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Micro-crack Characteristics of Aluminum 1050 Sheets in Bending at Elevated Temperatures

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ABSTRACT
Used in several industrial applications, aluminum 1050 sheets have good balance between ductility and strength. Its corrosion resistance and reflectivity make it preferred alternative for food processing containers and light reflective panels. However, forming and bending processes affect its surface quality by the formation of micro-cracks within the forming zones and along the bending lines, downgrading its reflective and microbiological advantages. Raising temperature through direct flame on the deformation region during bending lead to improvement in surface quality along the bend line by reducing micro-crack widths. Other mechanical properties were also found to benefit from elevated bending temperatures, including springback and micro-hardness within the bend region. Nevertheless, benefits gained from elevated temperature were noticed to overturn between 100°C to 150°C depending on sheet thickness and the measured mechanical property. In general, behavior of mechanical properties appeared to reasonably correlate with the average micro-crack width on the bent surface.

Keywords: Aluminum 1050, Rotary Bending, Micro-crack, Micro-hardness, Springback, Temperature, Infrared.

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I. INTRODUCTION

Sheet metal of Aluminum 1050 alloy is widely used in different industries including construction, furniture, food, and chemical process plants. Its product applications range from food containers, chemical vessels, lighting fixtures, decoration panels, house appliances, and solar reflective films. Production cost of this type of Aluminum sheets is commercially reasonable with a single process. The 1050 alloy is recognized for its high ductility, outstanding corrosion resistance at warm temperatures, and highly reflective finish [1–4]. Despite its moderate strength, excellent workability and forming characteristics make it a favorable alternative for products that require bending and drawing processes. However, these forming processes affects the surface finish of products made of Aluminum 1050 sheets. For example, micro-cracks that result mainly from bending deformations degrade coating quality and reflection performance, normally needed in decorative products and reflective surfaces of lighting, respectively. Micro-cracks can also affect the health aspects and microbiological characteristics of vessels and containers used in food preparation and processing facilities.

Although the strength of the bend zone increases by strain hardening, vulnerability to fracture becomes higher with the strains associated with bending [5]. Micro-plasticity instigates micro-cracks that signify early signs of failure. The micro-cracks can propagate with the amount of plastic deformation to a point where they become visibly detectible [6]. They are initiated by strain localization that causes necking of grains close to the bending surface [7]. As a result, intergranular cracks start to appear due to the necking effect and tend to propagate leading to failure. Generally, other factors can positively affect crack propagation, or growth rate, such as crack length [8].

A few scholars experimentally investigated surface micro-cracks on sheet metal surface when subjected to bending processes. A study by Hatakeyama et al. in 2002 explored the development of micro necks during 90° bending of different Copper sheets, which lead to some surface wrinkles [9]. They discovered that deformations tend to be minor towards the tips between the wrinkle grooves. In the same study, average width of micro necks and wrinkle grooves, found on the outer surface of the bent copper sheets, were measured and found to increase with the ratio of the width to the thickness of the bent copper sheets. If forming exceeds material formability limits, most cracks do not tend to propagate during deformation due to intense fracture that is usually concentrated in other deformed regions [10]. Occurrences of micro-cracks were also verified to be positively related to the bending angle for other sheet materials such as steel [11]. For instance, micro-crack average width for high strength steels can exceed 50µm when bending angles reach 160° [12].

Grain direction in sheet metal can affect crack manifestation within the deformation region. Although it requires higher forming force, bending across the direction of sheet metal grains, transversely, yields less cracks along the bend line, and vice versa. However, bendability of aluminum sheets depends on other factors such as the chemical composition of the sheet alloy and the prior heat-treatments [13]. Introduction of heat during forming can alleviate damage instigated by factors related to chemical composition, grain direction, and prior heat-treatments. Below-recrystallization heat in this case can be administered through the forming tool to avoid difficulties associated with formability. For example, raising the forming tool temperature to 250°C could yield 300% elongation for certain aluminum alloys, which facilitate complex shape deformations needed in products like automotive body components [14]. On the other hand, bent surface quality in terms of cracks, for magnesium sheets, was also found to be positively affect by higher forming temperatures [15]. Beside softening the deformation zone through heated forming tools, laser was also used to elevate temperature locally, in an attempt to decrease flow stress and improve formability, especially in laser-assisted bending processes [16].

Local heating through forming tools or laser has other advantages not directly related to forming limitations and surface quality. Reduction in springback and punch forces were also achieved by increasing forming temperature, to a certain extent, especially for certain Aluminum alloys [17]. The punch force can be reduced 30% in laser-assisted bending of high-strength steels [16]. In contrast, chemical and microstructural characteristics are the key influential factors in the elastic properties of any metallic alloy. Higher yield strength leads to increased elasticity causing wider angles of springback and, eventually, less forming accuracy [16]. Furthermore, the bend angle has also a positive relationship with springback [18]. Other mechanical properties such as elasticity and hardness of the deformed material are presumably correlated with the extents of the forming processes. These properties can also be affected by the temperature at which these processes are performed.

Rotary bending, also called folding or swivel bending, is a popular process of sheet metal forming especially in automated setups with CNC folding machines. In this process, product holding is performed on one side of the sheet metal via a holding die while the other end of the bent sheet is allowed to freely slide over a rotating die, diminishing any secondary stretching of the bent product. Adoption of this type of bending in this study was based on its ability to reduce the secondary drawing forces commonly found in other bending processes, such as V-bending. Nevertheless, the pure bending forces in rotary bending, along the tension layers of the deformation zone, are still presumed to cause some surface degradation on the outer surface of the bending line. Such degradation is originated by the formation of micro-cracks that reduce the overall quality of the processed product. Literatures are scarce on the topic of micro-crack quantification in bending and its relation to springback and hardness. Moreover, attempts to reduce the development of surface micro-cracks in deformed sheet metal, that degrade surface smoothness and reflectivity, were not evident in the reviewed literature.

The aim of this work is to study the effect of temperature on the bending surface quality of aluminum AA1050 sheets when subjected to rotary bending. Within the study context, the relationships among springback, micro-hardness, and micro-crack average width within the deformation zone will also be explored. Limiting the introduced heat to the deformation zone in rotary bending, through a focused flame, is hypothesized to enhance the bending surface quality without causing shape distortions. The expected results from this paper could be also useful to other scholars for the prediction of fracture development and deformation limitations of aluminum sheets when forming under different elevated temperatures.

II. MATERIALS AND EXPERIMENTAL SETUP

Sheets made of aluminum alloy AA1050 were used in this study with a composition shown in Table 1. They were commercially produced by rolling to different thicknesses of 0.5, 1.0, and 1.5 mm. The sheets used to prepare the experimental specimens are representing the most popular specifications demanded by local manufacturing to fabricate different types of products including food and chemical containers, decorative panels, lighting fixtures, and appliance body components. The specimens were sheared from the sheets to a size of 80×70 mm.

Table 1 Nominal composition (wt %) of studied Al 1050 (AA1050A/S1B).

Element	wt (%)	Element	wt (%)
Al	99.41	Sn	0.02
Fe	0.39	Mn	0.01
Si	0.09	V	0.01
Cu	0.05	Ga	0.01

Bending of the prepared specimens was performed by a folding die rotated through an electrical actuator. Speed of bending, folding, was constant at 2.5 mm/sec. Before initiation the bending process, the specimens were clutched between a two-part holding die with a bend radius (R) of 0.5 mm. The rotating die was 50 mm long and bent all specimens to a fixed angle of 135°. Bending line was always perpendicular to the rolling direction of the aluminum sheets. The rotary bending setup used in this experimental study is shown in Fig. 1. Rotary bending was adopted in this experimental study due to its substantial capability of reducing the drawing forces usually endured in other bending processes such as V-bending. This complies with the objectives of this study where micro-crack investigation, on the outer surface of the bent sheets, has to be related to the forces associated with bending action alone. Interference caused by the drawing effect was minimized in the adopted process, unlike other bending processes where the holding friction is applied on both sides of the bent sheet. Rotary bending also reduces contact between the bending die and the outer surface of the bent sheet within the bend region, avoiding scratch marks that might disturb the natural development of micro-cracks.

Heating the tool to improve forming performance is commonly adopted in the literature [15, 19, 20]. Moreover, forming with partial heating of the tool at the deformation zones demonstrated even better results than the homogeneous heating of the entire tool [14]. However, instead of heating the die itself to raise the sheet temperature, a more direct approach of heating limited to the deformation zone, through a flame focused on the bend line, was implemented in this experimental study. Different factors lead to the adoption of such approach, among which are applicability, reduction of energy, setup costs and speed of heating.

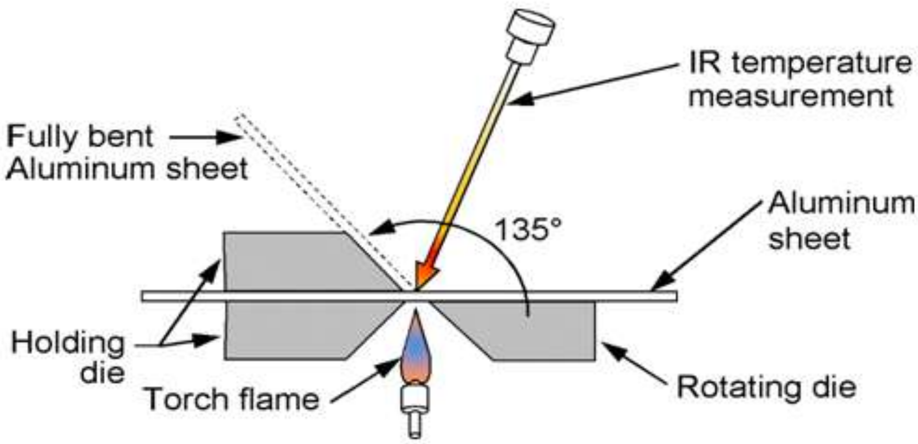

Fig. 1 Experimentation setup for rotary bending of Aluminum 1050 sheet under elevated temperatures.

Before initiating the rotary bending process, a concentrated torch flame was focused on the lower surface of the aluminum sheet along bending line. Sheet temperature measurement took place on the opposite surface with an infrared temperature sensor, after being adjusted for the energy emittance produced naturally by the aluminum sheet. After reaching the required temperature, within 5-15 seconds, the folding action starts until reaching a bend angle of 135°. As the heating flame was focused on the bending line, pre-experimental trials have shown no signs of warping on the bent sheet. Based on the experimental design of this study, three specimens of each thickness were bent under each preset temperature. Thus, each measured property in this study represents the average of three tested specimens under the same conditions. Bending temperatures were 27, 75, 100, 125, 150, and 200°C. Experiments were performed at different combinations of sheet thicknesses and temperatures, progressively, to detect the optimum points where temperature has a positive effect on the bending process, in terms of micro-crack and springback reduction.

At 200X magnification, each individual micro-crack on the top bent surface was identified by determining its longitudinal dimension. The width of each visible micro-crack was assessed by measuring the maximum distance between groove verges perpendicular to the micro-crack longitudinal direction, using an optical microscope and a calibrated metallurgical measurement software. All micro-cracks widths were measured on the top convex surface of the bent aluminum specimens within an area of 500×800μm, in the middle of the bend line. Fig. 2 illustrates the area where the micro-cracks were measured. Micro-crack widths were averaged for each experimental condition.

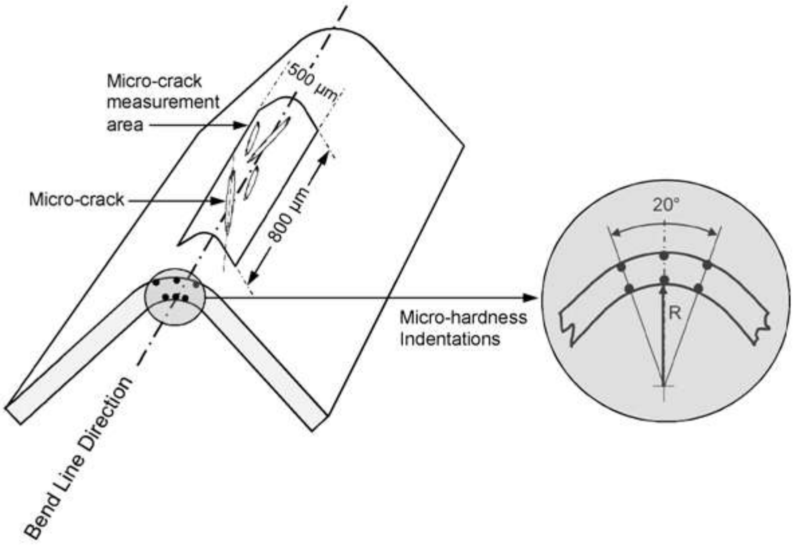

Fig. 2 Micro-crack measurement area on the top surface of the bent aluminum specimens and micro-hardness indentation locations.

After performing the rotary bending of the aluminum sheet specimens, other mechanical properties were assessed including micro-hardness and springback. Springback angles were measured by an optical comparator for each bent specimen under each experimental condition, thickness and temperature. The 1.5 mm thick specimens were split after bending across the bend line by a low speed saw. The cross-sectional surfaces were prepared by fine polishing for micro-hardness indentations. Vickers' micro-hardness was measured on the cross-sectional surface of the bent specimens at the bend region to evaluate the influence of bending strain and temperature. The indentations were made on the compression and tension layers within the bend region, close to the outside and inside surfaces of the bent sheet, within 200µm from the outer edges of the deformed layers. It was also performed on the flat flange surface away from the bend region emulating the neutral line between the deformed layers. Six indentations were made on the cross-sectional surface of the bend region, two on the bend centerline and two approximately 10° from the centerline on each side. The indenter was pressed into the metal with a load of 100 gf (gram-force) for a period of 10 seconds.

III. RESULTS AND DISCUSSION

Micro-cracks on the top convex area of the bent aluminum sheets are evident in all bending temperatures. Fig. 3 shows examples of these micro-cracks for 0.5 mm thick aluminum 1050 sheets bent under different temperatures. The mechanism proposed in this research to raise the processing temperature appeared to improve bent surface quality.

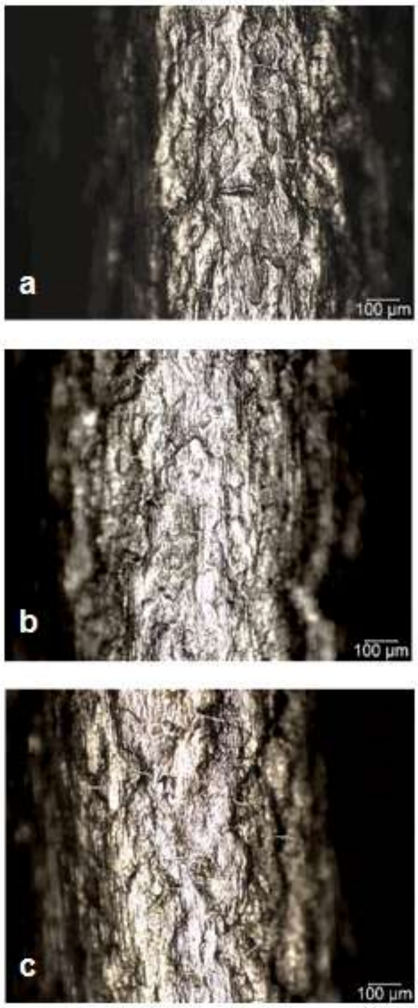

Fig. 3 Examples of micro-crack development on the top convex surfaces of 0.5 mm thick aluminum 1050 sheets after bending under: a) 200°C, b) 150°C, and c) 100°C.

Compared to other modified bending processes, such as laser-assisted bending, costly installation and high-power requirements were avoided in the proposed setup. In addition, processed product warping and shape distortion, frequently reported in laser bending, did not occur under all forming temperatures tested in this study. The outcomes of the adopted setup were investigated through the mechanical properties and the quality aspects of the processed product. These include the widths of the micro-cracks within the bending region, micro-hardness on the cross-sectional plane, and springback. Fig. 4 shows SEM image of a micro-crack development on 0.5 mm thick aluminum 1050 sheet bent at 100°C.

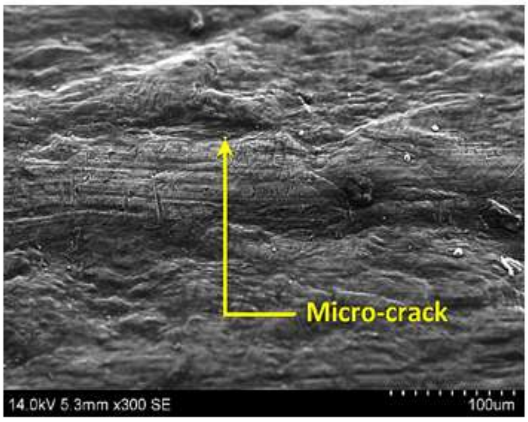

Fig. 4 SEM image of a micro-crack on 0.5 mm thick aluminum 1050 sheet bent at 100°C.

The average width of micro-cracks appeared to have a negative relationship with the forming temperature. Fig. 5 shows average micro-crack width in relation to sheet thickness and bending temperature. For 0.5 mm and 1.0 mm thick sheets, rise in bending temperature up to 150°C continues to reduce average micro-crack width by approximately 50%. This behavior accords with the logical inverse relationship between forming temperature and the strength and elastic modulus of metallic materials, and the direct relationship between temperature and metal ductility. It is also consistent with the familiar negative relationship between forming temperature and necking initiation. As bending temperature increases, average micro-crack width decreases due to added relief in the strain hardening of the deformation process, reduction in concentrated strains, and smoother slipping movements in the material microstructural scale. However, the reduction in micro-crack width in relation to bending temperature starts to reverse when the bending temperature rises above 150°C.

Such overturn can be attributed to the decreasing yield stresses that lead to increased deformation capacity before reaching the ultimate fracture point. On the other hand, aluminum alloys have low recrystallization temperatures that typically drop below 190°C, depending on purity, annealing temperature, and work hardening [21, 22]. Thus, when bending at temperatures are close to the recrystallization range, above 150°C in this material, bonds among aluminum grain boundaries start to loosen further allowing them to detach at greater rates and, eventually, leading to more growth in preexisting micro-cracks instead of initiating new ones.

Similarly, sheets that are 1.5 mm thick show comparable relationship but with 40% reduction in average micro-crack width attained at approximately 100°C, where the effect of bending temperature on average micro-crack width begins to reverse beyond 100°C. However, average micro-crack width appears to increases as the thickness of the bent sheet increases, especially at higher bending temperatures, as shown in Fig. 5. As bent sheets become thicker, greater deformation resistance caused by thicker bending layers leads to higher amounts of stresses and strains along these layers, especially at the outer fiber of the tension layer near the sheet convex surface. The variations in stresses and strains, caused by differences in sheet thickness, occur even if the rotary bending angle and speed are kept identical. Consequently, thicker sheets endure additional work hardening effect causing greater hardness and wider micro-cracks along the tension layer of the deformation zone. Furthermore, strain variations through sheet thickness become more apparent when bending thicker sheets, reflecting a plain-strain state of stress. Thus, higher strains occur near the sheet convex surface leading to more vulnerability to micro-crack expansion.

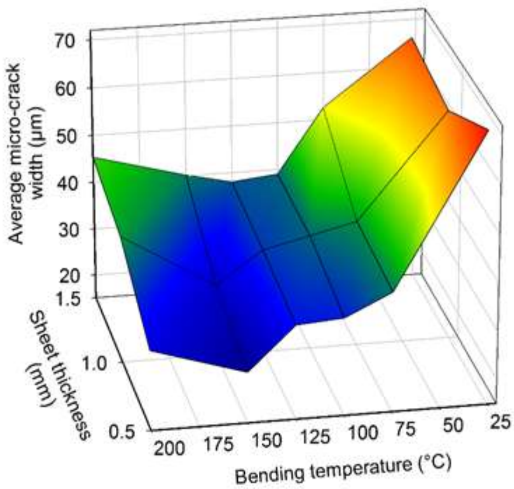

Fig. 5 Average micro-crack width in relation to sheet thickness and bending temperature for aluminum 1050.

Raising bending temperatures can also lead to additional expansions in the already developed micro-cracks instead of developing new ones, based on the localized necking phenomenon. The negative relationship between sheet thickness and surface quality at the bend region suggests a design limitation for bending aluminum 1050 sheets with reference to bending temperature. As apparent in Fig. 5, this relationship becomes more noticeable when bending temperature exceeds 125°C, since temperature rise beyond this limit contributes to further growth of micro-cracks that can develop to a full-scale fracture. Weak triple points along the grain boundaries associated with low recrystallization temperature levels of aluminum 1050 facilitate such micro-crack expansion when bending at temperatures above 125°C.

Most studied metallic alloys normally benefit from elevation in forming temperatures to reduce springback [23–26]. In contrast, aluminum 1050 sheets demonstrate opposite behavior when subjected to rotary bending, which can be related to the trends of micro-crack widths as discussed earlier in this section. As illustrated in Fig. 6, springback angle increases with higher bending temperatures for all tested sheet thicknesses, up to 125°C. Very few experimental studies in the available literature indicated a positive relationship between springback and bending temperature [27]. Since raising bending temperatures causes reduction in micro-crack widths, as discussed earlier, necking development in the tension layer was less probable. The reduced necking probability leads to more conserved elasticity in the bent sheet, causing greater springback. In contrast, springback starts to decrease beyond the 125°C, suggesting a temperature limit where microstructural bonds begin to fail and localized strains, caused by stress concentrations, start to dominate the deformation behavior.

Although sheet thickness was widely reported to have negative affect on springback for other alloys [28, 29], aluminum 1050 shows a positive relationship between springback and sheet thickness for all tested temperatures. This can be attributed to the substantial reduction in overall stretching forces accomplished in rotary bending compared to other types of bending. Lowering the drawing forces during bending thicker sheets increase molecular density and crystallographic distortions in the compression layer along the bend region, at the inside surface of the bent sheet, causing higher deformation resistance in the inner bending layer than the outer one. Such difference in deformation resistance between the compression and tension layers flexes the sheet outwards, especially since the compressive strengths of metals are usually higher than their tensile strengths.

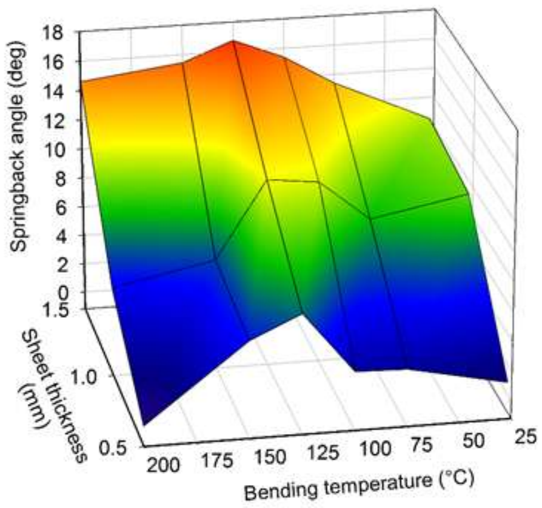

Fig. 6 Springback relationship with sheet thickness and bending temperature for aluminum 1050 in rotary bending.

Vickers indentations were performed according to the specification set earlier in the methodology section. The results of micro-hardness and average micro-crack width in relation to bending temperature for the aluminum 1050 sheets are summarized in Fig. 7, for a sheet thickness of 1.5 mm. As anticipated, the behavior of micro-hardness in both deformation layers, tension and compression, seems to relate to micro-crack width regardless of plotting scales. Increase in bending temperature up to 100°C improves sheet ductility in the bending region by reducing its hardness in the tension layer which, consequently, decreases the progress of micro-cracks on the bent surface. However, these trends for both properties seem to diminish between 100°C and 125°C. Moreover, the reduction in micro-crack widths appears to reverse as the bending temperature crosses the 125°C limit regardless of any additional decline in micro-hardness. This can be attributed to the overwhelming effect of necking development beyond the 125°C level, which is instigated by the reduction in bonds among aluminum grain boundaries. Particularly, relief of stain hardening by the added effect of heat does not seem to keep up with necking progress beyond 125°C. As in other metallic materials, the increase in micro-hardness values in the outer and inner fibers of the bent aluminum sheets between 125°C and 150°C can also result from the deformation resistance caused by dynamic strain aging [30].

Similar behavior and outcomes are evident when comparing micro-hardness on the compression layer, at the bend inner surface, with micro-crack width, as in Fig. 7. Micro-hardness value in the compression layer is higher than its value in the tension layer for room temperature bending, supporting findings in earlier studies for different Aluminum alloys [31]. Conversely, such difference diminishes at elevated temperature bending. The same figure also suggests more influence of temperature on the compression layer of bending than the tension layer. On the other hand, no clear relation was noticed between micro-crack width and micro-hardness along the non-deformed region of the aluminum sheet, at the flat flange, as apparent in Fig. 7. Since no process-related strain hardening exists at the flat flange, excluding the original hardening caused by the rolling of the sheet during production, the effect of temperature on hardness is minimal.

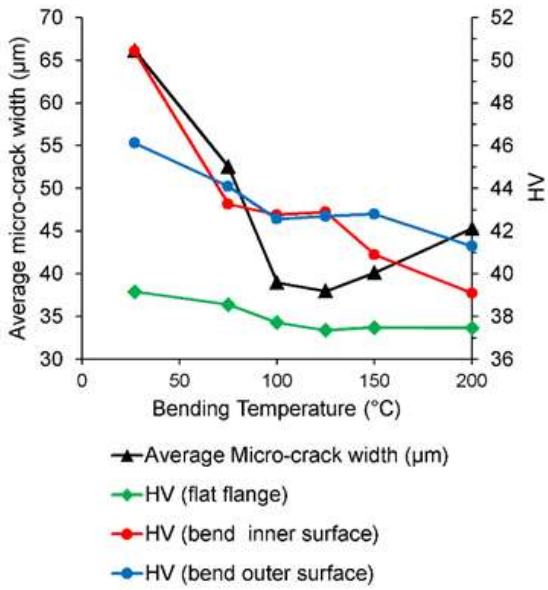

Fig. 7 Average micro-crack width and Vickers' micro-hardness in relation to bending temperature at bend outer surface, bend inner surface, and flat flange for 1.5 mm thick aluminum 1050 sheets.

By relating the trends of micro-crack width and springback for aluminum 1050 sheets when subjected to rotary bending under elevated temperatures, a threshold point at which these sheets benefit from temperatures can be detected. Raising bending temperature up to 125°C increases springback angle and, simultaneously, improves the aluminum sheets surface quality at the bending region. In contrast, the opposite takes place when bending temperature exceed the 125°C threshold. Knowing the threshold of this trade-off in bending quality, expressed by surface micro-cracks and springback, can be beneficial for designers to calibrate the process based on the type of quality desired in the final product.

IV. CONCLUSION

Applying conventional focused flame directly on the bend line during rotary bending provided a rapid rise in temperature at the deformation region. Beside its practicality, this adopted method of heating is cost effective and did not generate any noticeable distortion in the bent sheets. It also enhanced the surface quality of the bent aluminum 1050 sheets by reducing micro-crack widths on the outer bent surface. However, the accomplished improvement in surface quality diminished after reaching a temperature range of 125°C to 150°C, depending on sheet thickness. In contrast, springback demonstrated contradicting pattern where its reduction was accomplished only at temperatures above 125°C, for all tested sheet thicknesses. Contrary to common knowledge about metallic materials, thickness of aluminum 1050 sheets exhibited a positive relationship with springback for all bending temperatures.

Micro-hardness behavior in the tension and compression layers of the bent aluminum sheets appeared to correspond with the average micro-crack width below 125°C bending temperature, and vice versa. This threshold in bending temperature suggests that aluminum 1050 undergoes fundamental change in its microstructural characteristics at around 125°C. Dynamic strain aging between 125°C and 150°C also overturn the decline in micro-hardness in this range. However, micro-hardness resumes decline beyond this range due to softening. The trade-offs among the studied properties and other mechanical and microstructural properties for aluminum 1050 sheets, such as fracture toughness, necking development and grain recrystallization, pose as promising subjects for future research to further enhance our understanding of this material and its processing temperature limitations.

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