 SDHM, vol.6, no.1, pp.17-29, 2010

Experimental Study of Shot Peening Followed by Cold Spray Coating on Residual Stresses of the Treated Parts

R. Ghelichi[1], **S. Bagherifard**[1], **I. Fernandez Parienete**[2]
M. Guagliano[1,3] **and Simone Vezzù**[4]

Abstract: Coating deposition processes such as cold spraying are commonly employed to increase wear and fatigue resistance and consequently to enhance longevity of engineering components. Such processes typically introduce residual stresses into the coated surface, which in turn affect efficiency of coatings and play an important role in coating durability. In fact residual stresses are the key parameter to obtain compact and well-adherent coatings. They can modify several coating properties such as adhesion, structure, toughness, hardness reflecting on the macroscopic chemical and mechanical behavior of the coating.
Present study describes alteration of residual stress state of two types of aluminum coatings that are cold sprayed onto aluminum substrate, and subsequently treated by air blast shot peening (ABSP). Residual stress measurements have been made by means of X-ray diffractometer (XRD) on coated specimens both before and after shot peening process. The results indicate that residual stresses generated during coating process have been modified by the successive shot peening process.

Keywords: Cold spray coating- Aluminum alloys- Shot peening- Surface treatment- Residual stress.

1 Introduction

The ever increasing demand to manufacture weight efficient structures that are damage tolerant and can operate at elevated temperatures has driven the development of novel alloy compositions and radically different processing approaches over the last decades. In recent years, thermal spray technologies have evolved

[1] Department of Mechanical Eng., Politecnico di Milano, Via La Masa 34, 20156 Milan, Italy.
[2] Department of Material Science and Metallurgical Eng., University of Oviedo, Gijón, Spain.
[3] Corresponding author. E-mail: mario.guagliano@polimi.it; Tel.: 02.2399.8206; Fax.: 02.2399.8202.
[4] Associazione Civen, Marghera, Italy.

from fairly crude processes that were relatively difficult to control into increasingly precise tools for which the process is adapted to take into account properties of both the deposited material and the required coatings.

Cold gas-dynamic spray (or simply cold spray) is an emerging coating technology which has lately attracted the attention of many researchers [McCune, Papyrin, Hall, Riggs and Zajchowski (1995); Alkhimov, Klinkov, Kosarev and Paprin (1997) and (2003); Papyrin, Kosarev, Klinkov, Alkhimov, and Fomin (2006)]. In this process coating is formed by plastic deformation of sprayed particles during impact while maintaining their solid state. In figure 1 a scheme of the process device and an example of its possible applications are presented. It can be defined as a process of applying coatings by exposing a metallic or dielectric substrate to a high velocity (300–1200 m/s) jet of small (1–50 μm) particles accelerated by a supersonic jet of compressed gas at a temperature that is always lower than the melting point of the material, resulting in coating formation from particles in the solid state. The general principle of cold spraying has been described elsewhere in more detail [McCune, Papyrin, Hall, Riggs and Zajchowski (1995); Alkhimov, Klinkov, Kosarev and Paprin (1997); Raletz, Vardelle and Ezo'o (2006)].

The temperature of spray particles prior to impact is much lower than their melting point thus the spray materials experience little microstructure change, oxidation or decomposition during the process [Clyne and Gill (1996); Greving, Shadley and Rybicki (1994)].

Particular characteristics of cold spray process that offer unique advantages compared to existing spray technologies can be listed as followings [Papyrin, Kosarev, Klinkov, Alkhimov, and Fomin (2006)]:

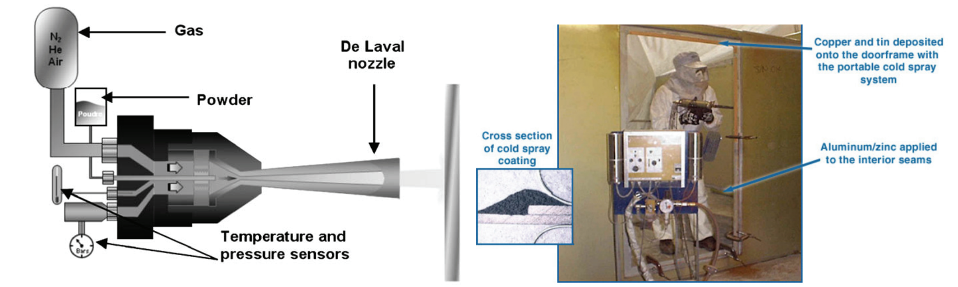
1. The coatings can exhibit wrought-like microstructures with near theoretical density values;

2. The spray trace is small (typically 1-25 mm^2) and well defined allowing for precise control on the area of deposition;

3. The coatings can be produced with compressive stresses, thus ultra thick (5-50 mm) coatings can be built-up without adhesion failure;

4. Coatings can be deposited on temperature-sensitive materials such as glass or polymers.

A cost study performed on financial advantages that can be gained through wide application of cold spray process affirmed that the use of this technique accomplishes the following aspects [Karthikeyan (2004)]:



a b

Figure 1: a) The schematic drawing of cold gas spray apparatuses b) an example of the CGDS applications [US army laboratory WebPages]

1. Reduction in material input;
2. Elimination of mold and melt pour cost;
3. Reduction in rework;
4. Reduction in finishing;
5. Large increase in material utilization (cold spray has deposition efficiency of 60-95%).

Cold spray process is based on the selection of the combination of particle temperature, velocity, and size that allow spraying at the lowest temperature possible. As a consequence, the deleterious effects of high-temperature oxidation, evaporation, melting, crystallization, deboning, gas release, and other common problems for traditional thermal spray methods are minimized or eliminated. Cold-sprayed coatings can be processed with very low numbers of defects and low oxygen contents, and therefore exhibit bulk like properties with respect to electrical or thermal conductivity that are not attainable by normal thermal spray processes [Alkhimov, Klinkov, Kosarev and Paprin (1997)]. A detailed review of cold spray evolution can be found in [Ghelichi and Guagliano (2009)].

Most metals including Cu, Al, Ni, Fe, Ti and their alloys can be deposited by cold spraying, and even cermets or ceramic particles can be embedded into metal substrates to form a thin layer coating. While the high rate of oxidation and considerable values of generated residual stresses are significant characteristics of thermally sprayed coatings, cold sprayed coatings are often characterized by relatively little oxidation, and low residual stresses. In cold spray the magnitude of residual stress values are significantly lower compared with different types of thermal coating [Bansal, Shipway, and Leen (2006)].

Thin and thick coatings show typically a residual stress state arising from deposition and depending on the deposition technique and parameters but also on the coating and substrate materials. Both the distribution and the magnitude of the residual stress influence noticeably the coating mechanical properties and the substrate-coating adhesion, so as a consequence, the range of applicability of the coatings.

In fact, It is recently stated [Molz, Valarezo, Colmen and Sampath (2008)] that the stresses in sprayed coatings can come from a number of different factors such as quenching stresses resulting from shrinkage due to cooling of the sprayed material; peening stresses due to the plastic deformation of impacted particles; thermal mismatch stresses resulting from the different thermal expansion coefficients of coating and substrate material and temperature gradient stresses resulting from addition of thermal input in multipass deposition processes.

On the other hand, shot peening (SP) is a mechanical surface treatment in which small spherical peening media with sufficient hardness are accelerated in peening device of various kinds and impact with the surface of the treated work piece with a quantity of energy able to cause surface plastic deformation [Marsh (1993); Schulze (2006)]. During the process each impacting shot imparts to the surface a small indentation or dimple. In order for the dimple to be created, the surface of the material must be yielded in tension. The material below the surface tries to restore the surface to its original shape, thereby producing below the dimple, a hemisphere of cold-worked material highly stressed in compression. Figure 2 presents a schematic of the typical effects of shot peening.

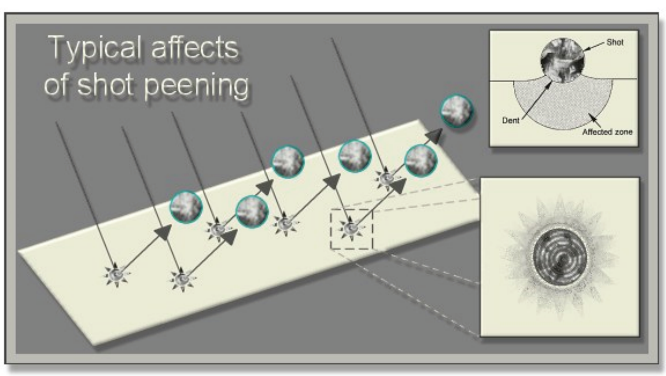


Figure 2: Typical effects of shot peening [AFCO]

It is well-known that SP is a considerably useful method to increase the roughness, improve fatigue properties, avoid fretting, wear, stress corrosion cracking. The aim of the process is the creation of compressive residual stresses close to the surface and the work hardening of the same layer of material. These effects are very useful in order to totally prevent or greatly retard the failure of the part and improve the mechanical behavior of materials [Almen and Black (1963); Blarasin, Guagliano and Vergani, (1997); Wagner (1999); Guagliano, Riva and Giudetti (2002)].

Most of the studies performed on this process affirm that the effect of shot peening is mainly related to the induced residual stresses [Guagliano (2001); Colombo, Guagliano, and Vergani (2005)]. This is particularly true in high strength materials that allow residual stress not to relax during load cycling. Notwithstanding this the contribution of surface work hardening should not be neglected and it could be also the main effect in different applicative situations.

In the case of cold sprayed specimens, effect of shot peening can be helpful to increase the residual stress and to harden cold sprayed layers in order to improve mechanical behavior.

This paper deals with the effect of shot peening on residual stress state of different as sprayed coatings of aluminum and aluminum/aluminum oxide composites. For this purpose, aluminum substrates were coated with aluminum in order to have equal substrate and coating thermal expansion coefficients and elastic properties; as a consequence erasing simultaneously quenching, cooling and thermal mismatch stresses. Al/Al_2O_3 powder mixture is also sprayed in order to identify the peening effect with the intervention of hard ceramic particles.

Results of residual stresses measured by XRD before and after shot peening are compared in order to elaborate residual stress state.

Notwithstanding the fact that residual stresses were not strongly altered by shot peening, as put forward in [Sampath, Jiang, Matejicek, Prchlik, Kulkarni and Vaidyi (2004)], the results suggest possible development about the application of shot peening after cold spray.

2 Experimental procedure

In this study two different types of powder have been used in spraying process: gas atomized aluminum powder, particle size ranging between 45 and 90μm (Sulzer – Metco 54NS) and a composite of the same aluminum powder mixed with fused and crushed alumina powder with particle size between 5 and 30μm (Plasmatec Inc. PT-105C-99).

Al/Al_2O_3 composite coatings are deposited in order to study the influence of ceramic powder's addition on residual stress behavior. Aluminum is mechanically mixed with aluminum oxide and then sprayed varying the nitrogen gas pressure. The weight percentage of the Al/Al_2O_3 blend is 70/30.

The depositions are carried out by means of CGT-Kinetics 3000 Cold Spray system upgraded in order to reach working pressure of 40 bars and provided with a special polymeric nozzle designed for aluminum powder spraying. The in-flight particles' velocity are monitored using an optical laser measure system Cold Spray Meter (Tecnar Automation DPV2000) which gives rise to a statistical particles distribution of velocity with respect to particles diameter distributions [Fukanuma, Ohno, Sun, and Huang (2006)]. The distance between nozzle and substrate is fixed at 20mm; the powder flow and carrier gas flow rates are kept constant for all depositions [Papyrin, Kosarev, Klinkov, Alkhimov and Fomin (2006)].

Two sets of square aluminum substrates (25x25x5.95mm) are deposited with aluminum powder and also the mixed aluminum-alumina blend in order to perform XRD stress characterizations. Both sets are obtained keeping constant the temperature at 350˚C and varying the nitrogen pressure (40, 32, 25 and 20bar). Specimens were deposited under different conditions in order to study the effects of deposition parameters on coating residual stress both using aluminum and aluminum/alumina blends.

Surface layer of specimens is characterized by measuring the residual stresses by means of a AST XStress 3000 X-ray diffractometer (radiation Cr Kα, 311 irradiated area 1mm^2, sen$^2\psi$ method, 11 angles of measurement, 10s of X-Ray exposition for each angle).

The XRD measurements give also another result that completes the information about the effect of shot peening on a treated surface: the full width at half maximum (FWHM) of the diffraction peak. This quantity is related to different factors: the size of the grain, the residual micro-strain (II order) and the instrument. Due to the fact that, in the present case, the first and the third factors do not change, the variation of FWHM before and after shot peening can be related to the hardening of the sprayed particles.

After coating process ABSP is performed on the specimens using S-230 cast iron shots with 0.6 mm diameter and a hardness of 40-50 HRC. The treatment which is carried out with 380mm stand-off distance and 1.5 bar air pressure satisfies the MIL-S-13165 standard, equivalent to an Almen intensity of 0.29mm (from the AFNOR NFL 06832 standard). The exposure time is about 33 second which provides coverage of 200%.

In order to study the trend of residual stresses after performing the SP process, subsurface layers are also characterized by XRD device. Measurements are carried out in depth step by step removing a very thin layer of material using an electropolishing device taking special precautions to avoid alteration of residual stress state induced by shot peening and cold spray process..

3 Results and discussion

3.1 Microscopic observations

The coating microstructure was investigated by means of cross-section light optical microscopy. The specimens were mechanically polished and then chemically etched with modified Keller's reagent. Both Al and Al/Al_2O_3 composites show compact microstructure with the presence of small isolated pores as represented in Figure 3.

The coating-substrate interface presents a good interlocking between impinging Al-particles and aluminum substrate with very low porosity content; as a consequence the coatings are well-adhered to aluminum substrates.

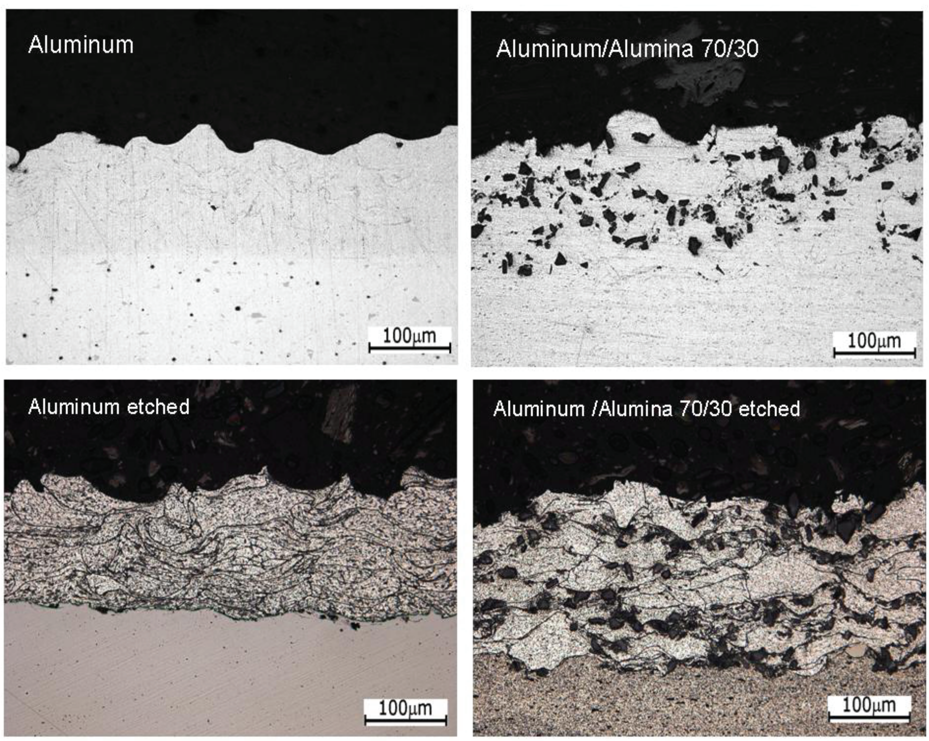


Figure 3: Light optical microscopy observations of (a) Al and (b) Al/Al2O3 coatings (c) Al and (d) Al/Al2O3 etched coatings on masked Al-substrate.

In all etched coatings the microstructure shows no noticeable variations due to the spray parameters such as pressure and temperature. Furthermore, in the case of composite coatings the alumina particles are homogeneously dispersed in metal matrix and an increase in deposition efficiency is reported with respect to pure aluminum according to previous studies [Irissou, Legoux, Arsenault and Moreau (2001); Rech, Trentin, Stoyanova and Vezzù (2008)].

3.2 XRD measurements on cold sprayed specimens

X-ray measurements were performed on all the specimens before shot peening. Figure 4 displays in-plane stresses obtained in the coating–substrate system after deposition of coated material (Al).

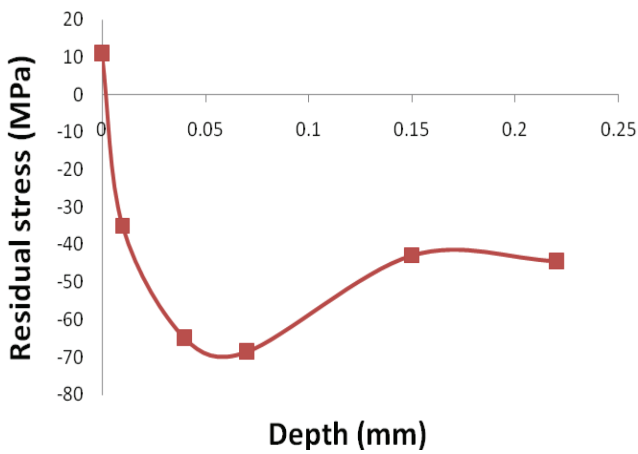


Figure 4: In plane residual stress profile as a function of position measured from coated surface after deposition of coated material (Al coating) measured by XRD device.

Untreated specimens exhibits negligible residual stresses on surface. After deposition tensile surface residual stresses can be noted, while they become compressive just under the surface, up to a depth of about 0.15 mm, where the residual stresses becomes negligible.

Observation of Figure 5, where the in-depth trend of the FWHM in the coating is shown indicates that cold spray process affects this quantity only on the surface, while it remains constant just under the free surface. This can be interpreted as the ability of cold spray to leave unaltered the status of the material.

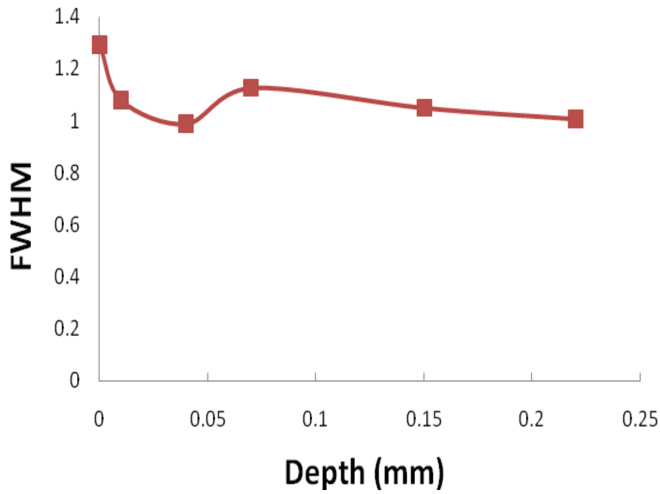


Figure 5: FWHM profile in depth as a function of position measured from coated surface after deposition of coated material (Al coating) measured by XRD device.

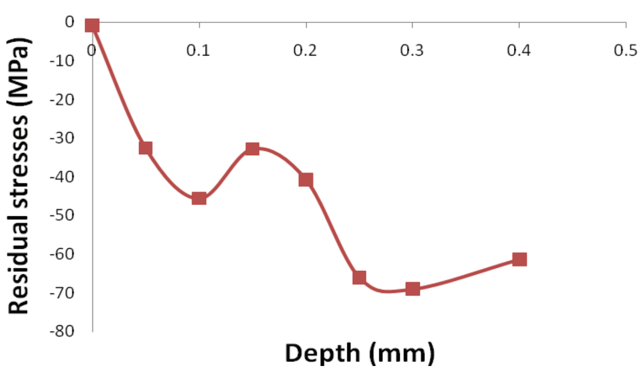


Figure 6: In plane residual stress profile as a function of position measured from impacted surface after deposition of coated material followed by shot peening (Al coating) measured by XRD device.

3.3 XRD measurements after shot peening performed on formerly cold sprayed specimens

A more marked difference between the un-peened and the peened specimens can be noted looking at the FWHM trend: in Figure 7 the in-depth trend of FWHM is shown: comparing with the trend of unpeened specimens (Figure 5) it can be concluded that, in this case, the effect of shot peening is more marked. Shot peening hardens a layer of material about 0.4 mm deep, that is about the depth of the sprayed layer.

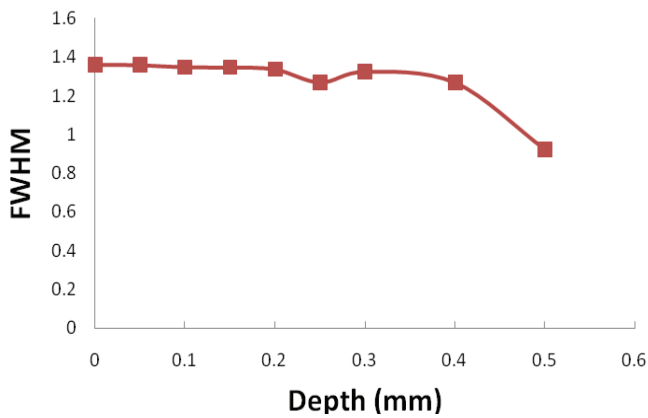


Figure 7: FWHM profile as a function of position measured from impacted surface after deposition of coated material followed by shot peening (Al coating) measured by XRD device.

The obtained results suggest some consideration about the effectiveness of shot peening on cold sprayed coatings. The first one is that, with the peening parameters used in this study, it seems that shot peening is not able to considerably influence the residual stress state induced by cold spray. This can be interpreted as a consequence of the porous nature of the coating, which is fixed to the substrate and to the inner layer of the coating itself only by adhesion. Thus, some porosity rate is expected and cannot be avoided: bearing in mind the mechanism of creation of residual stresses by shot peening, that involves no uniform plastic deformation of surface layer of material, it seems unavoidable that the peening cannot remarkably increase the residual stress state obtained from cold spray process.

At the same time it is to be expected that more severe peening parameters (with higher impact energy of the shot flow) can be more effective in alteration of residual stress state: indeed, if peening is able to involve plastic deformation of the substrate surface, the prevented recovery of elastic deformation of the inner substrate layers would have as a consequence caused in a more evident rising of compressive residual stresses in the coating.

The second point that can be evidenced is that shot peening is able to work harden the coating: this is clear by observing the FWHM trend and confirms the ability of shot peening in modifying the material state and the material properties also for cold sprayed coatings.

On the basis of the experimental results it can be stated that an improvement of mechanical properties of cold sprayed layers after shot peening is expected, even if a more marked effect can be reached only by changing the treatment parameters.

4 Conclusions

Aluminum and Al/Al_2O_3 coatings were deposited on aluminum substrate by cold spray deposition method. Two sets of different samples deposited in different pressures were shot peened after cold spray process.

X-Ray Diffraction was used to evaluate the residual stresses induced by deposition process and also after shot peening procedure. The influence of different pressures and ceramic particles addiction on coating stress was investigated.

Slight differences were reported in deposition of Al/Al_2O_3 composites materials. XRD analysis shows that the introduction of ceramic particles doesn't influence the aluminum matrix stress and in particular they are comparable with the value obtained in the case of pure aluminum coatings.

The application of shot peening is more able in work hardening the layer than in modifying its residuals stress state: on the basis of the results an improvement f the mechanical behaviour of the coating after shot peening is expected.

However, the results suggest that by using peening parameters able to increase the impact energy of the shot flow a more remarkable residual stress state could be reached and a more marked effect on the mechanical properties.

Notwithstanding the residual stresses were not strongly altered by shot peening, the results suggests possible development about the application of shot peening after cold spray. Thus further experimental investigations are to be planned in order to look in depth at the effect of shot peening and to accurately address the choice of treatment parameters for cold sprayed coatings.

References

Almen, J. O.; Black, P.H., (1963): *Residual stresses and fatigue in metals*, McGraw-Hill Publ. Company.

AFCO: abrassive finishing company INC's website: `http://abrasivefinishingcompany.com`.

Alkhimov, A.P.; Klinkov, S.V.; Kosarev, V.F.; Paprin, A.N. (1997): Gas-Dynamic Spraying: Study of a Plane Supersonic Two Phase Jet, *J. Appl. Mech. Phys.,* vol. 38(2), pp. 176-183.

Blarasin, A.; Guagliano, M.; Vergani, L. (1997): Fatigue crack growth prediction in specimens similar to spur gear teeth, *Fatigue Fract. Engng. Mater. struct.,* vol. 20, pp. 1171-1182.

Bansal, P.; Shipway, P.H.; Leen, S.B. (2006): Effect of particle impact on residual stress development in HVOF sprayed coatings J. Therm. Spray Technol. vol. 15 pp. 570-575.

Clyne, T.W.; Gill, S.C. (1996): Residual Stresses in Thermal Spray Coatings and Their Effect on Interfacial Adhesion: A Review of Recent Work J. Thermal Spray Technol. vol. 5 (4), pp. 401-418.

Colombo, C.; Guagliano, M.; Vergani, L. (2005): Fatigue crack growth behaviour of nitrided low and shot peened specimens, *SID* , vol.1, pp.253-265.

Fukanuma, H.; Ohno, N.; Sun, B.; Huang, R. (2006): In-flight particle velocity measurements with DPV-2000 in cold spray, *Surf. Coat. Technol.* vol. 201 (5), pp. 204-211.

Ghelichi, R.; Guagliano, M. (2009): Coating by the Cold Spray Process: a state of the art, *Frattura ed Integrità Strutturale, vol.8, pp. 30-44.*

Greving, D.J.; Shadley, J.R.; Rybicki, E.F. (1994): Effects of coating thickness and residual stresses on bond strength of C633-79 thermal spray coating test specimens. In: Proceedings of the 7th National Spray Conference; Boston, pp. 639–645.

Guagliano, M. (2001): Relating Almen intensity to residual stresses induced by shot peening: a numerical approach. *Journal of Materials Processing Technology*, vol. 110, pp. 277-286.

Guagliano, M.; Riva, E.; Giudetti, M. (2002): Contact fatigue failure analysis of shot-peened gears, *Engineering Failure Analysis.* Vol. 9, pp. 147-158.

Irissou, E.; Legoux, J. G.; Arsenault, B.; Moreau, C. (2001): Investigation of Al-Al2O3 Cold Spray Coating Formation and Properties, *J. Therm. Spray Technol.,* vol. 16 (5-6), pp. 661-668.

Karthikeyan, J. (2004): Cold Spray Technology: International Status and USA Efforts, ASB Industries, Inc., `http://www.asbindustries.com/media/1381/int_status_report.pdf`

Kosarev, V.F.; Klinkov, S.V.; Alkhimov, A.P.; Papyrin, A.N. (2003): On Some Aspects of Gas Dynamics of the Cold Spray, *J. Therm. Spray Technol.,*vol. 12(2), pp. 265-281.

Marsh, K.J. (1993): *Shot Peening: Techniques and Applications,* London, EMAS.

McCune, R.C., Papyrin, A.N., Hall, J.N., Riggs, W.L.; Zajchowski, P.H. (1995): An Exploration of the Cold Gas-Dynamic Spray Method for Several Material Systems, *Advances in Thermal Spray Science and Technology,* Houston, TX, ASM International, pp. 1-5.

Molz, R.; Valarezo, A.; Colmen, J.; Sampath, S. (2008): Comparison of coating stresses produced by high velocity liquid fuel and triplex pro 200 plasma guns using in-situ coating stress measurement, ITSC Proceeding on CD-ROM.

Papyrin, A.; Kosarev, V.; Klinkov, S.; Alkhimov, A.; Fomin, V. (2006): *Cold spray technology*, pp. 326.

Raletz, F.; Vardelle, M; Ezo'o. G. (2006): Critical particle velocity under cold spray conditions, *Surface & Coatings Technology*, vol. 201, pp. 1942–1947.

Rech, S.; Trentin, A.; Stoyanova, V.; Vezzù, S. (2008): Study of copper and copper/alumina coldsprayed deposits, *ITSC 2008 Proceeding on CD-ROM.*

Sampath, S.; Jiang, X.Y.; Matejicek, J.; Prchlik, L.; Kulkarni, A. and Vaidyi, A. (2004): Role of thermal spray processing method on the microstructure, residual stress and properties of coatings: an integrated study for Ni-5 wt.%Al bond coats, *Materials Science and Engineering A*, vol. 364, pp. 216-231.

Schulze, V. (2006): *Modern Mechanical surface treatment,* Wiley-VCH.

Stoltenhoff, T.; Kreye, H.; Richter, H.J. (2002): An Analysis of the Cold Spray Process and Its Coatings, *J. Thermal Spray Technol.*, vol. 11, pp. 542-550.

US army laboratory WebPages, Cold Spray Coating application, `http://www.arl.army.mil/www/default.cfm?Action=369&Page=375`.

Wagner, L. (1999): Mechanical surface treatments on titanium, aluminum and magnesium alloys, *Materials Science and Engineering A*, vol. 263, pp. 210 – 216.