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# Effect of residual stress on recrystallization behavior of mechanically alloyed steels

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This paper presents a finite element modeling analysis of deformation on iron-base mechanically alloyed oxide dispersion strengthened alloy by spherical indentations (Brinell test). Results of the model are used to interpret the role of residual shear stresses on the development of recrystallized grain structure and the temperature at which recrystallization occurs.


*Keywords:* Finite element analysis; Recrystallization; Mechanical alloying; Oxide dispersion strengthened alloy; Residual stresses

Mechanical alloying is a process in which mixtures of powders are severely deformed until they form atomic solutions. Inert oxides can also be introduced to form a dispersion of fine particles which strengthen the consolidated product. Significant quantities of iron and nickel-base alloys, with unusual properties, are produced commercially using this process. The total true strain during mechanical alloying can be as large as 9, and there are evidences that this leads to mixing on an atomic scale and to the development of a uniform grain structure which is sub-micrometer in size [1–3]. Following mechanical alloying, the particles are consolidated using standard powder metallurgical techniques. The consolidated metal has a very large stored energy, approaching 1 J $g^{-1}$ [4]. This ought to make it easy to induce recrystallization, but in practice the alloys fail to recrystallize except at very high temperatures close to melting [2]. On the other hand, the recrystallization temperature can be reduced dramatically by slightly deforming the consolidated product prior to heat treatment [5]. It is in this context that the effect of deformation on PM 2000 by spherical indentations (Brinell test) on the development of recrystallized grain structure is studied here.

The Fe-base oxide dispersion strengthened PM 2000 (Fe–20Cr–6Al–0.5Ti–0.5$Y_2O_3$), supplied by PLANSEE GmbH, is created by mechanical alloying. The powders with a grain size of about 70 nm were therefore consolidated by hot isostatic pressing and subsequently by hot rolling of vacuum-sealed cans with a finishing rolling temperature of about 800 °C to form a 7 mm wall-thickness tube. During this stage elongated deformed grains with a sub-micrometric grain size in the transverse direction and a strong ⟨1 1 0⟩-fibre texture are produced. Prismatic samples of 60 mm in length and 20 × 7 $mm^2$ section have been machined from the tube in as-received condition to perform spherical indentations at the inner wall. A 10 mm in diameter spherical indenter has been used. Loads ranging from 4.9 to 49 kN have been applied. The *XYZ* reference frame of the simulation has the *X*-axis parallel to the movement of the indenter (normal direction or ND), the *Y*-axis parallel to the rolling direction (RD), and the *Z*-axis in transverse direction (TD). Hereafter, the Brinell tested material is referred as deformed material.

A systematic study of the early stages of recrystallization as a function of annealing temperature and deformation was carried out. Table 1 lists the temperature at which recrystallization starts ($T_R$) after isochronal (3 h) heat treatments at different annealing temperatures. It could be concluded that the higher the deformation induced, the lower the temperature at which recrystallization is detected. The recrystallization temperature in the absence of deformation was determined at 1330 °C. The first observable result is seen in the case of 4.9 kN at 1320 °C. The higher deformation produced

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**Table 1.** $T_R$ values vs. Brinell load after 3 h isochronal heat treatments.

| Brinell test loads (kN) | $T_R$ (°C) |
|---|---|
| 49.0 | 1150 |
| 29.4 | 1210 |
| 19.6 | 1250 |
| 4.9 | 1320 |
| 0 | 1330 |

in the test of 49 kN induces recrystallization at temperature as low as 1150 °C.

Optical microscopy analysis on non-deformed samples revealed that a very elongated and coarse-grained microstructure, characteristic of a recrystallization process in ferritic ODS alloys [8–11], is developed. However, it was observed in indented recrystallized samples that recrystallized grains increase in size with increasing distance from the indentation zone, as well as losing the equiaxed shape to adopt a more elongated morphology in the normal direction to the surface. Figure 1 illustrates the effect of increasing deformations on subsequent recrystallization of PM 2000. The effect of the deformation magnitude on the recrystallization is evident, since the bigger the indentation load, the more extended the volume of recrystallized material and the finer the recrystallized grain size.

These results are consistent with the ones reported by Capdevila et al. [6]. Capdevila reported a twofold effect on the recrystallization behavior of specimens subjected to different bending angles: as cold deformation increases, a decrease in the recrystallization temperature and an increase in the density of recrystallization nuclei regardless of the stress direction was noted [7].

Recrystallization requires volumetric free energy terms of stored energy of dislocations to drive the migration of the boundaries around the growing grains. When

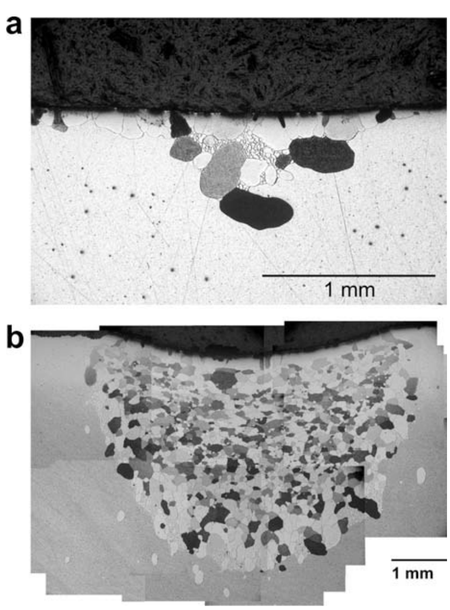


**Figure 1.** Recrystallized microstructure of deformed area after annealing at 1350 °C for 3 h: (a) 4.9 kN and (b) 49 kN. Transverse section to extrusion direction.

the material is under stress there are additional terms and it is these which we will concentrate on here. It was noted that both the velocity and the direction of migration of high angle boundaries varied, depending on their misorientation [12]. It is possible to interpret these results in terms of applied stress acted to drive the movement of structural dislocations in the boundary [13]. It was also noted that the migration mechanism of grain boundary motion is different in a stressed material than the mechanism of curvature driven grain boundary motion (or texture induced) in a non-stressed material [13–15]. During indentation the material flow occurs in the rolling direction ($Y$-axis or RD), so it is assumed that no texture change takes place. These facts and the grain morphology due to extrusion process suggest the special importance to the shear stress component of the beginning of recrystallization.

In order to discern the effect of the residual stress on the recrystallization, a finite element modeling (FEM) is performed by the multipurpose finite element program MSC. Marc provided by Luleå University of Technology. The results were analyzed comparing the aspect of the recrystallized zones with those of the iso-strain and $\sigma_{xy}$ iso-stress contours. Although Von Mises stress is related to dislocation glide, the glide related to parallel to grain boundaries are more important. Von Mises stress is isotropic and will miss the influence of the larger amount of grain boundaries parallel with the $X$-axis. As described above, the material flow is not isotropic, but occurring in extrusion direction. For this reason the stress analysis described below is focused on the $\sigma_{xy}$ shear stress component distribution instead of Von Mises stress distribution, the isotropic character of which will miss the anisotropy of the grain boundary movement.

The simulations were performed considering the cylindrical symmetry of the sample around the $X$-axis. Thus, the indenter is simulated as a half ball of 5 mm radius with isotropic linear elastic behavior, and the length of the sample considered is 30 mm (60 mm due to the axial symmetry around the center of the indenter). The multipurpose software Marc Mentat is able to simulate the complete geometry, and reproduce the sample geometry as the simulation has been computed with the sample geometry, saving 50% of computing time. The contact between spherical indenter and sample was modeled as Coulomb friction with a friction coefficient of 0.1. The loads considered in calculations ranged from 4.9 to 49 kN. The sample was modeled as an elastoplastic material with isotropic Von Mises yield criterion and with isotropic work hardening in which the Young's modulus was 210 GPa and the Poisson's ratio was 0.3. The flow stress curve defined by the expression

$$\sigma = 1000 + 865.7\bar{\varepsilon}_p^{0.505} \quad (1)$$

was obtained by fitting to experimental data. In this expression $\sigma$ is the true flow stress (in MPa) and $\bar{\varepsilon}_p$ is the true plastic strain. The model accounts for large deformations and strains using an updated Lagrangian formulation and a finite strain model derived from the incremental theory of plasticity.

Of particular interest is the state of deformation at the temperature when recrystallization is triggered for