International Journal of Applied Engineering Research ISSN 0973-4562 Volume 11, Number 24 (2016) pp. 11818-11825
© Research India Publications. http://www.ripublication.com

Effect of Temperature on Hardness and Microstructure in Rotary Bending of Copper Sheets

Naser Abdulrahman Alsaleh[1*]

[1]*College of Engineering, Department of Mechanical Engineering,*
Al Imam Mohammad Ibn Saud Islamic University (IMSIU),
P.O. Box 91992, Riyadh 11643, Kingdom of Saudi Arabia.

Abstract

The effect of temperature on hardness and microstructure in rotary bending of copper sheets was investigated. The process was subjected to a gradient of elevated temperatures reaching 200°C. The increased temperature caused further expansions in the grain dimensions along the bending layers. It also reduced the hardness within the bend zone. However, the temperature effect was decreased between 125°C and 200°C with respect to hardness, which was reversed for grain lengths along the tension layer. In this range, reduced dislocation resistance caused grains within the compression layer to ram into the tension layer, obstructing its grains from continuing their lengthwise expansion. Although no complete recrystallization was evident, the increase in temperature led to grain growth through diffusion in both bending layers.

Keywords: Copper; sheet metals; microstructure; hardness; grain; rotary bending

INTRODUCTION

Bending is one of the most popular forming processes which cannot normally generate scrap or metal waste. Unlike most sheet metal manufacturing processes, such as drawing and shear spinning, bending conserves raw materials. Acceptable accuracy and abundant deformation can be achieved by bending with reduced energy and time requirements. Bending processes produce a combination of tension and compression forces within the bend zone, depending mainly on the sheet metal thickness along with the physical, chemical, and metallurgical properties of the bent material [1, 2]. Additionally, the tolerances of bending processes affect their forces, mechanics, and final product surface properties.

Analytical examinations of bending processes have been widely addressed throughout the field of metal forming [3, 4], revealing layers of tension and compression across the thickness of bent sheets separated by neutral axes. Bend angle and its radius are considered the main controlling variables of bend sharpness. Thus, they can be directly related to fracture vulnerability and surface roughness in the bend zone. The physical and mechanical properties of metallic materials depend on their microstructural characteristics, which can be quantified using image analysis software [5-7]. The initial microstructure is assumed to control the feasibility and limitations of forming processes that can be applied to any sheet metal product. In 2006, Birol [8] studied the microstructure effect while sharply bending aluminum alloyed sheets and concluded that an extremely fine grain structure normally yields no cracking, undulations, or roughening on the outer tensile surface of the bent sheet. In 2002, Rhaipu [9] also found that fine structures yielded greater elongations and lower flow stresses when deforming rapidly heat-treated Ti-6Al-4V sheets.

Grain size was also found to influence other bending qualities, such as springback, with reference to different process variables, such as the bending radius, sheet thickness, and forming temperature [10, 11]. Conversely, deformation of metals can have a counter effect on the microstructure by altering the shapes and sizes of metal grains [12-14]. In 2005, Bach et al. [15] extensively investigated the effects of rolling and deep drawing of magnesium sheets on microstructure grain shapes by using heated forming tools. Under these conditions of forming and for deep drawing processes, grain sizes were found to increase close to the sheet surface, where contact with the heated tool was prolonged at the flange. However, grains along the drawn cup wall exhibited homogeneous elongation in the direction of the radial tensile stress. In contrast, grain size was found to have a generally negative relationship with the amount of deformation endured by a metal alloy [16, 17]. The average grain size also plays an important role in surface quality in terms of roughness, where larger grains typically yield coarser surfaces for most aluminum alloys [18].

Unlike heat treatments that take place prior to forming processes, some researchers have investigated the effect of temperature during deformation. In 2000, Walczyk and Vittal [19] studied the effect of intensive heat while bending by applying a laser to titanium sheets and observed microstructure degradation, which often rendered the end product useless. In contrast, a key experimental study by Popovic and Verlinden in 2005 [20], which used equal channel angular pressing of aluminum alloy (AA5182) at 200ºC, revealed a good balance between strength and work hardening with no evidence of discontinuous crystallization. However, performing the same process at 400ºC has yielded lower strength and the occurrence of discontinuous crystallization. In the same study, and as expected, processing at room temperature enhanced the strength and reduced the ductility, which consequently resulted in macrocrack development. In 1994, Chang and Chou [21] examined the effect of increased temperature on deep drawing processes of stainless steel sheets. By heating the forming tool, they found that brittle fracture tended to occur more frequently when forming at a certain temperature, approximately 150ºC. In general, numerous alloys of steel and aluminum sheets have been either experimentally or theoretically covered in the literature regarding their formability and limitations [22, 23].

In line with the stressed practicality of this study, industrial-grade copper sheets were used with a composition described in the subsequent section on materials and methods. The commercial copper sheets examined in this study are used in the industry mainly to manufacture products of an electrical and thermal nature, such as electronic conductor boards and cooling components that require bending processes. The copper sheets were subjected to rotary bending under controlled temperature conditions corresponding to the research objectives, as will be discussed in a subsequent section of this paper. A gradient of forming temperatures and their effects on the microstructure and hardness across the thickness of bent copper sheets were investigated in this study with a high level of detail [24]. Simultaneously incorporating the variables of temperature, grain proportions, and hardness is believed to provide an integrated understanding of rotary bending properties and its improvement limitations. A practical and industrially feasible technique of heating by a flame was implemented in the rotary bending process.

Based on the related literatures [25,26], copper microstructural characteristics in relation to bending temperature were not thoroughly examined despite their importance in modifying the mechanical properties of sheet metal [27], which ultimately influence surface quality and fracture initiation within the bend zone. Therefore, the main objective of the present study is to explore grain dimensions with respect to their orientations across the thickness of copper sheets in the tension and compression layers of bending. Bending temperatures, even below recrystallization, are hypothesized to influence grain proportions in the bending layers. Understanding the mechanical properties of the bent material, expressed by microhardness across the compression and tension layers, with respect to microstructure and temperature will further enhance our knowledge concerning the limitations of bending processes.

MATERIALS AND METHODS

The experimental specimens were obtained from commercially available 1.5 mm-thick C81100 copper sheets (ASM Cu515) with the following composition: 99.7% Cu, 0.15% Fe, 0.04% P, 0.02% Al, and remnants of Cr, Sn, C, Au, Te, and Co. The copper sheets employed are widely used in manufacturing to produce electrical boards and heat exchanger components. For each experimental condition, three specimens were prepared by a shearing process to a size of 80×70 mm.

The bending process was accomplished under elevated temperatures generated by a propane gas flame produced by a torch directed toward the top side of the sheet metal near the bend line. This technique of heating during bending was selected due to its reduced cost and practicality in actual manufacturing settings, compared to the laser forming used by other researchers [19]. Moreover, heat produced by a flame spreads more consistently along the bend zone to avoid unwanted shape distortions found in laser forming as reported by Reeves et al. [28]. The flame in this setup continues to heat the upper sheet surface near the bend line for 10 to 30 s until the required temperature (±1°C) is reached, at which point rotary bending is initiated. Temperature measurements were taken on the lower surface of the sheet metal using infrared temperature measurement technology. The location where the measurement was taken was painted with heat-resistant black paint to eliminate measurement bias caused by energy emitted by the sheet metal reflection.

The range of temperature gradients used in this study was assumed to be less than the re-crystallization temperature of the sheet material employed [29]. The manufacturing applicability and economic factors had to be considered when determining the temperatures under which the bending processes were performed. Accordingly, the forming temperatures considered in this study comprised bending at ambient temperature of 27°C and a gradient of warm temperatures of 75, 100, 125, 150, and 200°C. These allocated temperatures lie below the typical recrystallization temperature of non-hardened copper, which is 200°C. However, because copper sheets undergo extensive deformation by rolling, their recrystallization can be reduced significantly. Although recrystallization temperatures in most metals are typically 1/3 to 1/2 of their absolute melting points, copper has substantially lower recrystallization temperatures that can drop to 120°C [30] depending on the purity and extent of prior stain hardening. No specimen warping or pre-bending deformations were evident during the experimental procedures due to the allocated forming temperatures.

Rotary bending with a 50 mm-long rotating die, not a rocker, was performed using a desktop folding machine. An electrical motor rapidly revolved the rotating die through a gear mechanism delivering a constant speed of 2.5 mm/s, or approximately 1 rpm, simulating working speeds found in manufacturing-scale bending machines. Specimens were bent across the sheet metal rolling direction, transversely, at an angle of 135° with a bend radius of 0.5 mm. Compared to other bending processes, rotary bending reduces secondary deformations and external constraints imposed by the bending die, especially along the outer surface of the bend line. Forces in this process are largely limited to bending alone, where the holding friction exists only on one side of the bent sheet metal. Thus, rotary bending minimizes interference with drawing and stretching deformations not directly related to the bending process itself, which cause a reduction in the thickness of the bend zone. The eliminated contact between the sheet's outer surface at the bend zone and the bending die, as attained in rotary bending, also prevents scratch marks on easily marred surfaces, such as copper. Another advantage of rotary bending is the reduced force in a single rotating stroke to accomplish angles greater than 90°. Figure 1 illustrates the rotary bending apparatus used in this study.

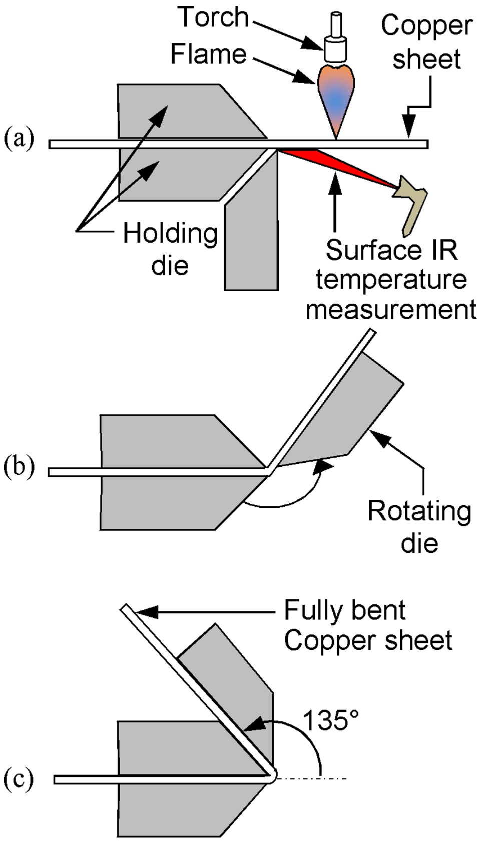

Figure 1. Experimental setup of rotary bending under elevated temperatures: a) heating and IR temperature measurement of the bending surface, b) bending when the intended temperature is reached, and c) release of the completely bent copper sheet.

To expose the cross-sectional area at the middle of the bend lines, where temperature was measured, each bent specimen was cut into two parts perpendicular to the bending line. Preliminary grinding with SiC-320 grit at 300 rpm for 1 min was initially performed. Subsequently, fine polishing was completed using DiaPro Allegro/Largo (9 μm diamond suspension) and DiaPro Mol (3 μm diamond suspension) abrasive suspensions at a low speed of 150 rpm for 3 and 5 min, respectively. All prepared specimens were then cleaned by alcohol rinsing (acetone) and blow-dried. Etching was achieved by immersing the prepared copper specimens for 10-20 s in nitric acid and distilled water. Digital image acquisition using a metallurgical optical microscope equipped with a CCD camera, together with metallographic analysis software, was used to accomplish the necessary inspection and analyses of the bent specimens. The required microstructure features, including grain dimensions and orientations in different locations on the cross-sectional surface of the sheet metal, were revealed. Grain measurements followed ASTM-E112 standards using horizontal, vertical, and circular line intercept methods under magnification of 100 x. Grain dimensions on the cross-sectional plane comprised grain lengths and widths, parallel and perpendicular to the outer surfaces of the sheet, respectively. Figure 2 illustrates the approximate locations of these measurements and their directions. The grain lengths were obtained by projecting five parallel and equally spaced lines, 1,000 μm long, on the obtained microstructure image and measuring the distance along each line between every two intersections with the grain boundaries. The lines were placed as parallel as possible to the outside and inside surfaces of the copper sheet at the bent zone or at the flat flange of the bent specimen adjacent to the bend zone. A similar procedure was followed to measure grain widths except that the lines were placed perpendicular to the outside and inside surfaces of the copper sheet.

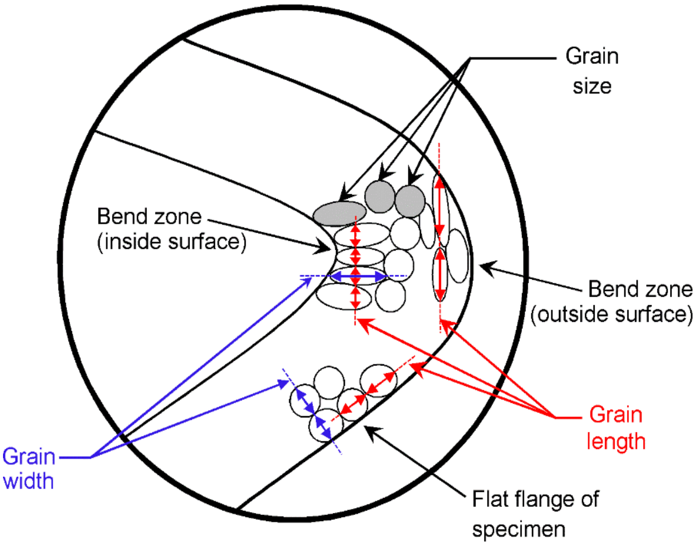

Figure 2. Grain measurements in the tension and compression layers of the bend zone.

Hardness is a reliable indicator of changes in mechanical properties that occur after deformation under different conditions. It was used in this study to explore the effect of temperature on sheet metal behavior when subjected to rotary bending. Microhardness testing appeared rather problematic at the bend zone close to the outside and inside edges of the cross-sectional plane on the compression and tension layers. Side views of copper sheet microcracks, undulations, or roughening appeared in these locations. However, accurate Vickers' indentations were possible on the specimen's cross-sectional plane within 200 μm from each edge on the tension and compression layers. On each layer, an average of three microhardness readings were calculated—one on the centerline of the bending angle and the other two 10° from either side of the centerline. Microhardness readings were averaged over three different locations at the bend zone to ensure a reliable and representative measurement. Microhardness measurements were also obtained for the flat flange of the specimen for comparison purposes. Hardness measurement was performed under a load of 100 gf and a dwell time of 10 s. To attain an acceptable level of accuracy, specimens' cross-sectional planes were prepared for the microhardness indentation by polishing with 3 μm grain paper on a plate device rotating at 100 rpm.

RESULTS AND DISCUSSION

Figure 3 shows a sample of the copper sheet microstructure in the bend zone, with stretched and compacted grains across the tension and compression layers, respectively. These patterns in grain orientation were maintained regardless of changes in the forming temperature up to 200°C. Persistence in grain orientation patterns negates the possibility of complete recrystallization in the bent copper sheet at all observed forming temperatures.

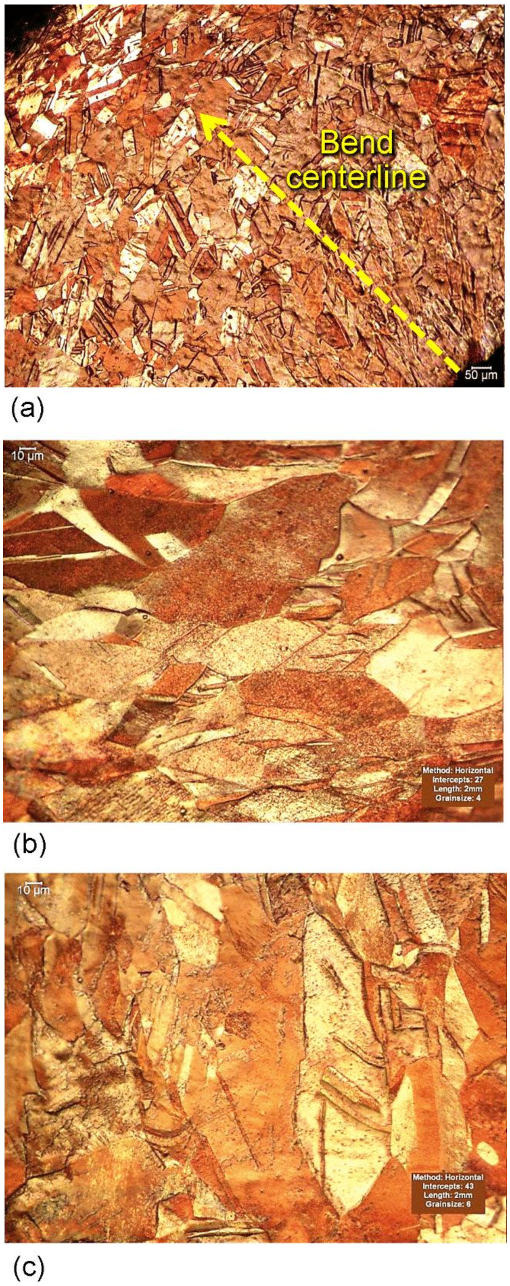

Figure 3. Microstructure of C81100 copper sheet metal after rotary bending showing grain shapes and orientation (a) on the entire cross-sectional surface of the bend zone, (b) in the tension layer close to the outside surface, and c) in the compression layer close to the inside surface of the bent sheet.

At ambient temperature, the intensities and directions of deformations resulting from rotary bending varied through the cross section of the copper sheet. Different patterns of grain orientation and arrangement were evident in the bend zone. Most grains within the bend angle and close to the outside surface of the bent sheet were stretched along the direction of the tension layer, causing expansions in the grain lengths. However, grains adjacent to the inside bent surface were compacted in proportion to the direction of the compression layer. In reaction to the negative stresses in the compression layer, grains were also squeezed perpendicularly toward the tension layer. These negative stresses reduced the lengths and increased the widths of grains in the compression layer. Meanwhile, at all bending temperatures, twinning appeared across the bend zone, especially toward the tension layer. Shear forces along twin boundaries shift atoms beyond their regular arrangements, causing twins. In a crystal structure, mirror image misorientations across planes form twin boundaries [31]. Thus, twin boundaries tend to disturb plain slipping during deformation, strengthening copper. Moreover, changes in grain dimensions and orientations were found to be significantly affected by the forming temperature.

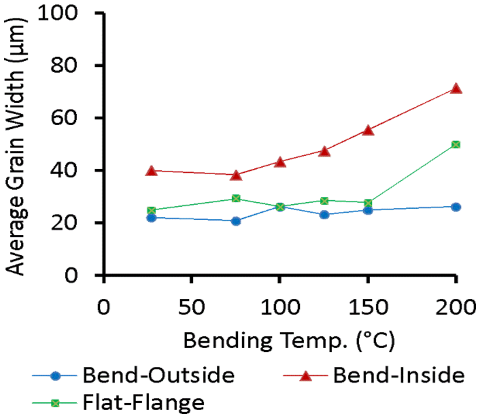

Figure 4. Average grain width in the bend zone of a copper sheet.

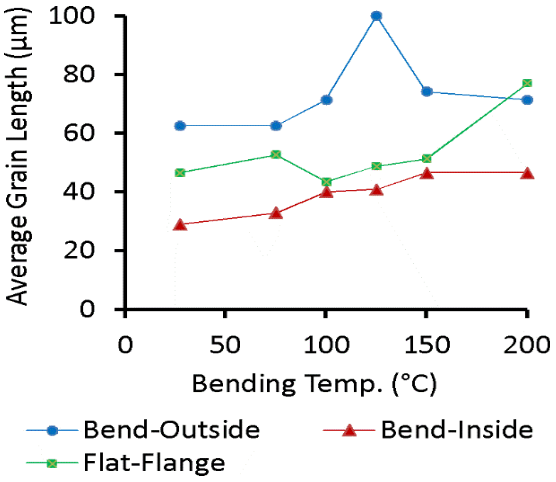

Figure 5. Average grain length in the bend zone of a copper sheet.

Figures 4 and 5 show the average grain lengths and widths for each bending temperature in the bend zone, near the outside and inside bend surfaces and at the flat flange of the copper specimen. Grains at the flat flange represent dimensions prior to deformation caused by bending and after deformation caused by sheet rolling. At the flat flange, neither grain lengths nor widths exhibited a well-defined trend with respect to the increase in temperature up to 150°C. However, both dimensions increased by approximately 25 μm as the forming temperature was increased from 150°C to 200°C. Grain expansion in this temperature range cannot be attributed to complete recrystallization because the patterns of grain expansion and compaction still exist at the bend zone as shown in Figure 3. If complete recrystallization occurred due to an increase in temperature, uniform grain shapes would appear even at the tension and compression layers. However, even without reaching the recrystallization temperatures, grain growth can occur when a polycrystalline material is kept at an elevated temperature [32]. Migration of grain boundaries at elevated temperatures initiates such growth, typically caused by diffusion that increases with increasing temperature. Diffusion of atoms from one side of a grain boundary to the other creates grain boundary movement in the opposite direction [33]. When grain growth is caused by diffusion of atoms during elevated temperatures, small grains tend to accumulate to form fewer large grains and reduce grain boundary areas. Holding at a specific elevated temperature plays an important role in this phenomenon, in which longer exposure to the elevated temperature instigates grain growth even without reaching the recrystallization point. Because specimens were bent after a flame-heating episode, lasting between 20 and 30 s, diffusion of atoms is believed to cause some grain growth without reaching complete recrystallization [34].

Due to positive stresses in the tension layer, grains near the outside surface of the bend zone significantly increased in length with increasing bending temperature from 75°C to 125°C. The effect of temperature in reducing dislocation resistance among boundaries and slip planes allows grain lengths to expand more freely within the tension layer [35]. Above 125°C, this temperature effect reversed, causing the average grain length to decrease to nearly its original value when bending was performed without heating. This behavior can be attributed to the counter-effect caused by the diffusion of atoms among grains in the opposite direction to the tension stresses, reducing grain lengths as the forming temperature exceeds 125°C. Moreover, increasing the temperature also enhances dislocation in the compression layer, permitting its compacted grains to penetrate farther between grains in the tension layer, obstructing their lengthwise expansions and increasing the thickness of the compression layer. Conversely, and for the same reasons, grain widths in the tension layer did not show significant change.

Figures 4 and 5 also show changes in the grain dimensions in the compression layer, near the inside surface of the bend zone. The average grain width, perpendicular to the compression layer direction, continued to increase nearly linearly with increasing temperature from 75°C to 200°C. Enhanced dislocations in the compression layer due to increasing temperature caused the increase in grain widths. The rate of compaction in the compression layer, which squeezes grains perpendicularly, likely overwhelmed the counter-effect of atom diffusion caused by elevated temperatures. Unexpectedly, the average grain length in the same layer also increased with increasing bending temperature but at a lower rate compared with the average grain width. However, the diffusion instigated by temperature rise and compression deformation is believed to overcome the reductions in grain lengths caused by negative stresses in the compression layer. Regardless, grain lengths in the compression layer are still lower than those at the flat flange for all bending temperatures.

As shown in Figure 4, the trends in grain lengths for the tension and compression layers tend to converge when the temperature increases above 125°C. Nearly the opposite trend occurs with regard to grain widths as shown in Figure 5. These trends suggest notable inferences regarding the rotary bending processes of C81100 copper sheets. First, grains in the compression layer continue to grow in all directions as a result of diffusion instigated by higher temperatures and compression stresses. However, the rate of expansion in grain widths exceeds that of grain lengths due to the squeezing of grains toward the tension layer as a reaction to the compaction forces within the compression layer. Second, positive stresses in the tension layer significantly expand grain lengths as the temperature increases to 125°C. Nonetheless, this trend reverses at temperatures above 125°C due to accelerated dislocations in the compression layer that cause compacted grains to penetrate toward the tension layer, restricting its grains from expanding. Temperature-instigated diffusion also assists in this downturn. Third, the rate of atom diffusion increases along the direction in which the compression forces are exerted—i.e., parallel to the forces of the compression layer and perpendicular to the tension layer [36]. Regardless, the difference between the average grain width and length are substantial in both the tension and compression layers despite the changes in bending temperature. This result certainly corresponds with the basics of bending mechanics.

Hardness reflects metal resistance to plastic deformation. Thus, it indicates the degree to which sheet metal withstands physical bends and dents. Hardness is also related to the characteristics of the material microstructure and the stored strain hardening. Vickers microhardness testing on the cross-sectional area of the bent copper sheet, according to the specifications stated previously in the methodology section, revealed consistent details. The average microhardness readings at the bend zone and the flat flange for the preset bending temperatures are shown in Figure 6. Regardless of the effect of temperature, the location where microhardness was measured significantly influenced its value. At the flat flange, microhardness ranged from approximately 90 to 100. As expected, it increased significantly in the tension and compression layers, close to the outside and inside surfaces of the bend zone. Strains caused by positive and negative stresses in the bending layers develop such hardening effects. However, hardness in the tension layer, near the outer bent surface, surpasses its value in the compression layer for bending temperatures less than 125°C. Accordingly, tension stresses in the outer tension layer exceed compression stresses in the inner compression layer, shifting the neutral axis between the layers toward the inner surface of the bent specimen.

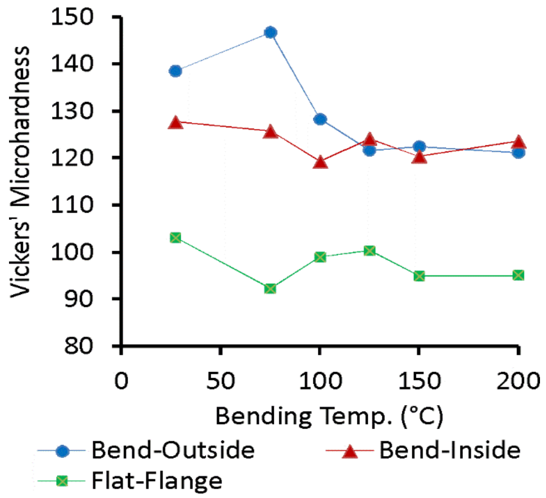

Figure 6. Vickers microhardness through copper sheet thickness.

An increase in hardness strongly indicates an escalation in the plastic strain [37]. However, this relation does not always hold when heat is added. In both the tension and compression layers, the introduction of heat during bending reduces hardness by relieving the effect of strain hardening, which results from deformations associated with bending. Accordingly, increasing the temperature while bending C81100 copper sheets loosens bonds between the grain boundaries and slip planes, enabling grains to move and slide with fewer restrictions. Thus, increases in temperature lead to further changes in grain orientation [38] and aspect ratio [39]. This also confirms the negative relationships between grain dimension change and hardness (Figures 4, 5, and 6). However, the effect of temperature on hardness begins to fade at temperatures above 125°C for the inner and outer bent surfaces of C81100 copper sheets. This result supports earlier findings concerning the diminishing change in grain lengths within the tension layer as the bending temperature reaches 125°C, signaling the beginning of atom diffusion among grains. Diffusion dominates after this temperature perimeter, allowing grains to release additional stored energy typically caused by strain hardening of bending [40]. Despite these temperature-related changes within the bend zone, the hardness in the tension and compression layers always exceeds the original hardness of the flat flange at all tested temperatures. This indicates that there was no extensive ductility or malleability added to the bent copper sheet due to temperature compared with its original after-rolling properties.

CONCLUSION

Higher temperatures may enhance the dislocation motion that relieves internal strain energy in metals. Accordingly, increasing temperature to a certain limit during bending—and forming in general—leads to better formability with lower tonnage requirements. In addition to its economic aspects, constraining increases in temperature within the perimeter of the bending line through a concentrated flame improves the process in terms of microstructural and mechanical properties within the deformation zone only.

In the rotary bending of C81100 copper sheets, higher temperatures allow for more expansion in grain lengths within the tension layer and no additional compactions in grains within the compression layer. In addition, hardness decreases with increasing temperature to a specific limit. This is attributed to the loosening of bonds along grain boundaries and between slip planes resulting from increased temperature in the bend zone. Nevertheless, the effect of temperature on grain lengths and hardness begins to diminish at approximately 125°C. Decreased dislocation resistance above 125°C allows compression layer grains to ram through the tension layer, obstructing its grains from lengthwise expansion. Correspondingly, higher temperatures lead to the instigation of atom diffusion among grains, causing grain growth in both the compression and tension layers of the bend zone.

Further exploration of microcracks on the outer surface of bent C81100 copper sheets with respect to elevated forming temperatures is required. Relating microcracks to grain dimensions, hardness, and forming temperatures in the bend zone would provide a better understanding of rotary bending and a prediction of its limitations.

ACKNOWLEDGEMENT

The author would like to be obliged to Al Imam Mohammad Ibn Saud Islamic University (IMSIU) for providing laboratory facilities.

REFERENCES

[1] Hu H, Marciniak Z, Duncan JL. Mechanics of Sheet Metal Forming. Butterworth-Heinemann: Wobum, MA; 2002.

[2] Pollack HW. Manufacturing and Machine Tool Operations. Prentice Hall: Englewood Cliffs, NJ; 1987.

[3] Boljanovic V. Sheet Metal Forming Processes and Die Design. Industrial Press: New York, NY; 2004.

[4] Tschaetsch H. Metal Forming Practise: Processes-Machines-Tools. Springer: Berlin Heidelberg, NY; 2006.

[5] Diógenes AN, Hoff EA, Fernandes CP. Grain size measurement by image analysis: An application in the ceramic and in the metallic industries. In Proceedings of COBEM 18th International Congress of Mechanical Engineering, Ouro Preto, MG, Brazil; 2005. p. 6-11.

[6] Gama J, Dantas C, Quadros N, Ferreira R, Yadava Y. Microstructure-mechanical property relationship to copper alloys with shape memory during thermomechanical treatments. Metall. Mater. Trans. A, 2006;37:77-87.
[7] Wu J, Wray P, Garcia C, Hua M, Deardo A. Image quality analysis: A new method of characterizing microstructures. ISIJ, 2005;45:254-262.
[8] Birol Y. Effect of processing on microstructure, texture and mechanical properties of twin roll cast 5754 sheet. Mater. Sci. Technol., 2006;22:987-994.
[9] Rhaipu S. The effect of rapid heat treatment on the high-temperature tensile behavior of superplastic Ti-6Al-4V. Metall. Mater. Trans. A, 2002;33:83-92.
[10] Chen CC. Experimental study on punch radius and grain size effects in V-bending process. Mater. Manuf. Process., 2014;29:461-465.
[11] Jiang CP, Chen CC. Grain size effect on the springback behavior of the microtube in the press bending process. Mater. Manuf. Process., 20014;27:512-518.
[12] Salem A, Langdon T, McNelley T, Kalidindi S, Semiatin S. Strain-path effects on the evolution of microstructure and texture during the severe-plastic deformation of aluminum. Metall. Mater. Trans. A, 2006;37:2879-2891.
[13] Da Costa Viana CS, Pinto AL, Candido FS, Matheus RG. Analysis of ridging in three ferritic stainless steel sheets. Mater. Sci. Technol., 2006;22:293-300.
[14] Banovic S, Foecke T. Evolution of strain-induced microstructure and texture in commercial aluminum sheet under balanced biaxial stretching. Metall. Mater. Trans. A, 2003;34:657-671.
[15] Bach F, Behrens B, Rodman M, Rossberg A, Kurz G. Macroscopic damage by the formation of shear bands during the rolling and deep drawing of magnesium sheets. JOM, 2005;57;57-61.
[16] Huh M, Lee JP, Lee JC. Formation of a random texture and ultrafine grains in AA 3003 aluminium alloy during the repeated shear deformation introduced by continuous confined strip shearing. Mater. Sci. Technol., 2004;20:819-824.
[17] Cui Q, Ohori K. Grain refinement of high purity aluminium by asymmetric rolling. Mater. Sci. Technol., 2000;16:1095-1101.
[18] Stoudt M, Ricker R. The relationship between grain size and the surface roughening behavior of Al-Mg alloys. Metall. Mater. Trans. A, 2002;33:2883-2889.
[19] Walczuk DF, Vittal S. Bending of titanium sheet using laser forming. J Manuf. Process., 2000;2:258-269.
[20] Popovic M, Verlinden B. Microstructure and mechanical properties of Al-4.4 wt-% Mg alloy (AA5182) after equal channel angular pressing. Mater. Sci. Technol., 2005;21;606-612.
[21] Chang JS, Chou SS. Microstructural effects on formability of type 304 stainless steel sheet in cylindrical deep drawing. J Mater. Eng. Perform., 1994;3:551-559.
[22] Xu S, Weinmann K. A new approach to predicting forming limits of steel sheet. J Manuf. Process., 2000;2:158-166.
[23] Aghaie-Khafri M. Predicting flow localization and formability of aluminium alloy sheets. J Eng. Manuf., 2004;218:1313-1322.
[24] Male AT, Chen YW, Pan C, Zhang YM. Rapid prototyping of sheet metal components by plasma-jet forming. J Mater. Process. Technol., 2003;135:340-346.
[25] Hu Y, Luo M, Yao Z. Increasing the capability of laser peen forming to bend titanium alloy sheets with laser-assisted local heating. Mater Des 2016;90:364-372.
[26] Roumina R, Bruhis M, Masse JP, Zurob HS, Jain M, Bouaziz O, Embury JD. Bending properties of functionally graded 300M steels. Mater. Sci. Eng. A, 2016;653:63-70.
[27] Rafizadeh E, Mani A, Kazeminezhad M. The effects of intermediate and post-annealing phenomena on the mechanical properties and microstructure of constrained groove pressed copper sheet. Mater. Sci. Eng. A, 2009;515:162-168.
[28] Reeves M, Moore AJ, Hand DP, Jones JDC, Cho JR, Reed RC, Edwardson SP, Dearden G, French P, Watkins KG. Dynamic distortion measurements during laser forming of Ti-6Al-4V and their comparison with a finite element model. J Eng. Manuf., 2003;17:1685-1696.
[29] Benchabanea G, Boumerzoug Z, Thibon I, Gloriant T. Recrystallization of pure copper investigated by calorimetry and microhardness. Mater. Charac., 2008;59:1425-1428.
[30] Campbell FC, Ed. Elements of Metallurgy and Engineering Alloys. ASM International: Materials Park, OH; 2008.
[31] Askeland DR, Fulay PP, Wrigh WJ. The Science and Engineering of Materials. Cengage Learning: Stamford, CT; 2011.
[32] Gertsman VY, Birringer R. On the validity of the hall-petch relationship in nanocrystalline materials. Scr. Metall., 1989;23:1679-1683.
[33] Chen YC, Huang YY, Chang CP, Kao PW. The effect of extrusion temperature on the development of deformation microstructures in 5052 aluminium alloy processed by equal channel angular extrusion. Acta Mater., 2003;51:2005-2015.
[34] Doherty RD, Hughes DA, Humphreys FJ, Jonas JJ, Jensen DJ, Kassner ME, King WE, McNelley TR, McQueen HJ, Rollett AD. Current issues in

recrystallization: a review. Mater. Sci. Eng. A, 1997;238:219-274.

[35] Li YJ, Zeng XH, Blum W. Transition from strengthening to softening by grain boundaries in ultrafine-grained Cu, Acta Mater., 2004;52:5009-5018.

[36] Humphreys FJ, Prangnell PB, Bowen JR, Gholinia A, Harris C. Developing stable fine-grain microstructures by large strain deformation. Phil. Trans. R Soc. Lond. A, 1999;357:1663-1681.

[37] Tokutomi J, Hanazaki K, Tsuji N, Yanagimoto J. Change in mechanical properties of fine copper wire manufactured by continuous rotary draw bending process. J. Mater. Process Technol., 2012;212:2505-2513.

[38] Rathmayr GB, Hohenwarter A, Pippan R. Influence of grain shape and orientation on the mechanical properties of high pressure torsion deformed nickel. Mater. Sci. Eng. A, 2013;560:224-231.

[39] Goma FAT, Larouche D, Bois-Brochu A, Blais C, Boselli J, Brochu M. Effect of extrusion aspect ratio and test temperatures on fatigue crack growth behavior of a 2099-T83 Al–Li alloy. Int. J Fatigue, 2014;59:244-253.

[40] Latief FH, Hong SI. Effect of pressing routes on the microstructure and strength in equal channel angular pressing (ECAP) of Cu3.75Ag. Met. Mater. Int., 2015;21:746-752.