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A multi-scale analysis of the residual stresses developed in a single-phase alloy cylinder after quenching

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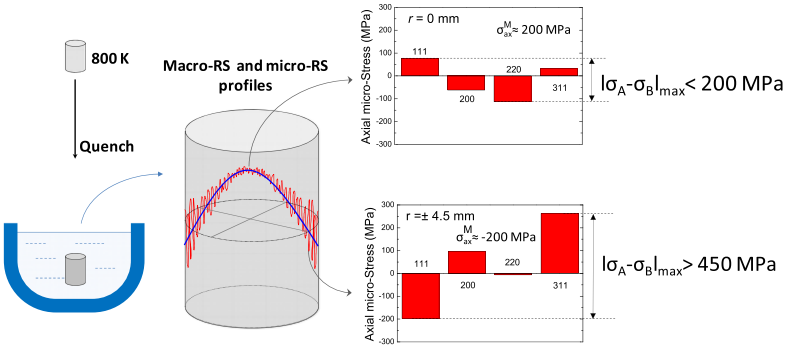
HIGHLIGHTS

- Macro and micro residual stresses resulting after quenching have been studied using synchrotron radiation diffraction
- The irreversible nature of the m-RS is verified, in contrast to the reversible one of the m-RS in MMCs
- The microscopic inter-granular stress is the highest at the sample surface and the lowest at the center
- A compressive M-RS on the surface is beneficial, but a quenching m-RS developed can be detrimental for structural uses.

GRAPHICAL ABSTRACT



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ABSTRACT

Residual stresses, RSs, both at the macroscopic and microscopic scales, are developed during component manufacture. Knowing the magnitude of these stresses is crucial in structural design optimization. While determining the macroscopic residual stress, M-RS, by diffraction methods is well known, the calculation of the microscopic residual stress, m-RS, which varies from grain to grain in single-phase alloys is still a pending task. In this work, a multi-scale analysis to calculate both types of stresses in a single-phase alloy has been conducted for the first time using synchrotron radiation diffraction data and a "composite material" approach. This analysis, together with the results derived from a finite element model, FEM, demonstrates the strong influence of the severity of thermal-mechanical treatments on the generation of a grain orientation dependent m-RS and, contrary to other kinds of m-RS (such as in metal matrix composites, MMCs), its irreversible nature. It is also seen that, while it is possible to generate an "appropriate" M-RS for a given application (*e.g.*, a compressive surface stress), a strong and detrimental m-RS field may arise simultaneously. This can be the origin of local inter-granular cracking during service of components.

1. Introduction

Residual stresses in industrial components are usually generated during thermo-mechanical treatments and manufacturing processes. Since these stresses must be added to the external ones that these components may undergo, their study is of great importance in industrial design for structural component optimization [1,2].

The so called macroscopic residual stress, M-RS, is usually analyzed in engineering. This stress is considered to be microstructure independent and, hence, directly linked with the macroscopic physical properties of the material, which is treated as a continuum medium. The magnitude of the M-RS varies from different regions of the material

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component. The final M-RS profile depends on the shape of the component and the precise thermo-mechanical treatment and/or manufacturing procedure [3,4].

Besides the M-RS, there are other kinds of residual stresses, linked to the material's microstructure, which can be also important. Since these stresses vary at the scale of the microstructure, they are commonly referred to as microscopic residual stresses, m-RS. A paradigmatic example of these stresses is that existing in multi-phase materials, such as metal matrix composites, MMCs. Due to the different coefficient of thermal expansion, CTE, between the ceramic reinforcing particles and the matrix (typically a factor of 6:1), a tensile (positive) stress in the matrix, and compressive (negative) in the reinforcement to balance the former one, appears during the cooling stages of material's fabrication. This m-RS field, similar to the M-RS one, is regularly determined using diffraction methods (neutrons and/or synchrotron radiation) [5–8].

The development of a m-RS is not restricted to multiphase materials. It is known that a m-RS which varies from grain to grain can be also developed in single-phase alloys as a consequence of thermo-mechanical processes. The origin of this m-RS relies on the anisotropic character of crystal plasticity, and evidence of its presence has been reported several times [9–15].

Whereas the calculation of the M-RS (and/or the m-RS in multiphase materials) by diffraction methods is almost a routine task [16–20], determining the m-RS in single-phase alloys is far more complex. This is primarily due to the nature of the diffraction experiments and to the fact that the diffraction peaks for different spatial directions cannot be identified with specific grains or crystallites (as can be readily done in the case of multiphase materials). Usually, the gauge volume (or the region inside the material, selected through appropriate size of the incoming and outgoing slits, from which the information from the diffraction process is collected) is significantly smaller than the sample/component under study. In fact, it is assumed that the M-RS at any point within the gauge volume is constant. In this way, the M-RS variation across the whole piece is readily revealed by scanning the sample/component with this gauge volume.

But at the same time, the gauge volume is significantly larger than the "*wavelength*" of the underlying microstructure, *i.e.*, a considerably large number of grains (hundreds or even thousands of grains) is covered. Then, the (average) m-RS in the different phases of a multiphase material can be determined owing to the fact that the diffraction peaks of the different phases can be easily distinguished from each other. For the case of the m-RS in single-phase alloys, however, all grains produce diffraction peaks which are located at nearly the same position in the diffraction pattern (resulting in peak broadening). Therefore, their association with individual grains is virtually impossible. In other words, a connection of diffraction peaks for different spatial directions with specific grains of known crystal orientation is not possible. Due to this circumstance, rigorous studies of the m-RS state in single phase alloys have not yet been carried out.

In this research, a first attempt to calculate, both, the M-RS and, in particular, the grain-orientation dependent m-RS generated during a thermo-mechanical process has been conducted using synchrotron radiation diffraction data and, as it will be seen, taking into account suitable approximations. Specifically, the tri-axial RS state resulting from quenching in a single phase aluminum alloy has been explored. The study has been possible due to the very specific circumstances of the problem investigated: (a) the material's microstructure, resulting from an extrusion process of the alloy into a round bar, has a cylindrical symmetry, (b) the sample investigated is machined as a cylinder, with the cylinder axis coincident with the extrusion axis direction and length larger than the diameter, and (c) the quenching step obeys the above symmetry, so that the m-RS generated in individual grains can be predominantly developed along the (un-constrained) axial direction. It is also assumed, as will be explained, that the m-RS of an individual grain is only crystallographic orientation dependent; therefore, grains belonging to a given texture component develop the same m-RS in the axial direction. A "composite material" approach is used to analyze, as in MMCs, the contribution of the M-RS and m-RS after quenching. Finally, it will be also considered that, owing to the cylindrical symmetry, the axial, radial, and hoop directions of the cylinder define a principal axis system, therefore, no shear stresses are present in the sample.

Iso-strain condition along the axial direction of deforming grains will be considered throughout the analysis and, both, the M-RS and m-RS resulting from the quenching step arises from a non-uniform plastic deformation and plastic anisotropy of grains, linked to different crystallographic orientation.

2. Experimental details

The material studied was 2014Al alloy (W2A00A) supplied by QED Extrusion Development Inc., San Diego, USA [21]. The as-received 38 mm diameter bar was obtained by extrusion at about 700 K and a ratio of 24.2:1, 1.7 mm/s ram speed, and using a flat die. This bar was subsequently re-extruded at CENIM's extrusion press to refine the grain size. The extrusion ratio was ~7.7:1, the ram speed 2 mm/s, and the extrusion temperature 850 K. A flat die was also used in this case. The final bar was 13.7 mm in diameter from which a cylindrical sample, 13 mm in diameter and 25 mm in length, was machined. The choice of this alloy is based on its high strength. High strength makes it possible to build up a high level of RS, which facilitates the present study on the basis of customary RS measurement by diffraction methods.

RSs (both M- and m-RS) were generated during quenching (free drop) in fresh water [22] after maintaining the sample at some 800 K and 90 min in a vertical furnace. Since the RS study was conducted at the mid-height of the sample, the cooling fronts originated at the top and bottom surfaces of the sample should have no effect on the RS generation in this region. This assumption is supported by a finite element model, FEM, constructed to simulate the quenching step and the resulting RS.

The material's microstructure was revealed using conventional metallographic techniques and the texture determined from laboratory X-ray diffraction. A Siemens Kristalloflex D5000 diffractometer equipped with an Eulerian cradle using the Schulz reflection method was employed [23]. The X-ray radiation used was the CuKα. Pole figures of the 111, 200, 220, 311 reflections were determined. TexTools software was used for data treatment to generate the orientation distribution functions, ODFs, from which the inverse pole figures were obtained and the volume fraction of crystallites belonging to the different texture components calculated [16,24].

The synchrotron radiation diffraction measurements were conducted on EDDI diffractometer of BESSY synchrotron of HZM, located in Berlin, Germany. This instrument is specifically designed for the study of RS in crystalline materials [25,26]. It operates in energy dispersive mode (in this case, in transmission) in the range of 10–150 keV. In this way, many diffraction peaks can be obtained simultaneously. On using synchrotron radiation in energy dispersive mode, Bragg's equation is expressed as:

$$d_i^{hkl} = \frac{\mathbf{h}c}{2E_i^{hkl}\,\sin\theta} \tag{1}$$

where d_i^{hkl}, is the lattice spacing of a given (hkl) along sample direction i, $\boldsymbol{h}$ is the Planck's constant, c the speed of light, E_i^{hkl} the X-ray energy for the specific (hkl) reflection along sample direction i, and θ the Bragg's angle.

The results from the 311, 111, 200, and 220 reflections have been analyzed since they give the most intense signal for the sample axial direction, as it is revealed by the texture measurements. The Bragg's angle used was $2\theta = 6°$. The gauge volume was a prism of $1 \times 1 \times 0.03$ mm^3, generated using primary and secondary slits of 1×1 mm^2 and 1×0.03 mm^2, respectively.

Measurements on different locations along transverse sample axes, perpendicular to the cylinder symmetry axis, have been conducted. Thus, information corresponding to the entire cross-section of the