

## Shot peening of a sintered Ni-Cu-Mo steel produced by diffusion bonded powders

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*The influence of the mechanical properties of a diffusion bonded Ni-Cu-Mo sintered steel on the residual stresses and the plastic deformation promoted by both steel and ceramic shot peening was investigated. While steel shots deform the surface more extensively than ceramic ones, leading to a thicker surface densification, ceramic shots are more effective in terms of maximum compressive residual stresses. The increase in the yield strength of the base material enhances residual stresses and reduces plastic deformation. The strain induced transformation of Ni-rich austenite in martensite causes a slight decrease of tensile elongation and of impact energy in specimens sintered at low temperature.*

**Keywords:** Steel - Powder metallurgy - Surface treatments

### INTRODUCTION

Shot peening is a flexible and cost effective technology to improve the fatigue resistance of mechanical parts due to the compressive residual stresses introduced in the surface layers, that oppose the nucleation and the propagation of the fatigue crack [1, 2]. A noticeable improvement of the high cycle fatigue resistance of some sintered steels is reported in [3-8], attributed to residual stresses and to the additional contribution of surface densification and strain hardening promoted by plastic deformation.

Molinari et al. [9] investigated the plane bending fatigue fracture surface of a sinterhardened 3%Cr-0.5%Mo-0.5%C steel after shot peening with steel shots of different diameters. The fatigue crack nucleates in the tensile residual stress zone, beneath the strain hardened layer, in correspondence to either cluster of pores or large irregular pores, as usual in porous sintered steels. The effect of shot peening is therefore that of moving the site for crack initiation towards the interior, where the stress intensity is lower than at the surface, and from this viewpoint it may

be concluded that residual stresses have a predominant role. Shot peening increases the resistance to contact fatigue of a sinterhardened Cu-Mo steel, as shown by Metinoz et al. [10]. Authors propose a model to predict the contact fatigue resistance, based on the comparison between the maximum stress and the yield strength profiles, that was validated by experiments. Surface densification increases the fraction of load bearing section, thus reducing the maximum stress and contributing to the increase in the contact fatigue resistance. The effect of strain hardening on the yield strength of the material is also significant.

Both plastic deformation, responsible for surface densification and strain hardening, and the amount of residual stresses depend on the mechanical properties of the base material. In the present work, a diffusion bonded Ni-Cu-Mo steel was produced by either cold and warm compaction and sintered at 1125°C and 1250°C to vary its mechanical properties, to investigate the response to shot peening. Both steel and ceramic shots were used. Ceramic shot peening is alternative to the traditional operation using steel shots, characterized by a tendentially higher efficiency in terms of surface residual stresses, due to the higher elastic modulus of ceramics, and by a better surface quality of the shot peened parts [11].

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### EXPERIMENTAL PROCEDURE

The steel was produced by adding 0.5% graphite to a diffusion bonded 4%Ni-1.5%Cu-0.5%Mo iron powder.

Green parts were produced by either cold or warm compaction (CC and WC in the following, respectively), and were sintered at two temperatures: 1125°C in a belt fur-

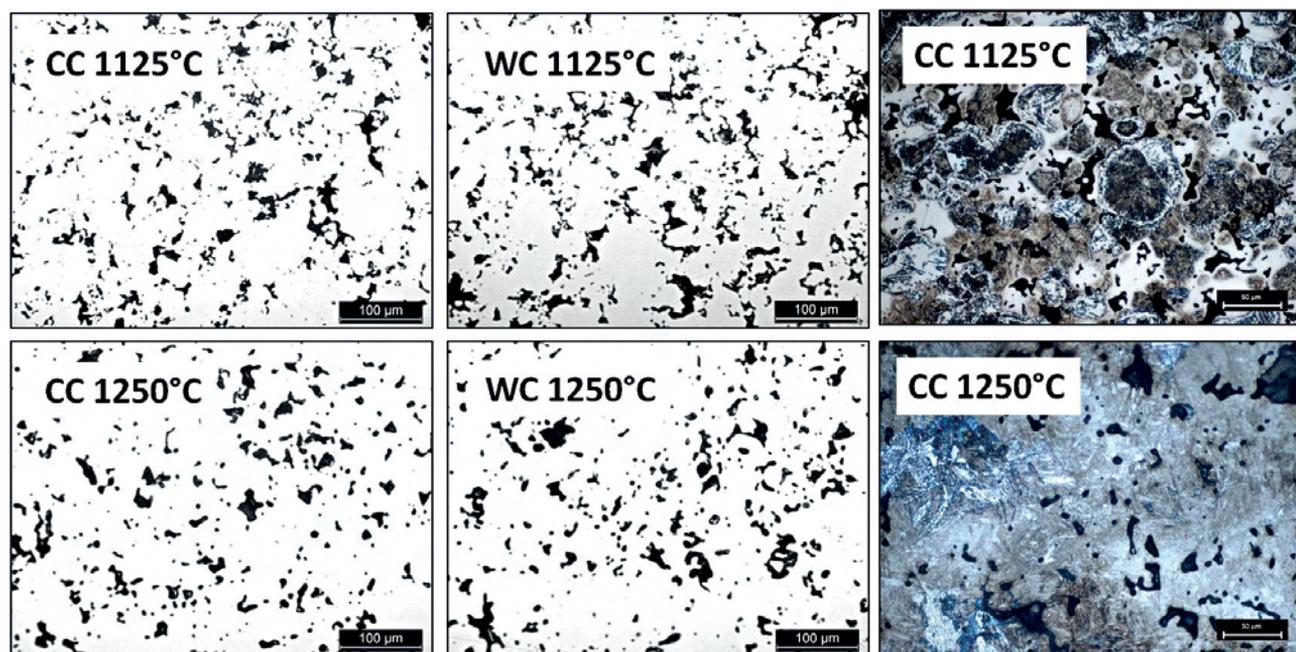


Fig. 1 - The microstructure of the investigated materials

nance under endogas atmosphere and at 1250°C in a vacuum furnace. Tensile and Charpy impact testpieces were produced.

Steel shot peening was carried out with quenched and stress relieved 1%C-0.8%Mn steel shots, 0.8 mm diameter and 12 Almen A intensity. Ceramic peening was made using 0.3-0.4 mm diameter Zirshot Y 300 shots (YSZ containing 30 wt.% glass), with a 4 Almen A intensity. According to the authors experience, the above conditions are typical for shot peening of hardened steel mechanical parts.

The microstructural analysis was carried out at the Light Optical Microscope after metallographic preparation and even after etching with 2% Nital. The thickness of the surface densified layer was measured by Image analysis on five metallographic images, according to a procedure reported in [8]. Microhardness profile was measured using HV0.1 scale. HV10 hardness, tensile and impact properties were also measured on both sintered and shot peened specimens. The micro-geometry of the die and punch surfaces was investigated by a roughness and contour measurement instrument, equipped with a stylus having a typical radius of 5 μm. Five scans 5 mm long were carried in the central part of each surface and the Abbott Firestone curves were obtained with a 0.8 mm cut off filter [12]. The residual stress profile was measured by X-ray Diffraction, according to EN 15305 standard, using the CrK $\alpha$  radiation and a spot of 2mm diameter. An 8mm diameter area was progressively thinned by electrochemical etching, and the thinning depth was measured by a micrometer.

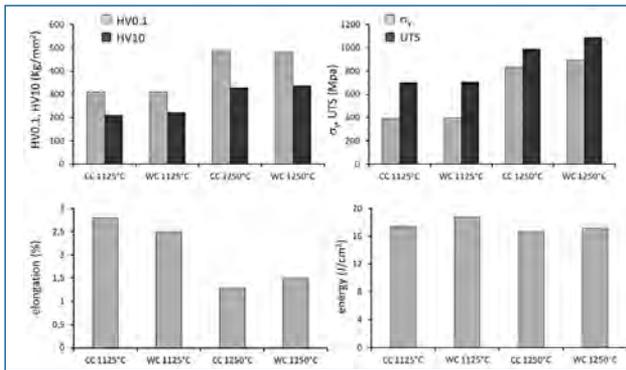
## RESULTS AND DISCUSSION

Figure 1 shows the microstructure of the as sintered materials; the microstructural characterization shows that the increase in the sintering temperature improves the pore morphology and slightly decreases porosity, while warm compaction does not have any evident effect on the microstructure. After metallographic etching, the decrease of the content of the Ni-austenite caused by the increase in the sintering temperature is well evident; the enhanced homogenization of Ni increases hardenability and microstructure evolves from ferrite, pearlite, bainite and Ni austenite after sintering at 1125°C to bainite and martensite with small Ni austenite areas after sintering at 1250°C. XRD analysis reveals that austenite content decreases from 15±2% down to 6±2% on increasing temperature, without any effect of warm compaction.

Density, open and closed porosity of the four materials, as measured by the water displacement method, are reported in Table 2; warm compaction and the increase in the sintering temperature increase density slightly, while porosity evolves from mostly open to mostly closed on increasing temperature.

	$T_{\text{sint}} = 1125^{\circ}\text{C}$			$T_{\text{sint}} = 1250^{\circ}\text{C}$		
	$\rho(\text{g}/\text{cm}^3)$	$\varepsilon_t(\%)$	$\varepsilon_{\text{open}}(\%)$	$\rho(\text{g}/\text{cm}^3)$	$\varepsilon_t(\%)$	$\varepsilon_{\text{open}}(\%)$
CC	7.05	9.1	7.6	7.15	8.4	3.9
WC	7.11	8.9	6.5	7.24	7.2	2

Table 2 - Density ( $\rho$ ), total ( $\varepsilon_t$ ) and open ( $\varepsilon_{\text{open}}$ ) porosity.



**Fig. 2 - Mechanical properties of the investigated materials**

Figure 2 shows the mechanical properties of the four materials. The increase in the sintering temperature increases microhardness, due to the microstructural transformations induced by the enhanced Ni dissolution in austenite, and hardness due to the additional effect of the increased density. The compaction technique does not affect microhardness and hardness significantly. Yield and Ultimate Tensile Strength follow the same trend as hardness, while tensile elongation decreases on increasing sintering temperature, due to the formation of a tendentially less ductile microstructure. Impact energy is almost unaffected by the sintering temperature, since the increased strength is

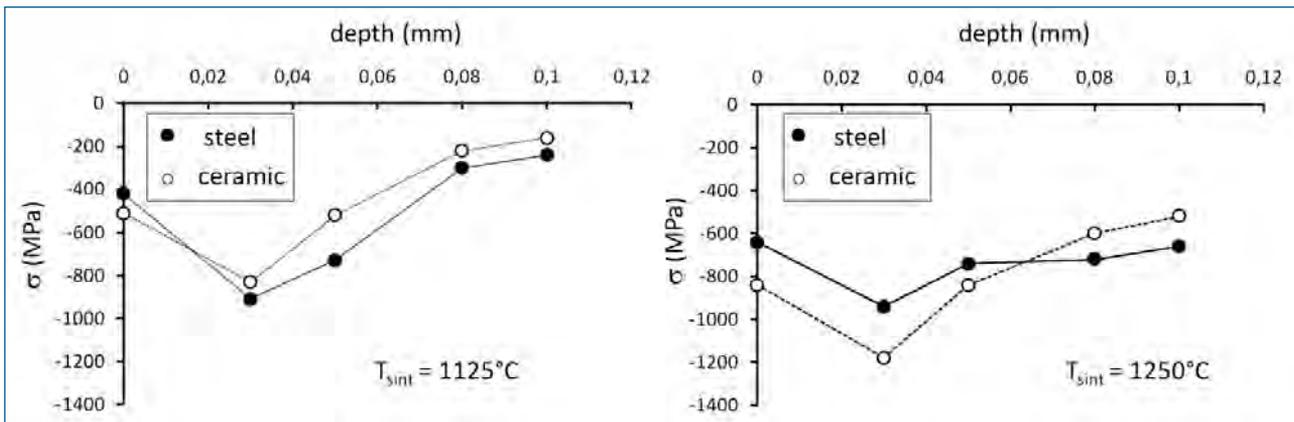
compensated by the decreased ductility.

Figure 3 shows the residual stress profiles of the warm compacted Charpy bars sintered at the two temperatures, after shot peening with steel and ceramic shots.

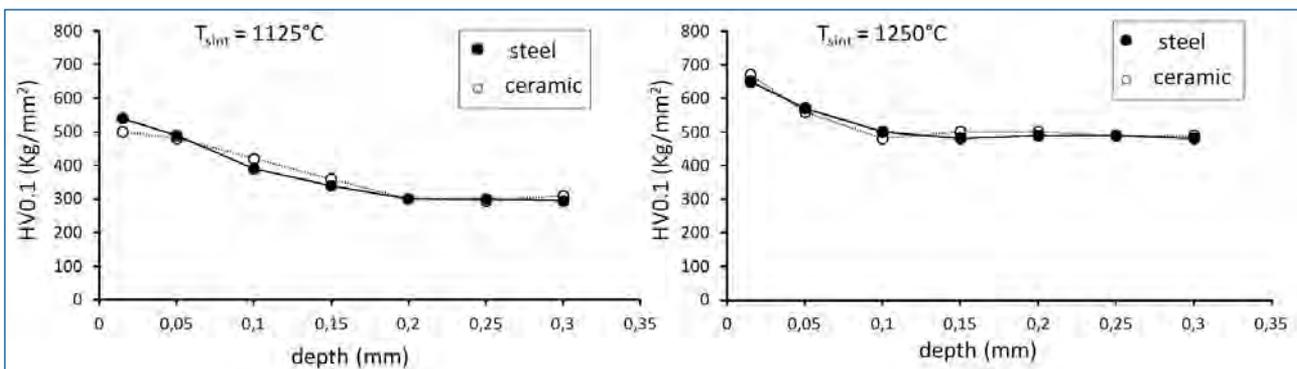
The compressive residual stress profiles show a maximum at around 0.025-0.03 mm. The transition from compressive to tensile stresses was not individuated but it may be expected to occur at a depth of 0.15 and 0.2 mm from the surface in specimens sintered at 1125°C and 1250°C, respectively. Ceramic shot peening tends to promote higher compressive stresses on the surface layers and a thinner compressed layer than steel shot peening, as expected. The residual stresses are higher in the specimens sintered at 1250°C.

Figure 4 shows the microhardness profiles of the specimens sintered at the two temperatures. Even in this case, no effect of the compaction techniques was observed.

Plastic deformation and the consequent strain hardening promote a microhardness increase towards the surface, and involves a deeper layer in the specimens sintered at the lower temperature. Energy spent for plastic deformation does not contribute to the accumulation of residual stresses, that are elastic in nature. Therefore, the lower yield strength and the higher ductility of the specimens sintered at 1125°C result in a greater plastic deformation, evidenced by the deeper strain hardened layer, and in a smaller amount of residual stresses. Since mechanical properties are not significantly affected by the compaction



**Fig. 3 - Residual stress profiles after shot peening**



**Figure 4 - Microhardness profiles after shot peening of CC specimens**

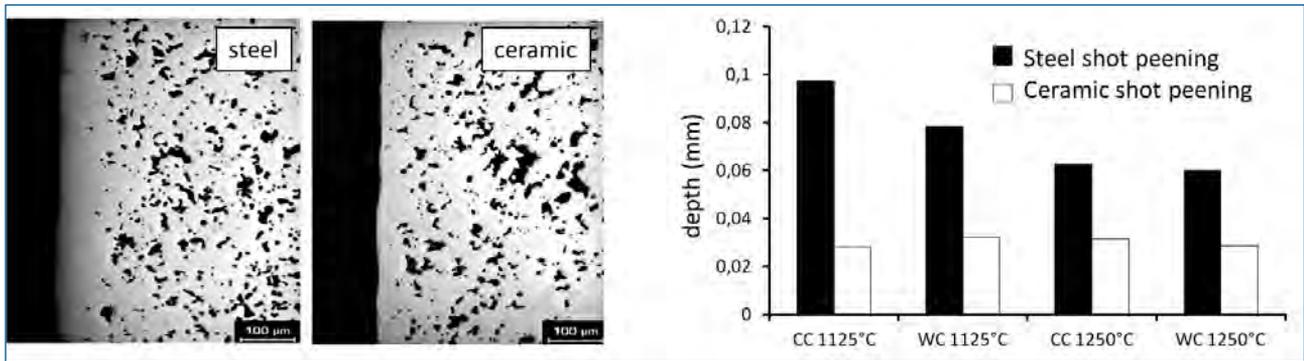


Fig. 5 - Surface densification promoted by shot peening

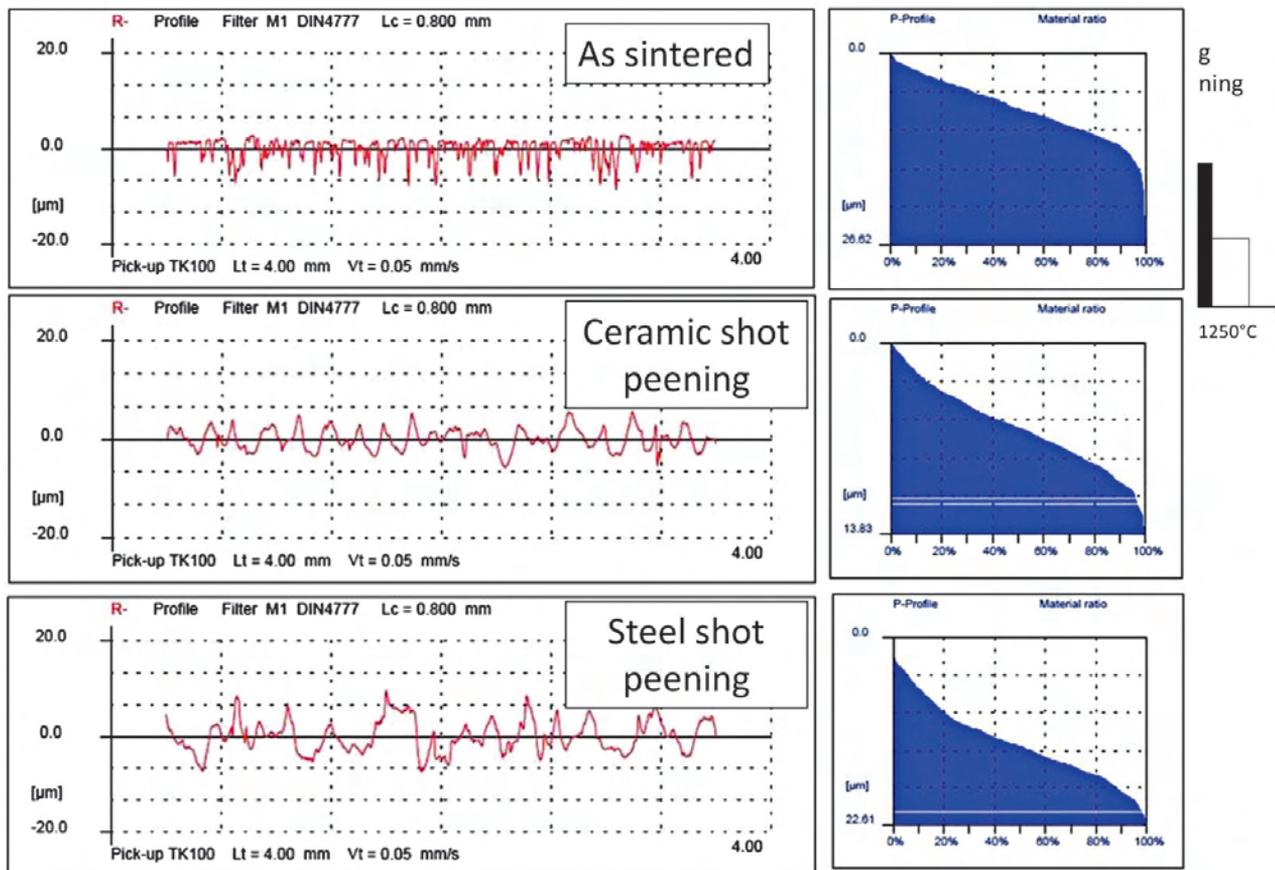


Fig. 6 - Surface profile and relevant Abbott-Firestone curves

technique, no difference in strain hardening and in residual stresses between cold compacted and warm compacted specimens is observed. Plastic deformation causes the densification of the surface layers. Figure 5 shows two examples of the microstructure of the shot peened specimens, relevant to materials cold compacted and sintered at 1125°C, and the surface densification depth of all the specimens. Densification involves a deeper layer in steel shot peening, as clearly shown by the micrographs and confirmed by the diagram in the figure. This is due to the higher energy involved in steel shot peening than in ceramic one, resulting from the larger shot diameter combined to the higher steel

density. Densification depth decreases on increasing sintering temperature in steel shot peening, whilst it result unaffected in ceramic shot peening; the effect of the resistance to plastic deformation of the base material can only be observed in the former. Surface densification increases the load bearing surface. Figure 6 shows some examples of the surface profile and of the Abbott-Firestone curves. The load bearing surface  $Mr_2$  and  $Ra$  were calculated from the surface profiles. Since  $Ra$  does not have a real meaning for sintered specimens, being strongly affected by the surface pores, it was not calculated. Figure 7 summarizes  $Ra$  and  $Mr_2$  relevant to the surface of the specimens in contact to the punch

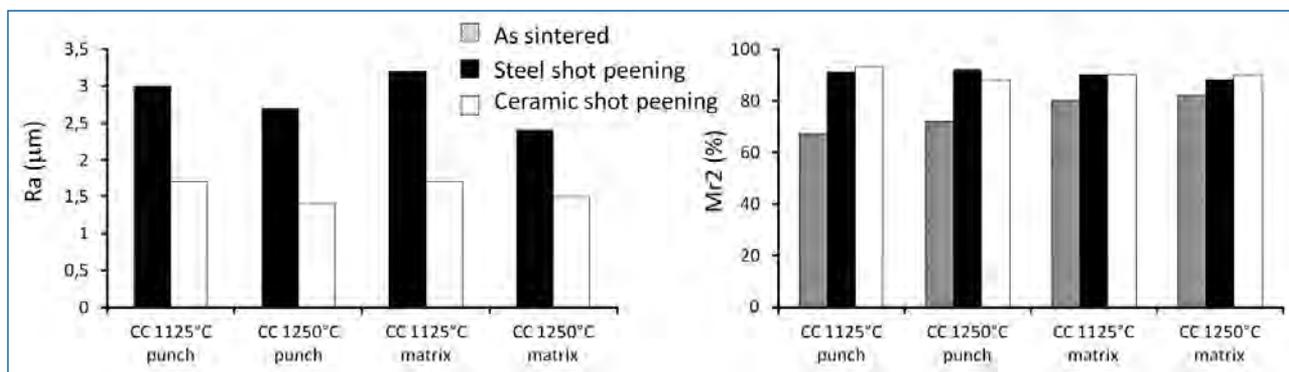


Fig. 7 - Roughness and load bearing surface

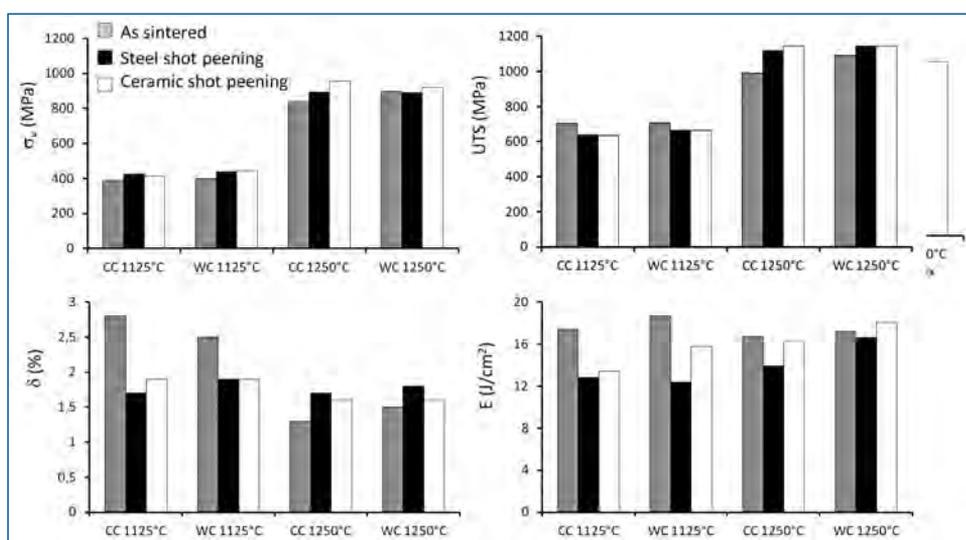


Fig. 8 - Mechanical properties of sintered and shot peened materials

and that in contact to the matrix.

The load bearing surface increases up to 90-92% on both the surfaces investigated, irrespective to the starting one that is smaller for the punch surfaces. No effect of compaction, sintering temperature and shot materials was observed. The main difference between ceramic and steel shot peening is relevant to roughness; Ra is significantly smaller after ceramic shot peening, because of the smaller diameter of the shots.

To summarize, ceramic shot peening promotes the formation of larger compressive residual stresses in a slight thinner layer than steel shot peening. On the other side, the latter is more effective to increase density of the surface layers but the final roughness is higher than after ceramic shot peening. From these results it may be concluded that steel shots tend to deform plastically the surface layers more than ceramic ones. On the contrary, ceramic shots are more effective in terms of residual stresses. In both the techniques, the increase in the yield strength of the base material enhances residual stresses and reduces plastic deformation, as it might be expected. The effect is very pronounced on residual stresses.

The effect of the shot material on the improvement of the mechanical and of the contact fatigue will be investigated. Here the effect on tensile properties and on impact

strength is presented. Both tensile and impact resistance depend on the bulk properties, and therefore the effect of shot peening is expected to be negligible. Figure 8 shows yield and Ultimate Tensile Strength, tensile elongation at fracture and impact energy of the sintered and of the shot peened specimens.

The differences between sintered and shot peened specimens are almost negligible, being comparable to the scatter band of the results, apart from the decrease of tensile elongation and of impact energy for specimens sintered at the lower temperature, that is significant of a decrease of ductility. Such a result may find justification in the complete strain induced transformation of austenite in martensite detected by XRD in all the shot peened specimens, within a surface layer comparable to the strain hardened one. The Ni-rich austenite contributes to ductility, and its transformation may worsen such a property in particular in the low temperature sintered specimens, having a less irregular pore morphology that enhances strain localization more than in the high temperature sintered ones. In other words, the better pore morphology of specimens sintered at 1250°C may partially compensate for the decreased ductility of the matrix. Since plastic deformation is allowed to propagate far from the neck regions before the critical conditions for ductile fracture are reached.

## CONCLUSIONS

A diffusion bonded Ni-Cu-Mo steel with different mechanical properties was produced by varying compaction technique and sintering temperature to investigate the influence of mechanical properties on the residual stresses and the plastic deformation promoted by shot peening. Both steel and ceramic shots were used

The steel shots tend to deform plastically the surface more than ceramic ones, leading to a thicker surface densification. On the contrary, ceramic shots are more effective in terms of maximum compressive residual stresses. The increase in the yield strength of the base material enhances residual stresses and reduces plastic deformation, and in turn surface densification. The effect on residual stresses is very pronounced.

Tensile and impact properties of sintered and shot peened specimens are almost negligible; only a slight decrease of tensile elongation and of impact energy is measured on specimens sintered at the lower temperature, attributable to the complete strain induced transformation of austenite in martensite.

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