（様式課程博士３）

学 位 論 文 の 要 旨

専　攻　名	物質生産工学	ふりがな 氏　名	くすの　かみる Kusno　Kamil　㊞
学位論文題目	Fatigue-induced damage and crack growth mechanism in ultrafine grained copper processed by equal channel angular pressing (ECAP) (等断面角度付押出(ECAP)による超微細粒銅の疲労誘起損傷とき裂進展機構)		

Since copper has superior characteristics in electrical conductivity, heat transfer, corrosion resistance, etc, it has been widely used as a base material in various electronics-based industries. Recent developments in electronic apparatus however mean that higher strength/ductile materials are now required to meet these needs. To improve the strength of copper requires the development of highly alloyed Cu materials. Alloyed Cu however, possesses inherently lower conductivity compared to their unalloyed counterparts. Therefore, in order to overcome this inherent shortcoming associated with conventional Cu alloys, the development of pure Cu with submicron grained structure is currently being explored by employing a severe plastic deformation principle, such as the ECAP (equal channel angular pressing) processing.

From an engineering viewpoint, fatigue damage must be clarified in order to apply ultrafine grained (UFG) metals to the components of machines and structures. Regarding the fatigue on ECAPed UFG materials, most studies have concentrated on cyclic deformation, fatigue life, shear band formation and underlying microstructural mechanisms. Since the fatigue life of machine components and structures is mainly controlled by the growth life of a fatigue crack, the crack growth behavior should be clarified for the design of safe machine components and structures. Recently, the growth behaviors of long (millimeter-range) cracks in UFG metals were studied for compact-tension, single edge-notched specimens. On the other hand, it has been shown that the crack growth life from an initial size to 1 mm accounted for about 70% of the fatigue life of plain members. Therefore, the growth behavior of small cracks must be clarified to estimate the fatigue life of smooth members. To date however, such studies are quite few, and certain questions remain unanswered.

The objective of this study is to discuss the physical basis of fatigue-induced damage and surface-crack growth mechanisms under high and low cyclic stresses.

Firstly, the formation behavior of surface damage was investigated. The study showed that, at high stress amplitudes, the SBs appeared on a plane inclined 45° to the loading direction mainly because it is the plane of maximum shear stress. The orientated distribution of defects relating to the final shear of ECAP pressing may be related to the choice of one set of shear banding plane among innumerable planes of maximum shear stress. At low stress amplitudes, the slip bands were generated within coarse grains formed as a result of dynamic recrystallization.

Secondary, the effect of difference in microstructural evolution on crack growth mechanism was studied. The fracture surface for UFG copper with the HAGB-dominated microstructures showed a planar, granular and striated surface as the crack continued to grow. The ratio of the RPZ size at the crack tip to the grain size, r_{rp}/d, was calculated for crack lengths where a planar, granular and striated surface was observed. The values of r_{rp}/d for crack lengths of the planer, granular and striated fracture surfaces corresponded to a range of $r_{rp}/d < 1$, r_{rp}/d between 1 and 2, and $r_{rp}/d > 3$, respectively. For UFG

（注）和文 2,000 字又は英文 800 語以内　　　　続紙　有■　　無□

copper with the LAGB-dominated microstructures, however, a planar surface followed by a striated surface was observed, which revealed the disappearance of the granular fracture surface. The transition from planar to striated fracture occurred under a range of $r_{rp}/d \approx 1$. The disappearance of the granulated surface was attributed to the LAGB-dominated microstructures and the dynamic recovery of the higher non-equilibrium microstructure during cyclic stressing. This allowed the dislocation to slide easily beyond the GBs, thereby preventing an intergranular cracking caused by the incompatibility of the localized strain at the GB regions. In addition, to understand the change in fracture surface morphologies, a quantitative model describing the crack growth mechanism was developed based on the RPZ size and microstructural factors. The changes in the CGR and morphological features of the fracture surface were successfully explained by this model.

Lastly, the crack growth mechanisms of high and low stress amplitudes were clarified through the crack growth behavior under two-step loading. At high stress amplitudes, the crack grew at an incline of 45° to the loading axis because of the shear banding induced by the maximum shear stress and SB decohesion process. At low stress amplitude, the crack propagated via the striation formation mechanism, which was associated with crack tip retardation and blunting. This was because the SB formation and decohesion that occurred at high stresses were suppressed at low stresses below a threshold value. The cracks grew nearly perpendicular to the loading axis in a large zigzag manner as a result of the occurrence of dynamically recrystallized grains in excess of 100 μm.

（様式課程博士８）

学位論文審査結果の要旨

専攻	物質生産工学専攻	氏名	Kusno Kamil
論文題目	Fatigue-induced damage and crack growth mechanism in ultrafine grained copper processed by equal channel angular pressing (ECAP) (等断面角度付押出(ECAP)による超微細粒銅の疲労誘起損傷とき裂進展機構)		
主査	後藤　真宏		
審査委員	劉　孝宏		
審査委員	濱川　洋充		
審査委員	田上　公俊		
審査委員	小田　和広		

審査結果の要旨（1000 字以内）

金属材料の強度特性改善のため，様々の手法を用いて組織の微細化が研究されている．ECAP などの強変形加工はバルク形状のまま組織を微細化でき，これまで組織構造，静強度特性などに重点が置かれ研究されてきた．一方，微細粒材料を実機に使用するには，疲労特性の解明が必要である．近年，S-N 特性，繰返し軟化特性など疲労に関する研究は増加しているが，表面損傷形成やき裂進展機構に関して未だ不明な点が多い．

本研究では，ECAP により組織を微細化した銅の疲労特性の解明を，特に表面損傷の形成挙動，疲労き裂の進展機構に注目して行い，以下に示す成果を得た．

1．表面損傷は，高応力ではせん断帯，低応力ではすべり帯に起因して発生した．高応力下のせん断帯は，ECAP 導入時の残存せん断帯によるひずみを開放すべく最大せん断応力に誘起され発生したものであった．低応力下では，形成駆動力が足らずせん断帯は発生しないが，繰返しにより非平衡組織が動的再結晶により粗大化し，粗大粒のすべり面に沿ってすべり帯が発達した．疲労き裂はこれらせん断帯とすべり帯から発生した．

2．き裂の進展速度とき裂長さの関係は微細組織の平衡状態の影響を受けた．その原因を SEM による破面観察と TEM による組織観察により明らかにした．また，力学的に計算したき裂先端の繰返し塑性域寸法と結晶粒径の関係に基づくき裂進展モデルを提案した．これによりき裂進展速度の変化が説明できた．

3．高応力と低応力ではき裂の進展方向に大きな差が生じた．この原因を検討するため，変動応力試験を行い，高応力と低応力のき裂進展機構を明らかにした．また，疲労損傷の物理的意味を検討するため，各種変動応力下で破壊した資料の EBSD 解析を行い，応力負荷順序に依存した動的再結晶粒の形成の違いが損傷形成に関係することを示した．

以上の成果は，材料強度学および金属組織学的見地から重要であり，学術上寄与するところが大きい．また，超微細粒材料を実機に適用する際の疲労損傷評価のためのき裂進展モデル構築の基盤となるものであり工学的にも有益である．なお，論文公聴会において適切な説明がなされ，討議・質問において的確な回答がなされた．以上から，審査委員全員一致して本論文が博士（工学）の学位に値すると判定した．