Residual stress measurement in carbonitrided shot-peened steel using the incremental groove machining coupled with speckle pattern interferometry

S. Van Wijk[1], M. François[1], M. Frabolot[2], E. Sura[2], N. Ghodhbani[1]

1 Université de Technologie de Troyes (UTT), ICD LASMIS, STMR UMR CNRS 6279, 12 rue Marie Curie, BP 2060, 10010 Troyes Cedex, France
2 Direction Ingénierie Process, Renault, 67 rue des bons raisins, 92508 Rueil-Malmaison, France

Abstract
Shot peening is a commonly used surface treatment to introduce compressive residual stress in carbonitrided gears. An effective measurement of stress gradient is an important factor in order to bring a better comprehension of shot peening mechanisms and to assess fatigue and wear properties of gears. Electronic Speckle Pattern Interferometry (ESPI or DSPI) is a technique which allows to determine the displacement field of a deformed object with high resolution.
The aim of this work is to quantify residual stress in carbonitrided and shot peened steel using an innovative method combining ESPI with incremental groove machining. ESPI is used to measure, with submicrometer resolution, the displacement field due to local stress relaxation occurring after machining a groove of a few micrometers depth. To obtain the complete stress profile, further machining increments are performed with ESPI measurement between each. To obtain the relation between measured displacements and the residual stress inside the groove, a finite elements model is developed to calculate the matrix of calibration coefficients for each depth.
The reliability of this technology is also tested in this work by comparing the residual stresses determined by ESPI with those measured by X ray diffraction method.

Keywords Residual stress, Electronic speckle pattern interferometry (ESPI, DSPI), Simulation, Shot peening, carbonitriding.

Introduction
Residual stress is the stress that remains in a body when all external loads have been removed [1,2]. The performance of the material under thermal, mechanical and other kinds of loading depends on the state of residual stress induced during the manufacturing process. Therefore, an excellent knowledge in the magnitude and distribution of residual stress in component is important in order to assess their effects in mechanical performance. Carbonitriding followed by shot peening is commonly used in industry to introduce compressive residual stresses to improve the fatigue life of components such as gears.
Measuring the relieved strains around a hole with strain gauges is a classical method to determine stress levels [3]. Drilling a hole in the surface of a body with inherent residual stresses disturbs the equilibrium which results in displacements and strains in the vicinity of the hole [4]. However, this technique requires a preparation of the surface in order to ensure appropriate bonding and only the strain in the direction of gauges can be obtained. Moreover, it gives the stress gradient along the depth only on one specific place, where the hole is drilled. The procedure proposed in this study is based on Electronic Speckle Pattern Interferometry

(ESPI) [5,6,7], a non contact optical method, to measure the displacement field on the surface around a groove that relaxes stress not only along the depth but also along its length. The principal advantage of ESPI method is the measurement full field displacement with high resolution (≈ 30 nm within one pixel) without the installation of strain gauges.
Since the 80's many papers used holography or ESPI with hole drilling to quantify residual stresses [8,9]. After that, several methods with various perturbation geometry were proposed for instance by. Plama et al. [10], Bendek et al. [11]. Montay et al. [6] studied the measurement of two dimension residual stress by combination of incremental groove machining and ESPI on a shot peened aluminium plate.
In this paper, we present a new numerical technique to determine residual stresses based on the ESPI method combined with incremental groove machining in carbonitrided and shot peened steel. Moreover, these stresses are then compared to the stresses measured by X-ray diffraction to validate the method. The form of groove [6] is chosen here because of its capacity to perform the machining in specimens with hardness of approximately 850HV. Compared to X-ray diffraction, the incremental groove machining method is less expensive in terms of equipment and maintenance. Another main advantage is, as for all mechanical methods, the capacity to obtain the macro stresses. For instance, in our case, carbonitrided and shot-peened steels contain two phases, austenite and martensite, and diffraction methods will give pseudo macro-stresses, i.e. phase stresses. The groove machining can also gives directly the stress gradient in two directions without the necessity to perform successive electropolishing removals.

Experimental set-up and results

The ESPI technique is widely used to measure surface displacement [1,4,6,7,10]. Figure 1 shows the schema for ESPI device used in this study with a 35 mW HeNe laser of wavelength 632.8 nm. One beam of the interferometer reflected by a mirror mounted on a piezoelectric actuator to perform a known phase shifting [12]. After each incremental machining, an image of the specimen surface is recorded by the camera. The difference of two images generates fringes which contains the displacement information between the two states [5]. The sensitivity of measurement is equal to 0.63 µm/fringe.

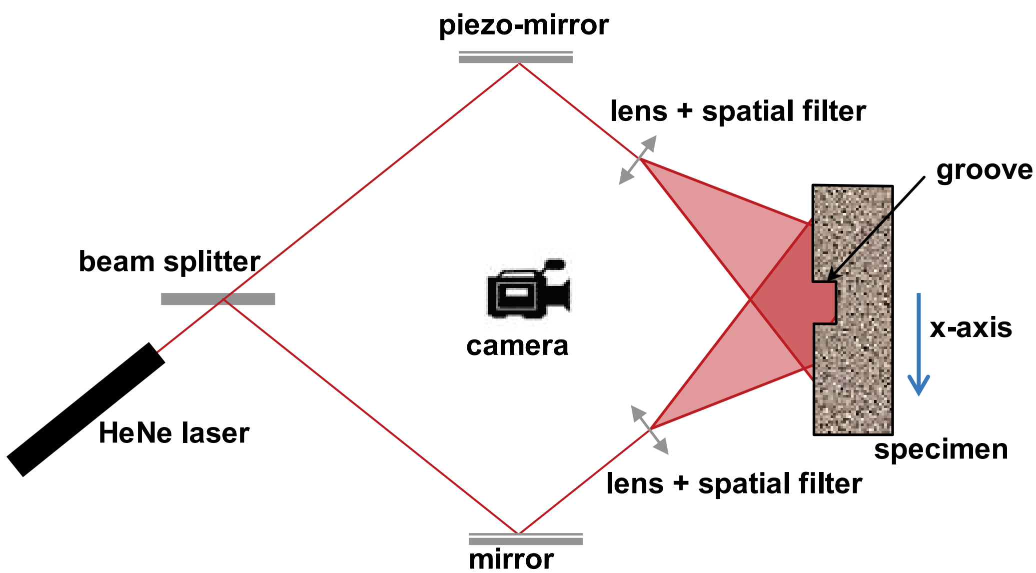

Figure 1: Interferometric set-up. Between the camera and the specimen, a machining device can be inserted and removed to drill the groove

The investigated specimen is made with 27MnCr5 steel carbonitrided at 907°C and then shot peened. Specimen dimensions are 9x16x80 mm^3 and the shot peened surface is 9x80 mm^2. Hardness obtained on the peened surface is approximately 850HV. The values of parameters used for shot peening were given in Table 1.

Table 1.Shot peening parameters

shot size[mm]	shot hardness[HV]	Pressure[bar]	Treatement time[s]	Impact angle[°]
0.7	640	3	6	65

The groove is realized by a 40 tooth carbide circular saw blade with 1mm width. Evolutions of phase fringes determined as a function of some machined depths are presented in Figure 2. The sensitivity direction depend the direction of the illumination and specimen position In this study, displacement field $U_x(x,y)$ is measured along x axis presented in Figure 1.

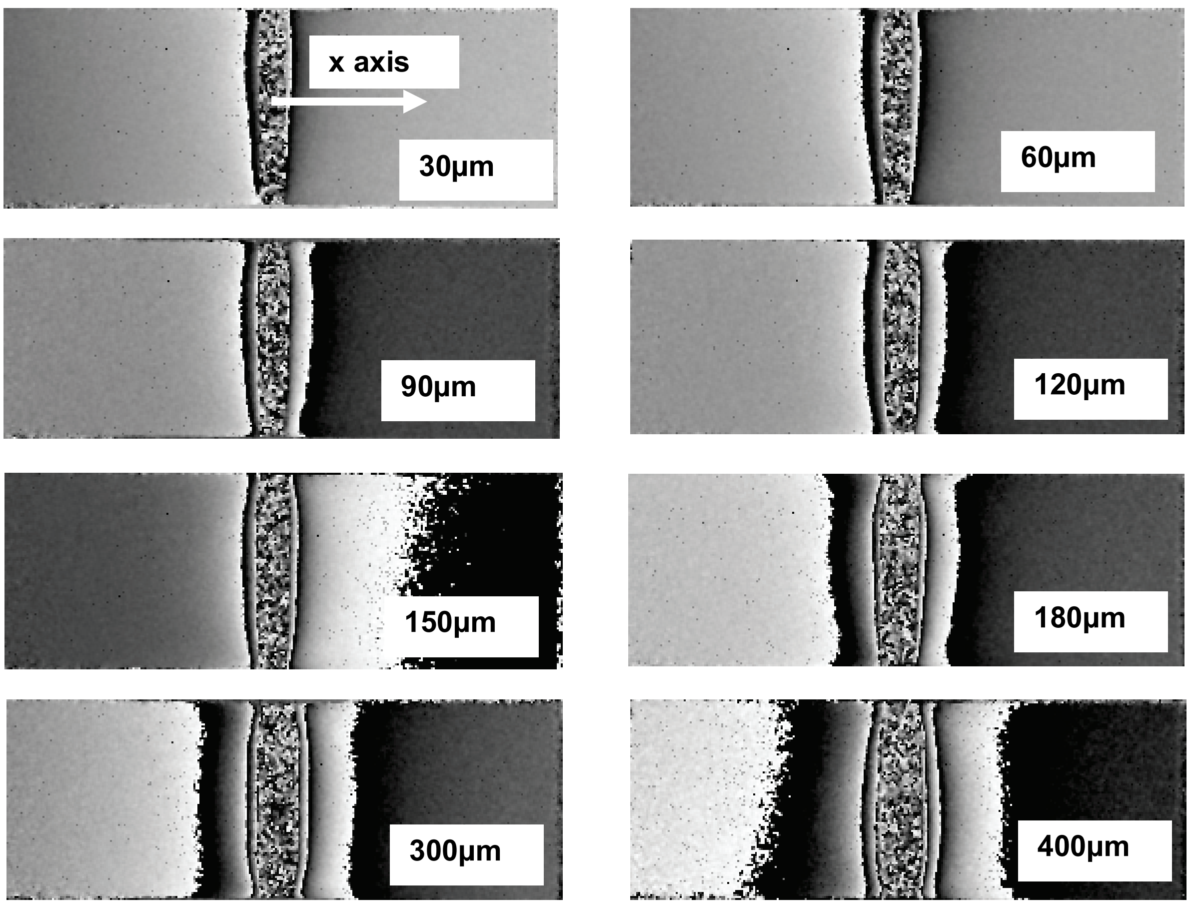

Figure 2. Phase fringes obtained by ESPI for different groove depths. One fringe represents a displacement of 0.63 µm in the horizontal direction. The noisy area in the centre is the groove (1 mm wide). The height of the picture represents the whole width of the specimen (9 mm)

Comparing the images in Figure 2, it can be seen that the depth of the groove is not perfectly constant along its length. This is particularly clear for small depth increment and it due to imperfect sample holder orientation with respect to tool translation. This shows the capacity of the proposed method to detect experimental errors. It can also be seen in Fig. 2 that the number

of fringes, i.e. the displacement, increases with increasing machined depth as the volume on which stress is relaxed evolves.
Figure 3 shows quantitatively the evolution of the displacement $U_x(x,y)$ versus the distance x from the centre of groove for different machining depths.

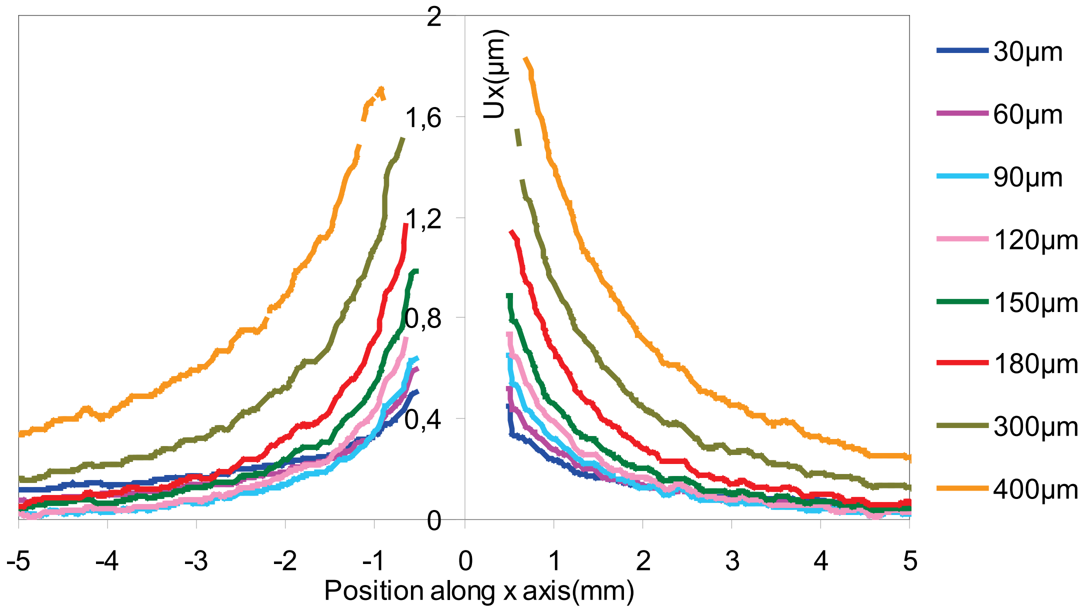

Figure 3. Displacement Ux measured by ESPI method versus distance from the centre of the groove, for various machining depth

Computation of stress from displacement data

Once displacement data as shown in Figure 3 is acquired, the stress gradient along the two directions y and z can be computed. For that, the material is assumed here isotropic and linearly elastic. Figure 4 presents the definition of coordinates for analysis. When a surface along plane (y,z), submitted to a residual stress field, is created through machining a groove of depth Z, the relaxation of the stress $\sigma_{xx}(y_k,z_j)$ produces a displacement $U_x(x_m,y_p)$ at point M on the free surface along plane (x,y).
The total displacement can be expressed as:

$$U_x(x_m,y_p) = G(x_m, y_p, y_k, z_j, Z)\ \sigma_{xx}(y_k,z_j) \quad (1)$$

where G is the matrix of calibration coefficients which depend on the geometry of the component, on the depth of the groove, on the elasticity constants of the material and on the indices m, p, k, j relative to the points at which the displacement is measured and the stress is computed. When the first increment i=1 is machined, the displacement measured U_p^1 at a given distance x_m on line y_p when all the k cells are loaded:

$$U_p^1 = \sum_{k=1}^{Nk} G_{pk}^{11}\,\sigma_k^1 \quad \text{or in matrix form} \quad \left[U^1\right]=\left[G^{11}\right]\left[\sigma^1\right] \quad (2)$$

When increment i is machined with j the cell number in z direction, we have:

$$U_p^i = \sum_{k=1}^{Nk}\sum_{j=1}^{i-1} G_{pk}^{ij}\,\sigma_k^j + \sum_{k=1}^{Nk} G_{pk}^{ii}\,\sigma_k^i \quad \text{or in matrix form} \quad \left[U^i\right]=\sum_{j=1}^{i-1}\left[G^{ij}\right]\left[\sigma^j\right]+\left[G^{ii}\right]\left[\sigma^i\right] \quad (3)$$

Eq. 3 shows the relationship between the measured displacements U_i for increment i, the stresses calculated for the previous increments i-1 and the unknown stress correspond to i increment σi. The calibration coefficients G^{ij}_{pk} are obtained through finite element analysis by loading a cell (y_k, z_j) with a unit stress $\sigma_{xx}(y_k, z_j)$ and calculating the corresponding displacement. In this study, the number Np=26 of measurement lines is larger than the number Nk=5 of unknown value, the system can be solved by a least square procedure.

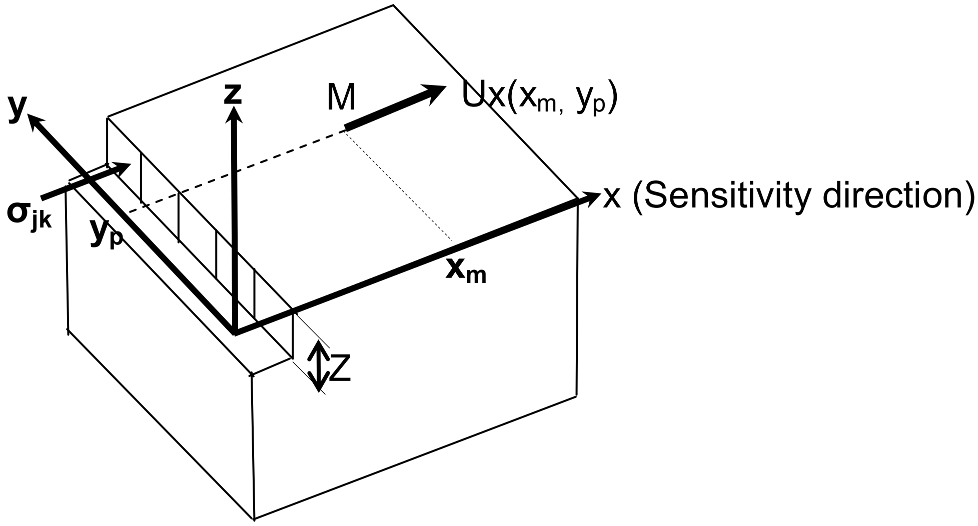

Figure 4. Groove machined in the component for the first increment (i=1). The displacement at point M is due to the stress applied on one cell defined on the lateral surface of the groove

Comparison with measurements by X-ray diffraction

In order to determine residual stress, the calibration coefficients G were computed for measured line x_m=2 mm. They were then used to calculate the residual stress by using Eq 3 with the displacements results of ESPI measurement. The calculated stress corresponds to the stress level located in the middle of each increment. In Figure 5, the stress obtained with groove machining method is compared with stress obtained by XRD method performed in martensite phase. It can be noted that these two methods give a similar stress level. The macro stresses in this case is very similar compared to the stress in martensite phase. It can be concluded that stresses are due to layer incompatibilities rather than phase incompatibilities.

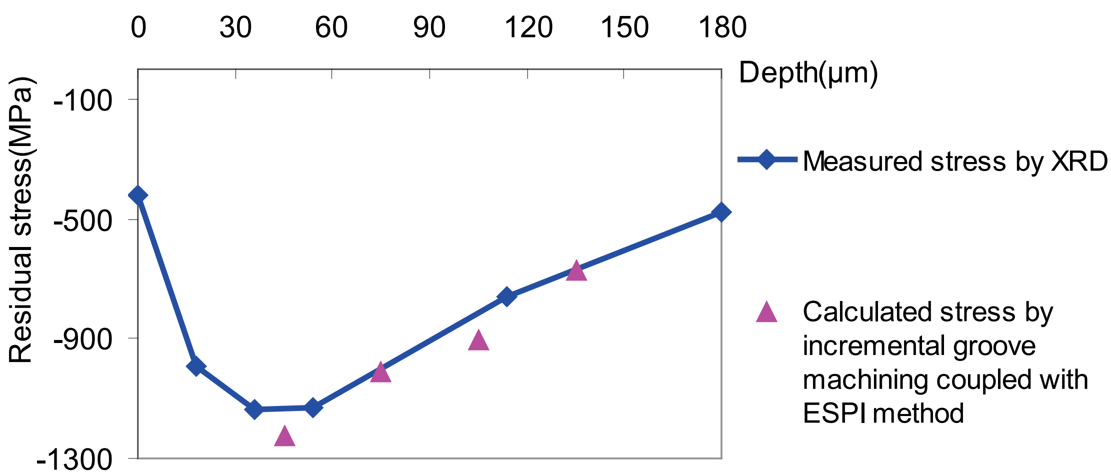

Figure 5. Comparison of residual stress determined by XRD and incremental groove machining method combined with ESPI

This comparison showed the capacity of the incremental groove machining coupled with ESPI method to determine the residual stress in carbonitrided and shot peened steel.

Conclusion

In this study, Electronic Speckle Pattern Interferometry (ESPI) and groove machining is employed to measure the residual stress field in 27MnCr5 steel carbonitrided and shot peened. The residual stress is quantified by using the displacement measured by ESPI and the matrix of calibration coefficient determined by finite element model. The calculated values are compared with the stress performed with XRD and a good correlation is obtained to validate this innovative method. This study also shows that displacements in very hard materials can be measured successfully by a mechanical method such as groove machining.

Acknowledgement

The authors are grateful to ANRT (French Agency for Research and Technology) for the CIFRE grant supporting this work.

Reference

[1] M. Steinzig, E. Ponslet, *Residual stress measurement using the hole drilling method and laser speckle interferometry*, part I, Part II, Experimental Techniques, (2003)

[2] M.Hertwig, T.Flemming, T.Floureux, H.A.Aebischer, *Speckle interferometric damage investigation of fibre reinforced composites*, Optics and lasers in Engineering 24(1996)485-504

[3] G.S.Schajer, G.Roy, M.T. Flaman, J.Lu, *Hole drilling and ring core methods, Handbook of measurement of residual stresses*, Society for experimental mechanics, 1996

[4] G. Focht, K. Schiffner, *Determination of residual stresses by an optical correlative hole drilling method*, Experimental mechanics, (2003)

[5] R. Jones, C. Wykes, *Holographic and Speckle interferometry*, Cambridge studies in modern optics, Cambridge university presss, (1989)

[6] G. Montay, O.Sicot, A. Maras, E. Rouhaud, M. Francois, *Two dimensions residual stresses analysis through incremental groove machining combined with electronic speckle pattern interferometry*, Experimental Mechanics, (2008)

[7] G.S.Schajer, M.Steinzig, *Full Field calculation of hold drilling residual stresses from electronic speckle pattern interferometry data*, Experimental mechanics, Vol. 45,No.6,December 2005, (2005)

[8] A. Antonov, AI. Bobrik, VK. Morozov , G. Chernyshev. *Residual stress determination by making a hole and holography interferometry*. Proc AN SSSR, Mekh Tverd Tela (1980);2:182–9.

[9] DV.Nelson, JT. McCrickerd. *Residual stresses determination through combined use of holographic interferometry and blind hole drilling*. Exp Mech (1986);26:371–8.

[10] J. Palma., R. Rivero., I. Lira., M. François., *Measurement of the residual stress tensor on the surface of a specimen by layer removal and interferometry*, Measurement Science and Technology, 20, (2009) 1-10

[11] E. Bendek., I. Lira, M. François.,*Uncertainty of residual stresses measurement by layer removal*, International Journal of Mechanical Science, 48 (2006) 1429-1438

[12] G. Cloud, *Optical methods of engineering analysis*, Cambridge university presss, (1998)