Thickness-Dependent Annealing Response and Microstructure–Property Evolution of 4J36 Invar Alloy during Ultrathin Processing

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The development of organic light-emitting diode (OLED) display technology has imposed increasingly stringent requirements on the thickness accuracy and synergistic control of microstructure and mechanical properties of ultrathin 4J36 Invar alloy strips used for fine metal masks (FMMs). However, as the strip thickness is further reduced, the competition between recovery and recrystallization associated with accumulated cold-rolling deformation and subsequent short-time annealing becomes increasingly complex, and the thickness-dependent annealing response remains insufficiently understood. In this study, 4J36 Invar alloy strips with different thicknesses and processing states were prepared by combining cold rolling with short-time annealing. The synergistic evolution of grain boundary characteristics, local misorientation, recrystallization behavior, texture, and mechanical properties during ultrathin processing was systematically investigated. The results indicate that, when the thickness of the 4J36 Invar alloy was further reduced from 0.11 mm to 0.04 mm, the annealing-softening mechanism changed from microstructural reconstruction dominated by extensive static recrystallization to a limited softening response governed primarily by dislocation rearrangement and limited recovery. Meanwhile, the retention of residual deformation structures further restricted the restoration of ductility. This study reveals the thickness-dependent evolution of recovery–recrystallization competition during the ultrathin processing of 4J36 Invar alloy and provides a theoretical basis for optimizing cold rolling–annealing processes and achieving coordinated regulation of microstructure and mechanical properties in ultrathin Invar strips for FMM applications.

KEYWORDS: 4J36 INVAR ALLOY – ULTRATHIN STRIP – COLD ROLLING – SHORT-TIME ANNEALING – STATIC RECRYSTALLIZATION – RECOVERY – MECHANICAL PROPERTIES

1 INTRODUCTION

4J36 Invar alloy is a typical low-expansion Fe-Ni alloy with a low coefficient of thermal expansion, good dimensional stability, and favorable processability, and it is widely used in precision electronic devices, display devices, aerospace applications, and precision measurement. In recent years, as electronic components have developed toward lightweight, thin, and highly integrated designs, higher requirements have been imposed on the thickness accuracy, shape quality, and uniformity of microstructure and properties of ultrathin 4J36 Invar alloy strips. Accordingly, product thickness has gradually decreased from conventional sheet gauges to the hundred-micrometer and even tens-of-micrometers scale [1-3]. Cold rolling, featuring high production efficiency and high thickness-control accuracy, is an important method for producing ultrathin 4J36 Invar alloy strips, while subsequent annealing is a key step for regulating their microstructure and mechanical properties [4,5]. Therefore, 4J36 Invar alloy strips with different thicknesses and processing states were selected in this study. The microstructural and mechanical-property differences between 0.11 mm and 0.04 mm strips after cold rolling and short-time annealing were compared, with emphasis on revealing the thickness dependence of the annealing response and the recovery-recrystallization competition mechanism during ultrathin processing. The results provide a theoretical basis for optimizing the cold rolling-annealing process and coordinately controlling the microstructure and properties of ultrathin Invar strips for FMM applications.

2 EXPERIMENTAL MATERIALS

The experimental material was an ultrathin 4J36 Invar alloy strip with an initial thickness of 0.35 mm. Its chemical composition is listed in Table 1.

Tab. 1 - Chemical composition of the 4J36 Invar alloy

Element	Fe	Ni	Mn	Co	S	Cr	P	Ti
Content	60.66	33.95	1.51	1.40	0.28	0.00	0.53	0.57

3 RESULTS AND DISCUSSION

3.1 Microstructure and property analysis

Figure 1 shows the kernel average misorientation (KAM) distributions of ultrathin 4J36 Invar alloy strips under different processing conditions. The 0.35 mm annealed and 0.30 mm annealed samples still exhibit a pronounced heterogeneous distribution of high- and low-KAM regions. The high-KAM regions are mainly located within elongated grains and near grain boundaries, indicating that a certain degree of intragranular orientation gradient and deformation substructure remains in the material. After cold rolling to 0.11 mm, almost the entire sample transforms into high-KAM regions, indicating that cold rolling causes extensive dislocation multiplication and produces a pronounced orientation gradient inside the grains, extending deformation from local regions to most grains [6]. After annealing, the interiors of the grains in the 0.11 mm sample are largely transformed into a uniform low-KAM state, indicating sufficient release of the stored cold-rolling energy and replacement of high-density dislocation structures by recrystallized grains with low lattice distortion. When the 0.11 mm annealed microstructure is further cold rolled to 0.04 mm, large continuous high-KAM regions reappear, indicating that the low-defect recrystallized grains undergo severe plastic deformation again during further rolling. After annealing, the 0.04 mm sample still retains a large amount of high-density dislocations, in sharp contrast to the extensive low-KAM microstructure of the 0.11 mm annealed state.

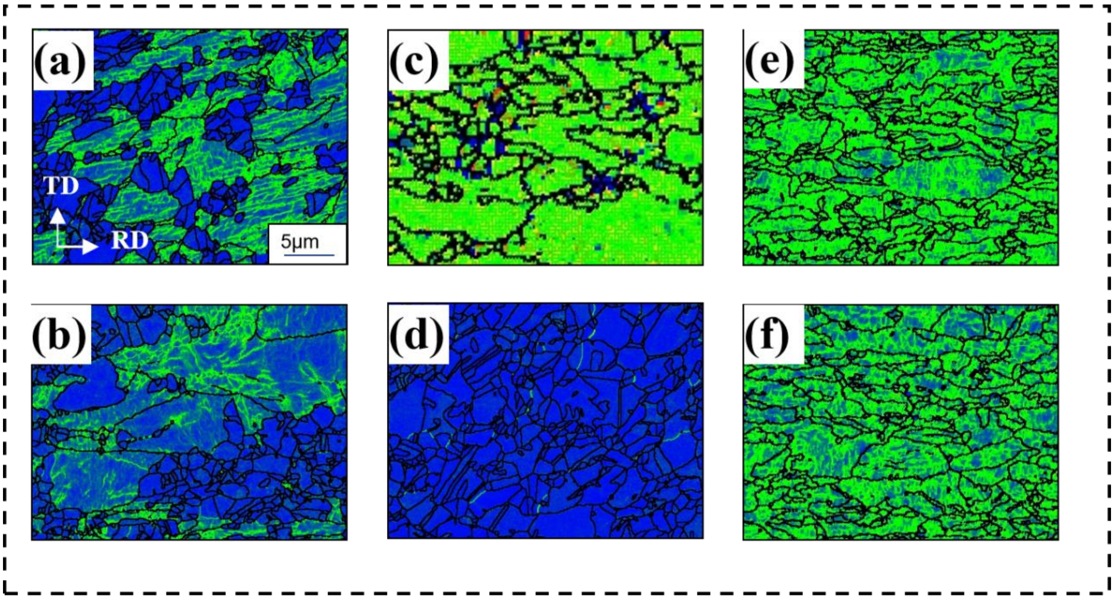

Fig. 1 – KAM distributions of 4J36 Invar alloy strips under different processing conditions

Figure 2 shows the recrystallization-state distributions of 4J36 Invar alloy under different processing conditions, where the blue, yellow, and red regions represent recrystallized grains, substructured grains, and deformed grains, respectively. Figures 2€ and 2(d) correspond to the 0.11 mm condition and show a pronounced change after annealing: the fraction of recrystallized grains increases markedly, while the fraction of deformed grains decreases significantly. The original elongated deformed grains are replaced by equiaxed grains with low dislocation density, accompanied by dislocation annihilation and rearrangement [6,7]. In contrast, when the strip is finally reduced to a thickness of 0.04 mm, as shown in Figs. 2€ and 2(f), the fractions of recrystallized and deformed grains remain almost unchanged before and after annealing.

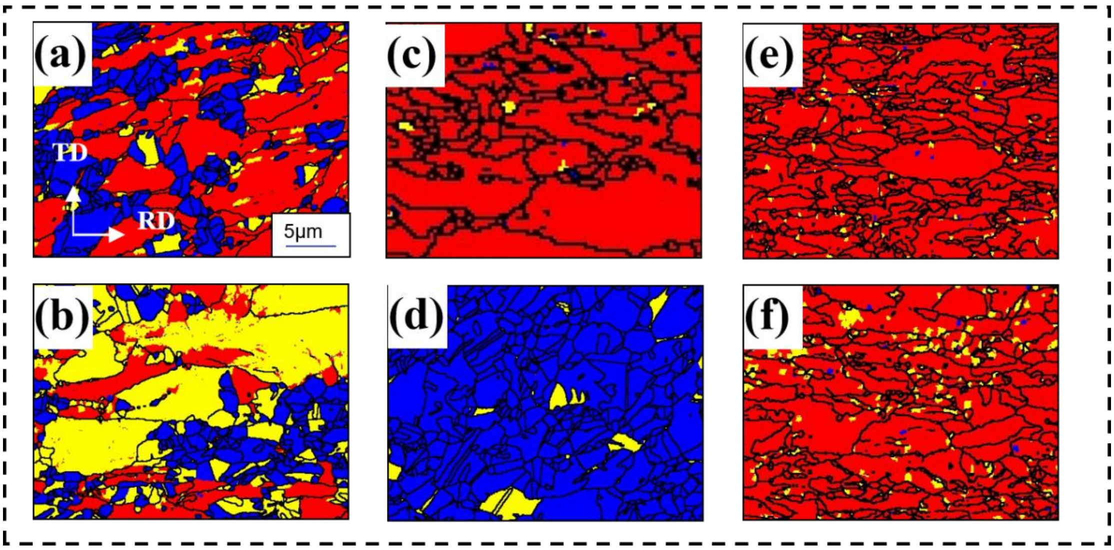

Fig. 2 - Recrystallization-state distributions of 4J36 Invar alloy strips under different processing conditions

3.2 Mechanical properties

Figure 3 presents the ultimate tensile strength (UTS), yield strength (YS), and elongation (EL) of 4J36 Invar alloy strips under different processing conditions. With cold rolling, annealing, and subsequent ultrathin processing, the strength-ductility behavior of the material changes significantly. After cold rolling to 0.11 mm, the strength increases markedly, with pronounced increases in both UTS and YS, whereas elongation decreases substantially. After annealing, the mechanical properties of the 0.11 mm sample change markedly and exhibit a trend opposite to that of the cold-rolled state. In general, cold rolling significantly increases strength while sharply reducing ductility; recovery and recrystallization induced by annealing generally reduce the degree of work hardening and promote ductility restoration [8].

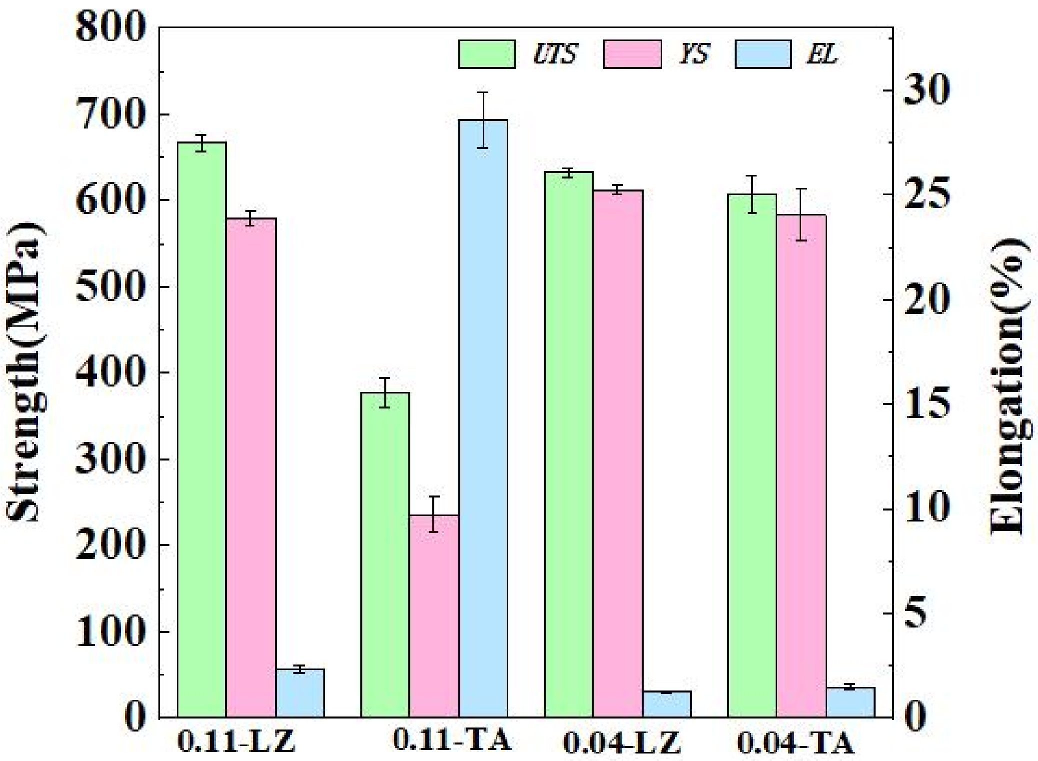

Fig. 3 - Mechanical properties of 4J36 Invar alloy strips under different processing conditions

4 CONCLUSIONS

The evolution of microstructure and mechanical properties of 4J36 Invar alloy during ultrathin cold rolling and annealing was investigated, with emphasis on comparing the annealing responses at thicknesses of 0.11 mm and 0.04 mm. The main conclusions are as follows. Microstructural evolution directly results in markedly different annealing-softening behaviors at different strip thicknesses. The 0.11 mm cold-rolled sample exhibits relatively high ultimate tensile strength and yield strength but low elongation. After annealing, both ultimate tensile strength and yield strength decrease substantially, while elongation increases, demonstrating pronounced strength softening and ductility recovery. In contrast, after annealing of the 0.04 mm sample, the ultimate tensile strength and yield strength decrease only slightly, and the improvement in elongation is very limited.

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