学　位　論　文　内　容　の　要　旨

博士の専攻分野の名称　　博士（工学）　　氏名　施 詩

学　位　論　文　題　名

Creation and Strengthening Mechanism of Nano-sized Bubble Dispersion in Copper
(ナノバブル分散銅の創製と転位-バブル相互作用メカニズム)

This dissertation contains research work attempting to improve a brand new idea on strengthening of metal materials. Experimental and simulation methods have been involved to investigate the interaction between nano-sized bubbles and dislocation in bulk copper. The polymer Poly (methyl methacrylate) (PMMA) was introduced to the production of bubble dispersion in copper. The PMMA decomposes and release gaseous products during the sintering over $700^oC$, which can be the sources for bubbles in bulk copper. By control the temperature and pressure during PMMA decomposition, well-dispersed bubbles can be produced in copper.

Although bubble-strengthening theory were well studied by calculations, before our study, there is almost no experimental data on copper to prove the model. At first we made abundant of attempts to get fine bubble dispersion in copper. Ball milling was used for the mechanical alloying of Cu-PMMA powder mixture and followed by spark plasma sintering (SPS) was applied for the consolidation of Cu-PMMA. Consolidation process which have different temperature and pressure history were compared each other. We concluded that to obtain the bubbles smaller and more densely in the matrix, it is better to apply low pressure in the initial heating stage and high pressure in the temperature holding stage. The obtained bubbles have mean radius of the bubble 2nm and an effective dispersion distance 75 nm from TEM observation.

To elucidate the mechanism, we investigate the bubble-dislocation interaction from three steps as follows: (1) we used the Vickers' hardness test to get the strength of bubble dispersed copper and pure copper to bubble dispersion effect; (2) in order to compare the experimental results and classical theory, we obtained the interspacing and dispersion status of bubbles from two separated ways, one is direct observation from TEM observation, and the other is by using the SANS and SAXS measurements; (3) we applied in-situ tensile test under TEM to get the critical angle and thus estimate the bubble barrier strength $\alpha$, which reflects the impeding ability of barrier on dislocation motion. The Vickers' hardness of bubble-dispersed copper is 133MPa more than that of pure copper sintered at the same SPS condition. Bubble spacing from the TEM observation and small angle scattering reach in a agreement of bubble radius in 2nm and spacing in 64nm,which indicate the fine bubble dispersion easily reached by using pyrolysis gases of PMMA. Combining the TEM observation and notable difference of bubble dispersed copper and pure copper in scattering intensity from the result of SANS and SAXS, we verified the existence of nano-sized bubbles in copper, which makes the basis of this study. The direct observation of interaction between nano-sized bubbles and dislocations under tensile test by TEM confirmed the pinning effect of the nano-sized bubbles on dislocations, further proves the strengthening effect of bubbles. From in-situ TEM tensile test, we obtained $\alpha$ ranges from 0.34 to 0.57,with $\phi_c$ from

$110^o$ to $140^o$.

Due to the negative interaction energy of bubbles and dislocations, bubbles act as strong trap of dislocations, nano-sized bubbles can attract dislocation easily. At the first stage, the dislocation line falls into this trapping energy valley and stay in a much more stable state, than in normal lattice. Thus to make the dislocation break out the pinning state, higher resolved Peach-Koehler stress is required comparing with the no-bubble case. For de-pinning, dislocations glide towards the series of bubbles, and bow out between bubbles until the applied stress supply enough energy for overcome the strong bubble-dislocation interaction energy. By combining the Molecular Dynamics (MD) simulation of void-dislocation in copper with our experimental results, we argue that bubble act as a strong barrier to dislocation motion as void, and the new developed synthesis method for bubble dispersion strengthened copper can be considered as a potential way for strengthening materials.