Quantitative determination of a change of dominant slip system in tensile FCC single crystals

M.S. Szczerba and P. Palka
Department of Metallic Materials and NanoEngineering
University of Science and Technology, al. Mickiewicza 30, 30-059 Kraków, Poland
E-mail: szczerba@agh.edu.pl

Abstract. A change of dominant slip system (CDSS) in tensile FCC single crystals, as illustrated by properties of Cu-11at.%Al alloy single crystals, is quantitatively analyzed. The analysis shows that before and after the changeover cumulative shear of the dominant slip system is of the order of a magnitude larger than that of any other active secondary system. It was also found that at the critical condition for the CDSS to occur the rate of work hardening of the previously dominant slip system becomes equal to that which is taking over.

1. Introduction
The changeover of dominant slip of FCC single crystals from one octahedral plane to another was probably first observed by Elam, as illustrated by room temperature tensile properties of Cu-Zn single crystals [1]. By means of the shape changes analysis of a distorted crystal and X-ray measurements of crystal lattice rotation Elam proved undoubtedly that the CDSS occurs at the end of overshoot, where the primary dominant slip system is replaced by another dominant system operating on the conjugate slip plane. Since then, the overshoot phenomenon has been the subject of extensive studies that confirmed its universality and importance in plasticity of FCC crystals. However, the experimental data were insufficient to be quantitatively discussed in terms of the CDSS effect (see review paper [2]). Very systematic qualitative studies of the CDSS effect in tensile FCC single crystals are more recently reported by Basinski, Szczerba and Embury [3]. Examination of a large body of stress-strain ($\sigma$–$\varepsilon$) and rate of strain hardening ($d\sigma/d\varepsilon$) curves of Cu and single phase copper alloys (Al, Ni, Si) has additionally shown that classical behaviour predicted by the Considère construction is never exhibited by soft oriented tensile single crystals. Instead the CDSS causes a sudden effective decrease in strain hardening which is accompanied by strain localization and the specimen fails prematurely, which makes it impossible to perform a complete quantitative analysis of the CDSS effect. On the other hand, very recently systematic quantitative studies of the amount of shear of primary and secondary slip systems in copper single crystals deformed in tension at room temperature are reported in [4]. The data show that prior to the entry of the CDSS the amount of cumulative shear of primary slip is usually of the order of a magnitude larger than that associated with secondary slip systems. However, the complete quantitative analysis of the CDSS effect has not yet been performed. This is probably because of the fact that in most cases the amount of slip in the new dominant slip system was either impossible to determine due to the neck formation - soft oriented crystals, or the measurements could be affected by inhomogeneous distribution of crystal strain due to Lüders deformation - orientations near the [001]–[111] symmetry line of the basic stereographic triangle. In this paper the properties of Cu-Al alloy single crystals, which allow studying efficiently the amount of dominant and secondary
slip before and after the CDSS, are analyzed. To perform the analysis, the full gradient deformation matrix was determined from current orientation and shape measurements at successive strain intervals and the magnitude of shears in eight independent slip systems was calculated by means of the Chin, Thurston and Nesbitt method [5]. Moreover, a mechanical condition for the CDSS effect to occur and its influence on deformation mechanisms at large strain plastic flow of FCC crystals will also be discussed.

2. Experimental procedure
Cu-11at.%Al alloy single crystal samples of prismatic shape and dimensions 4·4·100 mm³ were used in the studies. The initial tensile crystal orientation was less than 2 degrees away from the [001]-[111] symmetry line of the standard stereographic triangle and close to the [121] crystallographic direction. The solute concentration and the initial crystal orientation were chosen to ensure that the tensile single crystals will survive the overshoot instability/strain localization and they sustain further homogeneous deformation large enough to perform the complete and reliable analysis of the CDSS effect. The single crystals were grown in a natural temperature gradient furnace in a vacuum better than 10⁻⁵ hPa. The samples were mechanically and chemically polished with Mitchell reagent in order to obtain lateral surfaces of great smoothness. Then, the grids of measurement points were placed on the crystal surfaces by the indenter of an Instron Wolpert 2100 microhardness tester with a value of the indentation load within the range 0.1 – 0.2 N. Taking advantage of a micrometric X-Y table coupled with an optical microscope and the Bruker D8 Advance X-ray diffractometer, the measurements of the mutual placement of the grid points were conducted and the crystallographic orientation of both of lateral crystal surfaces was determined. The samples were then step by step deformed in tension at room temperature with an initial strain rate of 10⁻³ s⁻¹ and strain intervals of about 0.05 of the tensile logarithmic strain. The distorted samples were placed again in a specially-prepared holder that was adapted to fasten it both at the X-ray diffractometer and the micrometric X-Y table. Sets of experimental data describing the shape changes of the samples in terms of geometric crystallography after each deformation step were obtained in the form of 3D base vectors and a magnitude of the shear strains in eight independent slip systems could be calculated with a resolution of the measurement method better than 5·10⁻³. Additionally the stress–strain and rate of work hardening curves of the Cu-11at%Al single crystals were determined. More details about the experimental procedure and the method of calculation of shears in the independent slip systems have been given elsewhere [4-6].

3. Experimental results and discussion
The stress-strain (\(\sigma-\varepsilon\)) and rate of work hardening curves of the Cu-11at.%Al single crystals are shown in figure 1. These curves are limited to the range of tensile strain where the total crystal deformation is produced by slip only - it is well known that these single crystals deform at larger strains by mechanical twinning. The \(\sigma-\varepsilon\) curve can be divided into two distinct stages with a sharp transition somewhere in the middle, where catastrophic drop from 1000 MPa down to about 200 MPa of the rate of strain hardening (\(\frac{d\sigma}{d\varepsilon}\)) is observed. Watching lateral surfaces of a deforming crystal it was easy to see that the abrupt drop in work hardening was followed by a discrete plastic front travelling along the specimen. However, during this period of plastic flow (\(\varepsilon \approx 0.3-0.4\)) a specimen was hardened enough to sustain further homogeneous deformation and to restore the high rate of strain hardening. The X-ray measurements show that the transient local decrease in \(\frac{d\sigma}{d\varepsilon}\) corresponds to the end of overshoot of the crystal tensile axis as illustrated in figure 2. The figure shows the angular distance from the [001]-[111] symmetry line as a function of strain. Since the primary slip system, \(\{111\}\{011\}\) dominates at the very beginning of the deformation process, the tensile axis moves from the initial position towards the operating slip direction \([\bar{1}0\bar{1}]\) crossing the [001]-[111] symmetry line during the first strain intervals. Further crystal deformation proceeds in the state of the overshoot which at the critical point (\(\varepsilon=0.26\)) reaches the maximal value of about 7 degrees. Starting from the critical point the reverse process occurs. The tensile axis moves backward to the initial stereographic triangle crossing again at \(\varepsilon=0.47\)
the symmetry line, so the state of second overshoot is achieved. It is clear that at the end of overshoot the CDSS must take place which consists of the changeover of the dominance from primary (P) into conjugate (C) slip system, \((\overline{1}1\overline{1})[01\overline{1}]\). Corresponding changes of Schmid factors of the dominant P and C slip systems are shown in figure 3.

Now, taking the product of the tensile stress and the current Schmid factor value one can calculate the resolved shear stress \(\tau\) operating in the dominant C and P systems. The evolution of \(\tau_C\) and \(\tau_P\) values during the deformation process is shown in figure 4. It is to note that at the end of overshoot the difference between \(\tau_P\) and \(\tau_C\) is the largest and the ratio \(\tau_C/\tau_P\) at this point reaches the value of 1.3. It means that the entry of the new dominant C system is due to the latent hardening well over-stressed what may result in the sharp transient local decrease in \(d\sigma/d\varepsilon\) and the temporary strain localization. The key experimental data concerning the amount of shears operating in all four octahedral slip planes of the crystal lattice, or alternatively, in eight independent slip systems, is shown in figure 5. The two important points are: (i) prior to the CDSS the crystal deformation is totally dominated by the P slip system and the amount of shear in this system is of the order of a magnitude larger that any other secondary slip system including the C slip system; (ii) after the CDSS crystal deformation is totally dominated by the C slip system and the amount of shear in this system is of the order of a magnitude larger that any other secondary slip system including the P slip system. So, at the end of the overshoot the CDSS effect consists of the dominant slip changeover of the \(P\rightarrow C\) type. Moreover, figure 6 shows that the changeover does occur when the gradually decreasing strain hardening rate \((d\tau/d\gamma)\) of C system approaches the same numerical value as the gradually increasing strain hardening rate of P system. It is important to note that operation of the new dominant C system leads quickly to the state of the end of the second overshoot and another CDSS effect might occur where the opposite \(C\rightarrow P\) type of the changeover can take place. Such multiple CDSS effect can occur in copper [4] and less concentrated Cu-Al alloy single crystals [6] where the sequence of \(P\rightarrow C\rightarrow P\rightarrow C\) have been observed before the tensile specimen necked to failure. However, at the end of the second overshoot of the investigated Cu-12at.%Al crystals mechanical twinning is observed instead. Such the dominant slip – mechanical twinning transition in the case of Cu-8at.%Al single crystals oriented for single and double glide was discussed in detail by Szczeba, Bajor and Tokarski [7]. Summarising the obtained results and the performed discussion it seems reasonable to support strongly an idea that the CDSS
phenomenon might be of great importance in large strain plasticity of FCC materials. The phenomenon should be also seriously considered as a process which is transformational in nature.

![Graph showing resolved shear stress evolution for P and C slip systems](image)

Fig.4. The evolution of resolved shear stress of the dominant P and C slip systems

![Graph showing work hardening rates for P and C slip systems](image)

Fig.6. The rates of work hardening of the dominant P and C slip systems

**4. Conclusions**

On the basis of the obtained results and the performed discussion the following conclusions can be drawn: (i) – the complete quantitative analysis of the CDSS effect occurring in the investigated Cu-11at.%Al single crystals was successfully done; (ii) - the amount of shear of the dominant slip system prior to and after the CDSS is of the order of a magnitude larger than for any other secondary slip system; (iii) - The CDSS does occur at the end of overshoot when the strain hardening rates \( \frac{d\tau}{d\gamma} \) of the dominating slip system and the system which is taking over the crystal deformation become equal.

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