Ultrasonic characterization of the effect of cold work and grain size in copper and 68:32 brass sheets

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The effectiveness of ultrasonic velocity measurements was evaluated as a means for non-destructive characterization of cold-rolled copper and 68:32 brass sheets. An apparatus was designed to generate and receive the zeroth symmetrical mode of ultrasonic Lamb waves in thin copper and brass sheets. The effect of angular variations in propagation direction with respect to the rolling direction on the measured Lamb wave velocities is shown. Interpretation of the variations of ultrasonic Lamb wave velocity were related to deformation mechanisms and texture development in copper and 68:32 brass sheets. Results show that the grain size and cold work influence the velocity as well as the texture of copper and 68:32 brass sheets. Results indicate the possibility of using ultrasonic Lamb wave velocity as a tool to monitor elastic anisotropy.

1. Introduction

Crystallographic texture, grain size, shape, and strain hardening are all important material effects which influence the subsequent forming behaviour of metal sheets. A textured material usually exhibits certain levels of anisotropy which may or may not be desirable from an application point of view. During some forming processes, strip is progressively bent into complex shapes by passing it through a series of rolls and/or dies. Normally, punches and dies are designed so that successive stages in forming of the part are carried out in the same die at each stroke of the press in a progressive forming operation. However, total automation and the improvement of productivity and quality of the product can be hampered by the variability and anisotropy of the physical and mechanical properties of material feed stock. For example, the bending properties may be quite different when the bend line is parallel to the rolling direction than when the bend is made perpendicular to the rolling direction.

The characterization of plastic anisotropy by uniaxial tensile or bend testing is time-consuming, costly and can only be performed off-line on a small fraction of the feed-stock material. The necessity of developing an on-line, in-process non-destructive sensing method is therefore desirable to minimize both material and time losses during subsequent processing and ensure adequate feedback control as well as consistency of material properties.

Ultrasound may offer a practical way to extract some information concerning the character of the material. Propagation velocities of ultrasound are determined, to a large extent, by the crystallographic grain orientation and elastic properties of the material [1, 2]. Generally speaking, a higher propagation velocity indicates a higher average elastic modulus in the propagation direction. On the basis of the ultrasound–texture relation, ultrasonic velocity has been proposed as an indicator for texture characterization [1,3, 4]. The high orientation dependence of the formability of cold-rolled copper and brass sheets might then be predicted from velocity information.

From the viewpoint of crystal structure, one might presume a preferential orientation of maximum stiffness along the fast propagation direction. The degree of texture might then be inferred by comparing the velocity in the rolling direction with that in some other direction in the material. Tittmann and co-workers [5–7] observed that ultrasonic Lamb waves are more sensitive to the texture of a material than Rayleigh waves. Roe [8] hypothesized that the anisotropy of the elastic properties can be characterized by three orientation distribution function (ODF) coefficients, which are known as W_{400}, W_{420}, and W_{440}. In the long-wavelength limit, Thompson *et al.* [9, 10] showed that these three coefficients can be deduced from the velocities of the fundamental symmetry Lamb mode S_0.

The interest here is to characterize the effect of rolling deformation, including the formation of rolling texture and deformation mechanisms, on the speed of the S_0 mode as a function of propagation angle, for variously deformed copper and 68:32 brass sheets.

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2. Background

2.1. Types of crystallographic texture

The types of annealing and rolling texture developed in face-centred cubic (fcc) copper and 68:32 brass sheets are well known and have been investigated by many researchers [11–13]. Sheet textures are usually described by "ideal orientations", a simplified means of an approximate description of the texture. In the case of copper and brass sheets, the principal rolling textures are $\{1\,1\,2\}\langle 1\,1\,1\rangle$ (the C texture), $\{1\,2\,3\}\langle 6\,3\,4\rangle$ (the S texture), $\{0\,1\,1\}\langle 1\,0\,0\rangle$ (the Goss texture) and $\{0\,1\,1\}\langle 2\,1\,1\rangle$ (the B texture). According to the relative amount of these four texture components, a distinction of deformation texture development between the copper-type texture in copper sheets and the brass-type texture in brass sheets is noticed [11]. For the annealing texture, in general, if the rolling texture developed is a copper-type texture, a $\{1\,0\,0\}\langle 0\,0\,1\rangle$ ("cube") texture is produced upon recrystallization. If the rolling texture developed is a brass-type texture, the annealing texture can be an α-brass or some other type of annealing texture which is considerably more complex than the cube texture [11]. It should be pointed out that as a metal is deformed, texture components often compete with each other and certain texture components may dominate to affect the characteristics of the material's properties. The amounts of the various textures are usually measured in the relative sense [11, 13].

2.2. Effect of cold work in copper

It is generally recognized that the deformation mode in f.c.c. metal is slip on octahedral planes with varying amounts of cross-slip [14–20]. The stress necessary to recombine the partial dislocations into cross-slip depends on the equilibrium distance of separation of the atoms, which in turn depends on the magnitude of the stacking fault energy (SFE) [15]. Generally speaking, the SFE in copper is high enough to activate sufficient numbers of independent slip systems. In slightly deformed copper, dislocations are formed and arranged on $\{1\,1\,1\}$ planes while the elementary structure is first established to form the equiaxed cells [15, 17, 18]. This equiaxed cell structure can withstand high strain levels with unchanged dimensions. Malin [17] assumes that this cell structure is in a relaxed state, because the relaxation after removal of the applied stress congregates the dislocations on crystallographic planes of easy slip. The dislocations accumulate locally to develop slip within the cell. Many transmission electron microscopy (TEM) and scanning electron microscopy (SEM) investigations have been conducted which have verified this assumption [17, 18, 20]. Results have shown that the interiors of cells are relatively free from dislocations while the boundaries are rather diffused regions of high dislocation concentration.

Microbands are also developed to maintain a stable deformation. Hatherly and co-workers [17, 18, 20] observed that microbands form and lie on $\{1\,1\,1\}$ planes with high dislocation densities concentrated along the grain boundaries. The formation of microbands dominates the second stage of deformation reactions. Most of the deformation in the range of 20–80% reduction contributes to the alignment and clustering of microbands. Fig. 1, obtained from TEM, shows the formation and clustering of microbands in 75% cold-rolled copper. Copper type texture is also evidenced at this stage [11, 18, 19]. Attempts to correlate the observation of microbands with the formation of copper-type texture have so far not been successful. Consideration of strain dependence and morphology suggest that certain texture transformations do occur with further plastic deformation [15, 18]. Based on the assumption that microbands form on $\{1\,1\,1\}$ planes throughout the full deformation stage, rotation of the microbands is necessary to align them with the rolling stress axes.

2.3. Effect of cold work in 68:32 brass

The microstructure and rolling textures of deformed 68:32 brass are different from those of pure copper [18, 19, 21–23]. The intrusion of twinning and shear banding at medium strains dominates the deformation process [22, 23]. The texture transition from copper-type to brass-type texture shows that the decrease in SFE initiated by increasing the zinc content is the primary reason for this transition behaviour [15, 18, 19].

In 68:32 brass, deformation begins mainly by slip on octahedral planes. The texture developed by gliding on $\{1\,1\,1\}\langle 1\,1\,0\rangle$ systems is very similar to that of copper [22, 23]. Because of the difficulty in initiating cross-slip in low-SFE material, the dislocations remain in planar arrays without developing a well-defined cell structure. Therefore a number of dislocations, stacking faults and defect clusters are found in the deformation substructure. Insufficient independent slip systems constitute an environment of barriers to dislocation movement, and the twin mode is needed to reorientate slip planes to contribute more by slip processes [21, 22].

Wassermann [21] proposed that deformation twinning occurred preferentially in grains (crystallites) orientated near $\{1\,1\,2\}\langle 1\,1\,1\rangle$ which are reorientated near $\{5\,5\,2\}\langle 1\,1\,5\rangle$, and then the twin matrix can be rotated by a normal slip process to $\{1\,1\,0\}\langle u\,v\,w\rangle$. In

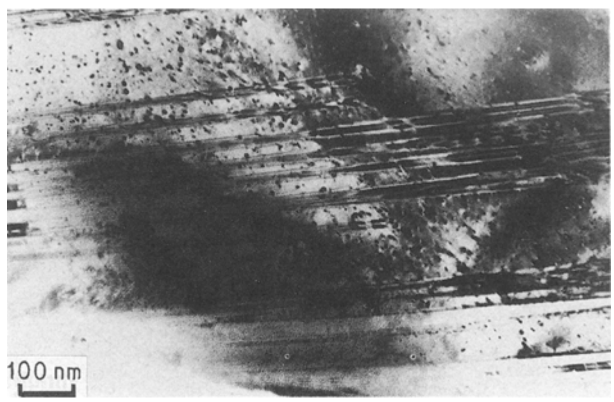

Figure 1 TEM showing the formation and clustering of microbands in 75% cold-rolled copper.

this case, the only slip systems which can continue to operate are those gliding planes that are parallel to the twin composition planes, so that the twin boundaries do not obstruct dislocation movement. Considerable overshooting (localized breakthrough of piled-up dislocations in certain directions) may be produced by this process, and the resolved shear stress on the primary systems can be decreased [23].

At 45% cold reduction the twins are fine and profuse, but unevenly distributed and some grains contain a very high twin density. These twins align themselves to provide an effective resistance to dislocation motion. As deformation proceeds, the force exerted by the piled-up dislocations continue to increase which results in the formation of a highly unstable structure. The intense localized deformation leads to development of shear bands [20]. Shear bands form preferentially in regions where the twin alignment is complete and the initiation of a shear band may involve a local break-through of piled-up dislocations. Fig. 2, obtained from TEM, shows twins and a shear band crossing the twinning structure in 75% cold-rolled 68:32 brass. Formation and clustering of shear bands are the dominating features in 68:32 brass after 45% cold reduction. The plastic work now applied is used to rearrange the misorientated grains and elongate them in the shear bands. The volume fraction of preferentially orientated grains gradually increases and deviates from the $\{111\}$ plane, thereby contributing to the overall brass-type texture, especially the $\{110\}\langle uvw\rangle$ component [21, 22].

2.4. Effect of grain size in copper and brass

Texture development in fcc material depends on the initial grain size [24–28]. Leffers *et al.* [24] summarized the various effects of grain size on rolling textures, and noticed little difference in texture development in undeformed and highly deformed materials. However, at intermediate deformations a delayed texture development was encountered in coarse grained materials. For a fixed degree of cold reduction

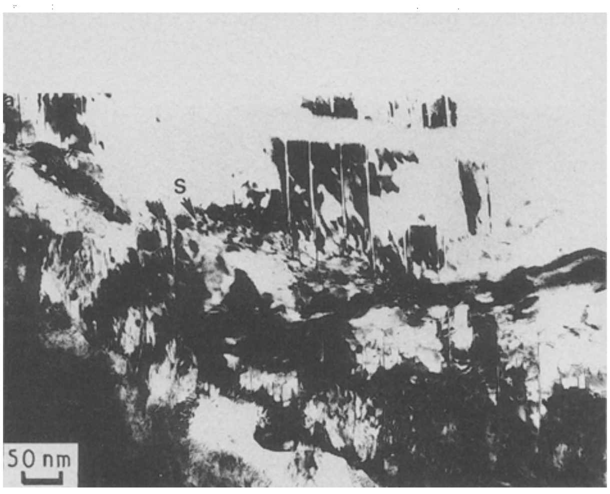

Figure 2 TEM showing twins and a shear band crossing the twin structure in 75% cold-rolled 68:32 brass. S:shear band

in copper, the severity of the texture was shown to be lower in coarse-grained materials than in fine-grained ones. Three reported cases [25–27] of the delayed development of copper-type texture in coarse-grained materials indicate that the delayed texture phenomenon dominates the texture development difference in two grain sizes. However, the difference in initial texture has not been considered to affect further texture development in high-SFE material. Microstructural observations [26] on high-SFE material were found to reflect changes in deformation patterns in different grain-size specimens. Generally speaking, the slip-line spacing decreases and the dislocation density increases when the grain size decreases, and the fine-grained materials show more homogeneous deformation patterns than the coarse-grained materials [25, 26]. For brass (considered as low-SFE material), the formation of the $\{110\}\langle uvw\rangle$ texture component might be linked to mechanical twinning via some overshooting mechanism which makes slip planes intersect with the twin lamellae. This is most likely to be the mechanism most responsible for activating the brass-type texture [22, 23]. Leffers *et al.* [24] also showed that coarse-grained brass has more pronounced twin lamellae near $\{110\}\langle uvw\rangle$ than fine-grained brass. Therefore, coarse-grained brass has a higher degree of brass-type texture than fine-grained brass. However, it is still not possible to prove that this is a genuine grain-size effect and not due to initial texture.

3. Experimental procedure

C110 copper and 68:32 brass specimens, 30 cm long, 15 cm wide and 0.25 mm thick were supplied with the long axis parallel to the rolling direction in the strip. Two different sets of samples were provided, each representing different annealed grain sizes with a small grain size of 5 μm and a large grain size of 20 μm. The annealed (0% cold-worked) samples were processed in a manner designed to produce "random" texture. Each set of samples contained three different cold-rolled conditions: 15, 45 and 75% cold work. All specimens were finish-rolled to a surface roughness of approximately 0.13–0.23 μm. The specimens are listed in Table I.

A device was designed to transmit and receive the fundamental symmetric Lamb wave mode (S_0 mode). Two precisely machined Lucite wedges, including a free-to-rotate cylinder that allowed for angle adjustment, were pressed to the surface of each sample by spring-loading. A commercial miniature piezoelectric transducer with a frequency at 2.25 MHz was fixed to each cylinder to generate longitudinal waves in the Lucite wedge. Fig. 3 shows a schematic drawing of the experimental arrangement and Fig. 4 presents details of the ultrasonic transducer and loading frame. By finely adjusting the incident wave to a critical angle approximately 47.5° with respect to the normal direction as shown in Fig. 5, the longitudinal waves propagating in the Lucite wedge transmitted into the sheet and propagated in the form of Lamb waves. A thin film of viscous gel served as the coupling medium between each wedge and the specimen surface to

TABLE I Test matrix

Set	Sample	Cold work (%)			
		Condition 1	Condition 2	Condition 3	Condition 4
1	C110/A	Annealed	15	45	75
2	C110/B	Annealed	15	45	75
3	32% Zn brass/A	Annealed	15	45	75
4	32% Zn brass/B	Annealed	15	45	75

[a] Grain size A: 5 μm, B: 20 μm.

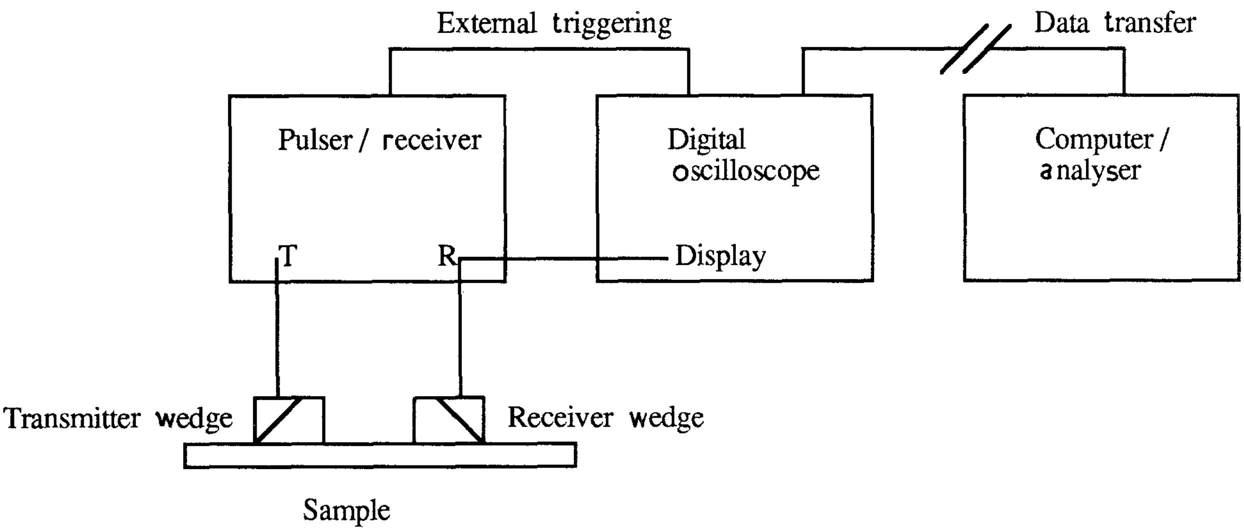

Figure 3 Schematic drawing of ultrasonic experimental set-up.

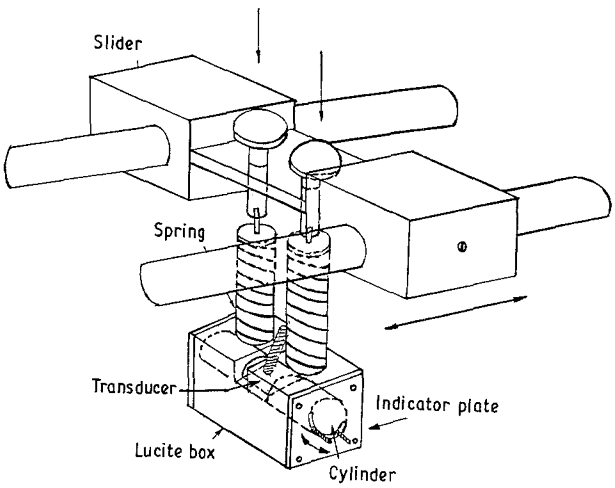

Figure 4 Ultrasonic transducer and loading frame.

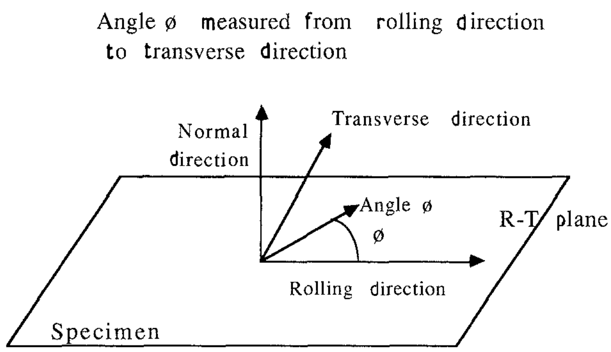

Figure 5 Definition of measurement directions, where the rolling direction $\phi = 0°$ and the transverse $\phi = 90°$.

provide a consistent contact. In-plane velocity measurements were taken every 5° from the rolling direction to the transverse direction at two different distances. An assumption of material non-dispersiveness was made in the long-wavelength limit. This assumption was predicted by computer analysis and experimentally found to be valid on all specimens tested. The measurement of wave transit time was made based on this assumption. The velocities were obtained from the linear slope of change in distance versus change in the propagation time. Also, an assumption of orthotropy was made so that only one quadrant of the 360° ϕ angle rotation in Fig. 5 was measured. The assumption is valid when the wavelength is large compared to the grain size in a multi-pass rolling process, as in this case where the wavelength was about 1700 μm. A total 1% experimental error was anticipated including the errors caused by the inhomogeneity of material (less than 0.7%) and manipulation of apparatus (less than 0.3%).

4. Results and discussion

4.1. Copper

An effort was made to relate the observed S_0 mode velocity measurements to the microstructure and texture development during rolling deformation in copper and 68:32 brass. Generally speaking, grain size and orientation as well as dislocations were expected to affect ultrasonic wave propagation [1, 28, 29]. An increase in propagation velocity suggests a preferred wave propagation direction and higher elastic modulus [5–7]. Comparison of Figs 6 and 7, obtained from the velocity measurements in copper for the 5 μm and 20 μm grain-size specimens, respectively, shows that the wave propagation velocity is affected by grain size in copper. Variations in velocity measurements as a function of propagation angle for the 5 μm grain-size specimens are much larger than those measured for the 20 μm grain-size specimens. Since the same types of texture development have been confirmed through X-ray diffraction measurements in these copper specimens, it is expected that this effect is related to the degree of homogeneous deformation process in the two grain sizes of copper. The small grain-size specimen deforms more homogeneously than the large grain-size specimen. Higher dislocation density, more grain-boundary interaction and grain alignment tend to cause more severe dispersion, and thus greater variation with direction, ϕ, of wave propagation in the small grain-size specimen. This is especially true for the high stacking-fault energy material copper after the intermediate plastic strain levels, i.e. 45 and 75% of cold roll [24, 26].

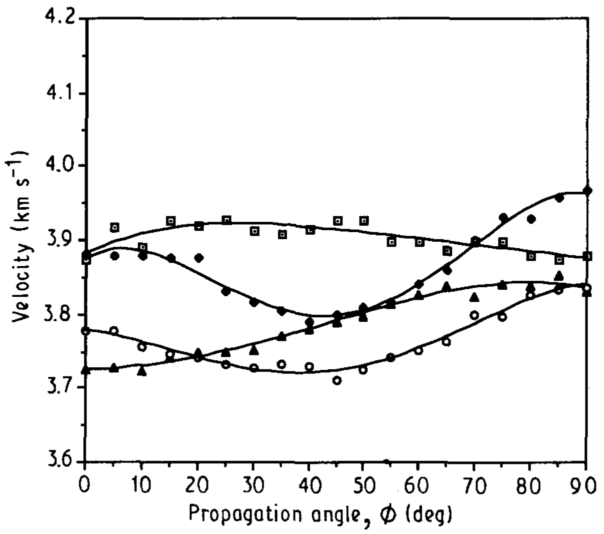

Figure 6 Ultrasonic velocity versus propagation angle for annealed and different cold-reduction copper samples where grain size is controlled at 5 μm in the annealed state. Cold-reduction (□) 0, (△) 15, (○) 45, (◇) 75%.

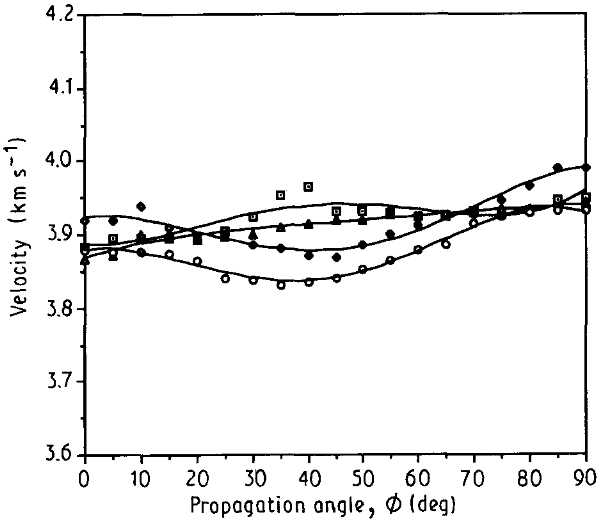

Figure 7 Ultrasonic velocity versus propagation angle for annealed and different cold-reduction copper samples where grain size is controlled at 20 μm in the annealed state. Cold-reduction (□) 0, (△) 15, (○) 45, (◇) 75%.

Velocity measurements made in the annealed copper for the two grain-size levels, as shown in Figs 6 and 7, indicate small increases of velocity between the rolling and the transverse directions in the annealed specimens for the two grain sizes in copper. It is expected that a small amount of initial annealing texture existed in annealed specimens which could account for this preference of wave propagation. Figs 6 and 7 also show the effect of cold work on the velocity in copper. For the 15% cold-rolled specimens of the two different grain sizes, the velocity shows a minimum in the rolling direction followed by an increase in velocity to the maximum in the transverse direction. This may be caused by the production of a high dislocation density that results in the early development of deformation textures. At this stage of deformation, copper-type rolling texture has not been well developed and the initial annealing texture still influences ultrasonic velocity measurements. Thus the profile of velocity measurement shows a transition shape representing a mixture of initial annealing texture and deformation texture [30].

Both grain sizes for 45% cold-rolled copper specimens show the same trend in velocity profile. This is especially noticeable at the 45° propagation angle. A change in velocity profile, from an increasing trend for the 15% cold-rolled specimens to an initial decrease followed by an increase in velocities above 45°, was evident in both grain sizes suggesting similar deformation mechanisms. This mechanism is possibly related to the formation of copper-type texture [11, 19]. Similar profiles of copper-type texture in the form of elastic moduli calculated from X-ray pole figures have been observed [27, 31–33]. At the 15% deformation stage, the equiaxed cell structure tends to rearrange dislocations instead of mass-producing dislocations [13]. Upon further deformation, the majority of plastic work is used for rotation of the misoriented grains and the development of microbands. The microbands have fewer misorientated grains and tend to align the grains to their preferred orientations. Many investigations have tried to relate this to the development of copper-type texture [15, 16, 18]. As cold work increases from 45 to 75%, the additional deformation results in an upward shift of the velocity profile, especially in the rolling and transverse directions for both grain-size levels. This apparent increase in velocity could be due to the clustering of microbands which results in an alignment of grains to orientations showing higher velocities in the rolling plane [19]. However, it is still not possible to prove that this is a genuine effect of microbands.

4.2. 68:32 brass

As mentioned previously, considerable overshooting (localized breakthrough of piled-up dislocations in certain directions) was noticed in the microstructure of 68:32 brass, hence the grain-size effect on the variation of ultrasonic velocity was not significant. As shown in Figs 8 and 9, the velocity profiles for the two grain sizes for 68:32 brass specimens are nearly the same. Nevertheless, several interesting phenomena are observed in these figures. The annealed specimens show a variation of velocity with propagation direction which is probably due to the annealing texture. It is noted that for the 15% cold work, 68:32 brass specimens, velocity profiles are similar to those observed in the 75% cold-worked copper. Propagation velocities initially decrease from the rolling direction to approximately the 45° propagation direction and then begin to increase toward the transverse direction. This similarity of velocity profile in 68:32 brass and highly cold-worked pure copper could be caused by the early development of copper-type texture in deformed 68:32 brass [19, 30, 31].

For the 45% cold-worked brass samples, a continuous increase in propagation velocity is observed from about the 30° propagation direction to the transverse direction. This change in profile is likely to be related to the transition of copper-type texture to brass-type texture [11, 19]. Similar profiles of brass-type texture in the form of elastic moduli calculated from X-ray pole figures have also been noticed [27, 31, 32]. The formation of shear bands could be mainly responsible for this change in velocity. Several investigations [20, 22, 23] have indicated that somehow the formation of shear bands activates the mechanism to cause the texture transition from the typical copper-type texture to brass-type texture. The 75% cold-worked specimens show a sharp decrease in propagation velocity in the rolling direction and a nearly linear increase to the transverse direction. At this stage of deformation, shear bands are the dominating features of the microstructure [11]. The rearrangement and elongation of the unoriented grains increases the volume fraction of preferentially orientated grains, leading to the development of the brass-type texture. This results in the velocity profile presenting a continuous increase in ultrasound velocity as the transverse propagation direction is approached [27, 34].

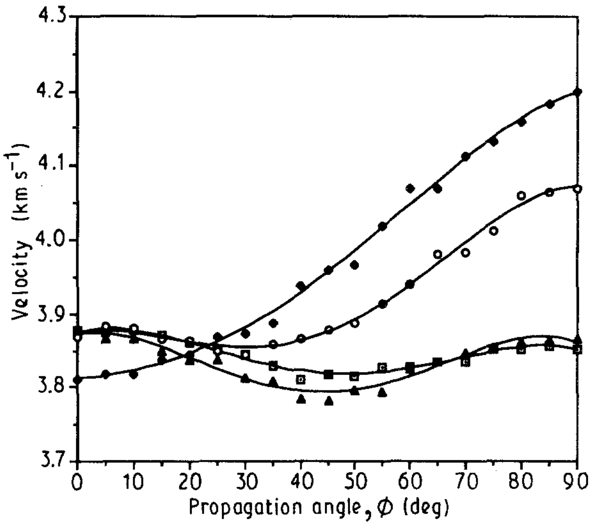

Figure 8 Ultrasonic velocity versus propagation angle for annealed and different cold-reduction 68:32 brass samples where grain size is controlled at 5 μm in the annealed state. Cold-reduction (□) 0, (△) 15, (○) 45, (◇) 75%.

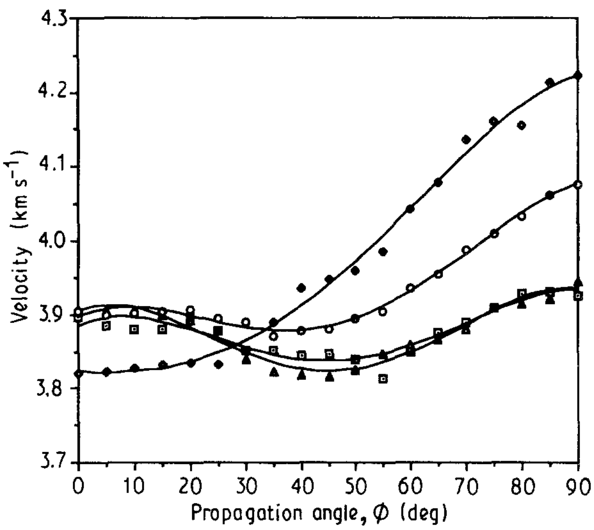

Figure 9 Ultrasonic velocity versus propagation angle for annealed and different cold-reduction 68:32 brass samples where grain size is controlled at 20 μm in the annealed state. Cold-reduction (□) 0, (△) 15, (○) 45, (◇) 75%.

5. Conclusion

The propagation of fundamental-symmetry Lamb waves on a suite of tailored copper and 68:32 brass sheet specimens has been investigated. An apparatus was designed to generate and receive ultrasonic Lamb waves. The dependence of the long-wavelength velocity S_0 on the propagation direction with respect to the rolling direction has been measured with different cold-work and grain-size conditions. Grain size and cold work have been shown to affect the variation of measured velocities as a function of orientation to the rolling direction. Experimental results indicate that grain size and cold work are explicit parameters which determine the degree of texture development and anisotropy in cold-rolled copper and 68:32 brass, and the velocity of S_0 waves is sensitive to these effects. Also, the possibility of using the S_0 wave velocities to monitor material properties is indicated.

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