SX178 powder with hall density of 5.28 g/cm^3 (SEM images). (b) Detailed view near an indentation

deformed microstructure although the substrate was exposed to high temperature.

Figure 10(a) shows the microstructure of a substrate ''sprayed'' without powder, in this case, substrate hardness is very close to that of the coated substrates, and higher than hardness of the substrates which were grit-blasted alone. Figure 10(b) shows an indentation in the highly deformed region, while Fig. 10(c) shows an indentation outside the highly deformed region [Fig. 10(b) and (c) created almost identical hardness value]. Powder particle impact during thermal spray did not create further hardening near surface, which was possibly because surface hardening caused by grit blasting had already reached the saturation limit of 1010 carbon steel strain hardening, and the surface harden shell (the highly deformed layer) provided a shield layer for the substrate beneath the surface, so that this region was not harden further by particles impacting which had not enough momentum penetrating the surface's highly deformed layer.

Trompetter et al. (Ref 11) investigated deposition of NiCr splats on several substrates with varying hardness during HVAF (a low-temperature thermal spray process compared with HVOF). There were three sorts of NiCr splats: (a) un-melted solid splats, (b) semi-molten splats, and (c) molten splats. Predominantly un-melted solid splats penetrated into softer substrates. Conversely, splats themselves were observed to deform strongly when incident onto a hard substrate. When sprayed onto a harder substrate, impacting solid particle was significantly deformed and molten because of 90% of its kinetic energy (estimated by modeling) could be transferred into thermal energy. Similarly, in the study of deposition of aluminum powder during cold spray, Zhang et al. (Ref 12) found that when high-velocity aluminum particles were sprayed onto softer tin substrate, tin was melted, when sprayed onto the substrates of aluminum alloy, brass and copper, which are considerably harder than impacting aluminum particles, and induced deformation of these substrates. However, when sprayed onto steels with higher hardness compared with non-ferrous alloys, the substrates exhibited no deformation. Therefore, the interaction between impacting particle and

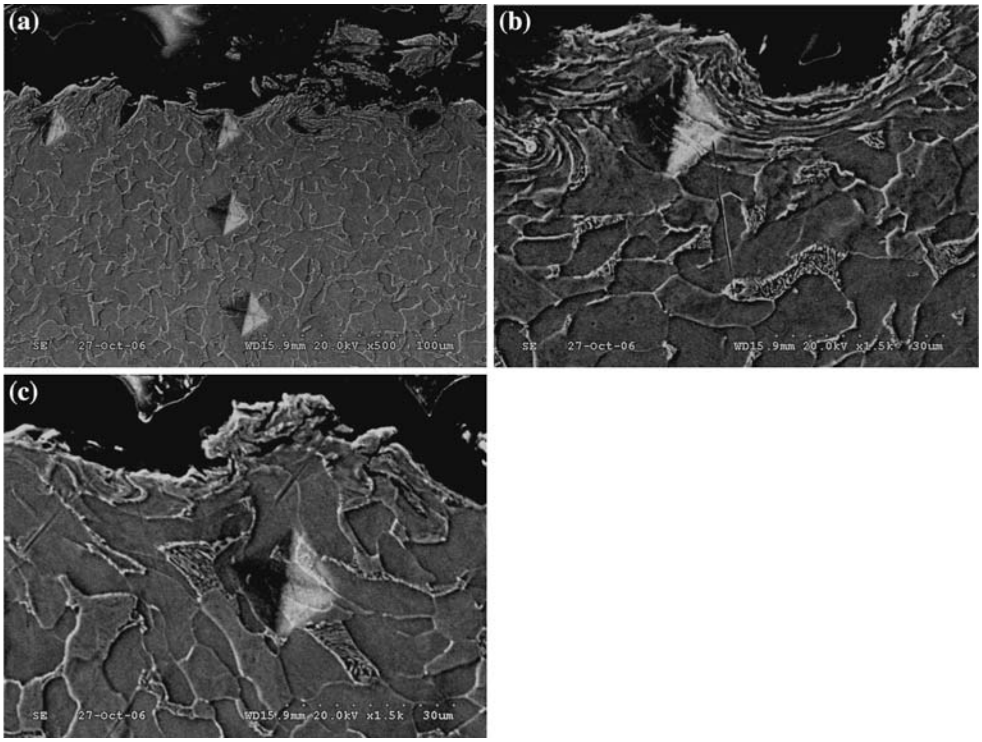

Fig. 10 Microstructure of substrate sprayed without powder. (a) Grit-blasted by No. 36 grit and sprayed by JP without powder. (b) Detailed view of (a), an indentation in the highly deformed layer. (c) Grit-blasted by No. 36 grit and sprayed by DJ without powder, and an indentation outside the highly deformed layer

substrate depends on relative hardness value of the impacting particle and the substrate. When a hard particle is sprayed onto a soft substrate, the substrate is deformed (even is locally molten) and is penetrated by the impacting particle, whereas when a soft particle is sprayed onto a hard substrate, the majority of impacting particle's kinetic energy is transferred into thermal energy, the particle itself deforms, even melts. Therefore, it is assumed in the present study the substrate, which had been already harden by grit blasting, is only suffered to a minimal impact during thermal spray, and no further mechanical hardening is created.

What is the reason for the further increase in hardness in the coated specimen? It was suspected that the surface of the substrate was locally heated to the austenitic region, and subsequently quenched to transform to martensite or binate, or normalized to more and finer pearlite phases. But a detailed investigation on microstructure indicated no evidence of phase transformation. In fact, the highly deformed microstructure was unchanged on the surface, and no part of the substrate was heated into the austenite region. The reason why heat treatment hardened the substrate is not clear and further investigation is needed. Another possible mechanism might be attributed to the increase in hardness of the substrate near the surface. During thermal spraying or simply heating, the highly deformed layer on the surface could be thermally expanded, thus creating extra stresses onto the near surface layer, and therefore higher hardness values were obtained in the heated or coated substrates compared to the substrates which were grit-blasted alone (Fig. 7).

Deformed regions next to interface between substrate and coating and the deformed regions surrounding entrapped grit particles, elongated grains are spirally oriented surrounding impact spots (optical metallographs of the substrate coated by JP using SX178 powder with hall density of 5.28 g/cm^3).

4. Conclusions

In conclusion, the experimental results show that both the grit blasting and thermal spraying processes harden the substrate. The microhardness on or near the surface was noticeably increased. Grit blasting created deformed regions next to the surface of the substrate and interface between entrapped grits and substrate. In addition, initial equiaxed grains in the deformed regions were elongated and spirally oriented surrounding impact spots. There were no visible changes in microstructure caused by thermal spraying, and the elongated grain regions were completely unchanged in the coated substrate. Grit size, feedstock powder, and individual thermal spray technology had no influence on substrate hardening, including powder particle impacting during spraying. Substrate hardening was attributed to grit blasting and associated heating due to thermal spraying.

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