Surface & Coatings Technology 254 (2014) 175–186

Contents lists available at ScienceDirect

Surface & Coatings Technology

journal homepage: www.elsevier.com/locate/surfcoat

Experimental parameter sensitivity analysis of residual stresses induced by deep rolling on 7075-T6 aluminium alloy

M. Beghini [a], L. Bertini [a], B.D. Monelli [a], C. Santus [a,*], M. Bandini [b]

[a] University of Pisa, DICI — Department of Civil and Industrial Engineering, Largo L. Lazzarino 2, 56122 Pisa, Italy
[b] Peen Service Srl., Via A. Pollastri 7, 40138 Bologna, Italy

ARTICLE INFO

Article history:
Received 26 February 2014
Accepted in revised form 9 June 2014
Available online 21 June 2014

Keywords:
Deep rolling
Residual stresses
Hole drilling method
X-ray diffraction
7075-T6 aluminium alloy

ABSTRACT

The residual stress distribution induced by deep rolling depends on several factors: the material elasto-plastic curve, roller shape, indentation force and rolling feed. Among these, the force and the feed are those parameters that can be easily handled without cost or layout modifications. This paper shows an experimental investigation about these two parameters and a comparative analysis on the obtained residual stress profiles. The deep rolling treatment was performed on aluminium alloy 7075-T6 samples and the used tool was a carbide roller with conical and rounded contact. The residual stresses were measured by combining the hole drilling method and the X-ray diffraction technique. A first evident result was the large difference between the two principal residual stress components. The feed direction residual stress was almost a factor of two larger than the rolling direction residual stress. Parameter trends on residual stress distributions were investigated. The depth of the compressive region increased with the rolling force and the maximum stress position also tended to be subsurface, while for lower loads the maxima were at the surface. On the other hand, the feed parameter did not produce any effect at large depth, and just the initial subsurface distribution was slightly influenced. However, the surface hardness was noticeably affected by the feed, while the rolling force had a less predominant role. Finite element simulations were also carried out and reported in the paper, mainly to obtain information on induced work hardening. The plasticity depth was only affected by the load, indeed it was very similar to the compressive residual stress depth, while the maximum accumulated plasticity was significantly increased by the feed.

1. Introduction

Mechanical treatments that produce plasticity deformation by means of a hard rolling indenter pushed against the surface of a ductile metal component can be categorized as: “Burnishing”, “Low Plasticity Burnishing” and “Deep Rolling”. Burnishing [1] is a treatment mainly for surface finish enhancement and/or surface hardness improvement [2–4], where the plastic deformation is limited to the scale of surface roughness asperities. This treatment is not primarily dedicated to the induction of residual stresses. On the other hand deep rolling (DR) [5] (sometimes also referred to as “Deep Cold Rolling” [6], or “Deep Ball Burnishing” with the spherical indenter [7]) is a treatment basically designed for introducing surface and subsurface highly compressive residual stresses. In specific applications, DR can be limited to the notch radiused region, such as with shaft fillets [8,9]. Otherwise the treatment can be performed under feed operation [10], following a setup comparable to burnishing, and merely using the same tools, however with enhanced rolling forces. The surface finish improvement is still obtained even with DR, along with high cold working [6,10,11]. This latter surface effect can be beneficial as associated to the hardness improvement, but also detrimental since it is the reason of material embrittlement [12,13], these two controversial factors can have relative roles depending on the applied load and the specific material. Low plasticity burnishing, developed and patented by Lambda Technologies, also referred to as “Roller Burnishing” e.g. by Ecoroll Company and by Klocke and Liermann [14], or “Ball Burnishing” by López et al. [15], is both dedicated to surface roughness reduction and high and deep compressive residual stresses. The main difference, with respect to deep rolling, is that high residual stress is obtained with reduced work hardening [16–18], essentially due to the large size of the spherical indenter. This kind of burnishing is usually performed on common machine tools, with a hydrostatic bearing system for the ball roller that requires a pressurization unit. Even complex geometries, such as impeller blades, can be treated by means of this technology [19,20], but obviously there are limitations at notches due to the roller shape.

Besides burnishing and deep rolling, there are other techniques aimed at surface improvement, specifically for introducing residual stresses. Among these, shot peening is the most common [21–23]. This mechanical surface treatment is more flexible for different and complex geometries such as sharp notches [24–26]. Despite the detrimental effect of surface roughness, severe work hardening, and the

---

* Corresponding author. Tel.: +39 0 50 2218007; fax: +39 0 50 2210604.
E-mail address: ciro.santus@ing.unipi.it (C. Santus).

http://dx.doi.org/10.1016/j.surfcoat.2014.06.008
0257-8972/

Nomenclature

DR	deep rolling
HDM	hole drilling method
XRD	X-ray diffraction
FE	finite element method
E	Young's modulus
S_Y	yield strength
S_U	ultimate tensile strength
δ_N	toolholder imposed normal displacement
d_R	residual indentation depth
F_N	normal force during deep rolling treatment, also referred to as rolling force
$F_{N,av}$	average value of the normal force during deep rolling
$F_{N,std}$	standard deviation of the normal force during deep rolling
f	rolling feed: the pitch between rolling subsequent traces
α	clearance angle: inclination of the rolling tool conical surface
r_R	fillet radius of the rolling tool
R_a	surface average roughness
σ_x,σ_y,τ_{xy}	residual stress components along generic directions
σ_f,σ_r,τ_{fr}	residual stress components along feed and rolling directions
σ_{f0},σ_{r0}	residual stress components at the surface, feed and rolling directions
$\sigma_{f,max}$, $\sigma_{r,max}$	maximum residual stress components, feed and rolling components
d_c	depth of compressive residual stresses
$d_{f,max}$, $d_{r,max}$	maximum compressive residual stress depths, feed and rolling directions
ε_p	accumulated plastic strain after rolling
$\varepsilon_{p,max}$	maximum of the accumulated plastic strain distribution

limited depth of residual stresses [5,16], the fatigue strength enhancement produced by shot peening still is remarkable. This can be attributed to the shallow depth of the fatigue "process volume", or the so called (fatigue) critical distance [27], that actually can be quite small for high strength structural alloys. For example, this size is smaller than 0.1 mm for 7xxx aluminium alloys and thus completely within the shot peening compressive depth, as well discussed by Benedetti et al. [24].

Parameter investigation is a crucial task for surface treatments. An accurate choice of parameters can give optimal performance, such as surface roughness or fatigue strength improvement, on the contrary the erratic selection of treatment parameters can even be detrimental with respect to the untreated condition. Regarding the burnishing process, a parameter investigation was performed by El-Axir [2]. This author showed the effects on micro-hardness and surface roughness, and proposed empirical equations for the parameter dependencies. He found that the after treatment surface properties are dependent on force, number of passes, feed, and also rolling speed. El-Axir showed that the rolling speed indirectly produces an effect on burnishing due to tool chattering, also confirmed by El-Khabeery and El-Axir [28]. This effect can be the reason of concern for high production rates, while it is not an issue for low speed rolling. Moreover, El-Axir showed that multiple passes cause material overhardening. As mentioned above about low plasticity burnishing, it is desirable to have surface improvements: low roughness and compressive residual stresses, just with a limited hardening to avoid embrittlement and also to have residual stress stability [12,13,17]. The small value of the feed produces remarkable results in terms of hardness and surface finish, however, similarly to multiple passes, severe work hardening of the material again results. Parametric analysis was also reported by Rodríguez et al. [7] showing the effects of the speed, the feed and the rolling load (here the load was the hydrostatic pressure for supporting the ball). They found that the optimum burnishing results are in the range 0.2–0.1 μm in terms of final R_a, though a "good enough" surface treatment can be considered when the roughness is less than 0.5 μm that is a typical value of the grinding process, thus the grinding itself could be replaced by the burnishing (or the deep rolling) as finishing. They also showed that the after burnishing roughness significantly depends on the previous surface roughness, which was also confirmed by Prabhu et al. [6,10,11] and also evident in the present study.

The present research investigated the residual stresses induced by deep rolling with a tool having a "conical and radiused shape". The literature is mainly focused on burnishing and deep rolling with the ball type indenter. Nevertheless, remarkable deep rolling results were obtained with this tool that has practical advantages with respect to the low plasticity burnishing. This roller shape can easily manage shouldered geometries, not accessible by the ball type indenter, moreover no external fluid pressurization unit is required to control the rolling load. Balland et al. [29] investigated a similar rolling tool, cylindrical and rounded, with the axis having a small inclination angle with respect to the specimen surface. The contact reduced to a small area with largely different curvatures, and consequently the residual stress components were quite different. More specifically, the component along the high curvature radius was notably higher than the other. This residual stress anisotropy, also well evident in the present study, is a quality rather than a shortcoming when the loading is mainly applied along a specific direction. E.g. a shaft under rotating bending fatigue has the cyclic normal stress direction aligned with the axis, thus the higher residual stress component along this axial direction generates a well dedicated fatigue crack prevention.

Finite element (FE) simulation is a common tool for residual stress prediction. There is a large literature on modeling residual stresses produced by different industrial processes such as welding, heat treatment, and machining (see the review paper by Mackerle [30]) and on surface plastic deformation processes, such as shot peening [22,31,32] and also deep rolling [7,29,33–39]. The main results of a literature review on low plasticity burnishing and deep rolling FE modeling can be summarized as follows:

- Plane strain simulation may be preferable rather than full 3D modeling. Though the unavoidable geometry simplification, in a plain model the element size can be remarkably reduced, especially at the initial subsurface region that experiences high stress gradients. The plane strain does not allow the material from flowing along the out-of-plane direction, however, the 3D cumbersome model reduces the modeled geometry to a very small portion of the specimen surface with evident limitations in terms of adequate boundary conditions.
- Final surface finish can be successfully modeled both with plane and 3D models. Also pre-existing surface roughness can be introduced in the FE model to more realistically reproduce the final surface texture.
- Residual stress distribution is usually considered as uniform along any direction parallel to the specimen surface, and the stress gradient is just assumed along the depth. The cyclic indentation, however, produces some non-uniformity along the feed direction. Usually, stress components are averaged on several equi-spaced vertical lines distributed in one single feed pitch.
- Numerical residual stress predictions are sometimes coherent with the measurements only in terms of parametric trends, though significant differences can arise. Unfortunately, these large divergences usually are at the surface, where the assessment of the residual stresses is of major importance e.g. for fatigue.

An experimental parametric investigation on aluminium alloy 7075-T6 is reported in this paper by showing in depth residual stress distributions for increasing load and different feed values, generated with this conical and rounded roller shape. A comparison analysis and related discussion are provided in terms of parameter sensitivity on residual stress distributions. FE simulations, with a plain strain model, are also reported