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ORIGINAL ARTICLE

Pin axis effects on forces in friction stir welding process

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Abstract In this paper, the effect of the position of the pin relative to tool shoulder has been investigated in the process of friction stir welding on aluminum 5083. Firstly, the preparation of the process was performed that included tool, workpiece fastened to dynamometer by special fixture, and milling machine. A test was performed by a tool with pin coaxial with the axis of tool shoulder in this process. So, the tool entered the edges of joint location and moved along the joint line. Force in joint region was measured during the process. Then, the parameters of the shape and the position of tool pin changed and joint test was performed. The shape of the tool changed by offsetting the axis of tool pin relative to the axis of tool shoulder with different designs, and the results of welding forces were considered.

Keywords Friction stir welding (FSW) · AA5083 aluminum alloy · Welding force · Tool pin shape · Shoulder

1 Introduction

Friction stir welding (FSW) is a solid-state welding process introduced by Thomas et al. in the welding institution TWI [1]. In the FSW process, a metal never reaches its melt temperature and weld is produced with high quality and low welding defects. In this process, an inconsumable rotational tool is used for the generation of friction heat and plastic deformation in the direction of the weld. Designing of a suitable tool can improve weld quality and maximize possible speed of the weld [2–5].

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The behavior of material flow is mainly affected by the profile of the shape of tool pin and the parameters of friction stir welding process. Very high rotational speed can increase strain rate and it affects recrystallization. The properties of the pin play a vital role in material flow and the adjustment of the parameters in friction stir welding process. FSW has been characterized by nugget and defined flow lines as well. In almost all pins with circular section, flow lines depend on tool design, welding parameters, and the conditions of used process [6–10]. Critical parameters that affect forces and internal temperature in FSW process include rotational speed, translational speed, shoulder diameter, and tool pin. A tool with a shoulder diameter of 18 mm and the profile of square pin has shown very good tensile property. When a pin has more ability for mixing materials and creating necessary conditions of material flow from the front of the pin to the back, it can improve mechanical properties of the weld and decrease welding forces [11–13].

In welding of two different materials, the harder material is in advancing direction and tool axis relative to joint is offsetted toward the softer part in order to achieve desirable welding [12, 14].

Elangovan and Balasubramanian [13] used five tool pins with different shapes to find the effect of tool pin profile on FSP zone formation in aluminum 6061. They found that square pin could offer the best mechanical and metallurgical properties compared to other pin profiles. They also studied FSW on AA2219 aluminum at three different welding speeds and five pin shapes in another research [15]. They reported that square pin offered the best results. Padmanaban and Balasubramanian [16] studied friction stir weld AZ31B magnesium alloy with five pin profiles, five tool materials, and three tool shoulder diameters. They could find the best pin profile, tool material, and tool shoulder diameter regarding the metallurgical and mechanical characteristics of the produced welds. Song et al. [17] investigated the effect of probe offset distance on the interfacial microstructure and mechanical properties of weld in friction stir butt welding of titanium alloy Ti6Al4V and aluminum alloy A6061-T6. They found that in a proper range of probe offset distance, sound dissimilar butt joints, that have comparatively high tensile strength and fracture in heat-affected zone of the aluminum alloy, can be produced.

In FSW, forces on tool/pin are considerable so it is important to predict them [18] and to find the best pin shape having the greatest strength against forces. In addition, the effect of the offsetting of the axis of tool pin relative to the axis of tool shoulder in FSW has not been considered in researches. In this paper, the offsetting of the axis of tool pin with different shapes relative to the axis of tool shoulder (on workpieces with the same materials that tool axis (shoulder) and joint are at the same direction) and its effect on welding forces are studied. Then, optimum conditions are obtained by the change of the parameters rotational speed and translational speed.

2 Process preparation and test performance

Four tools from AISIH13 have been used in this research. Figure 1 shows tools used in friction stir welding process.

According to Fig. 1, these tools with a shoulder diameter of 18 mm, pin diameter of 5.5 mm, angle of 9°, and pin height of 3.85 mm have different shapes of pins. They include pin without thread, concentric cone-shaped pin with tool shoulder (Fig. 1(C)), offset cone-shaped pin relative to tool shoulder with the size of 1.5 mm (Fig. 1(O)), tool with half cone-shaped

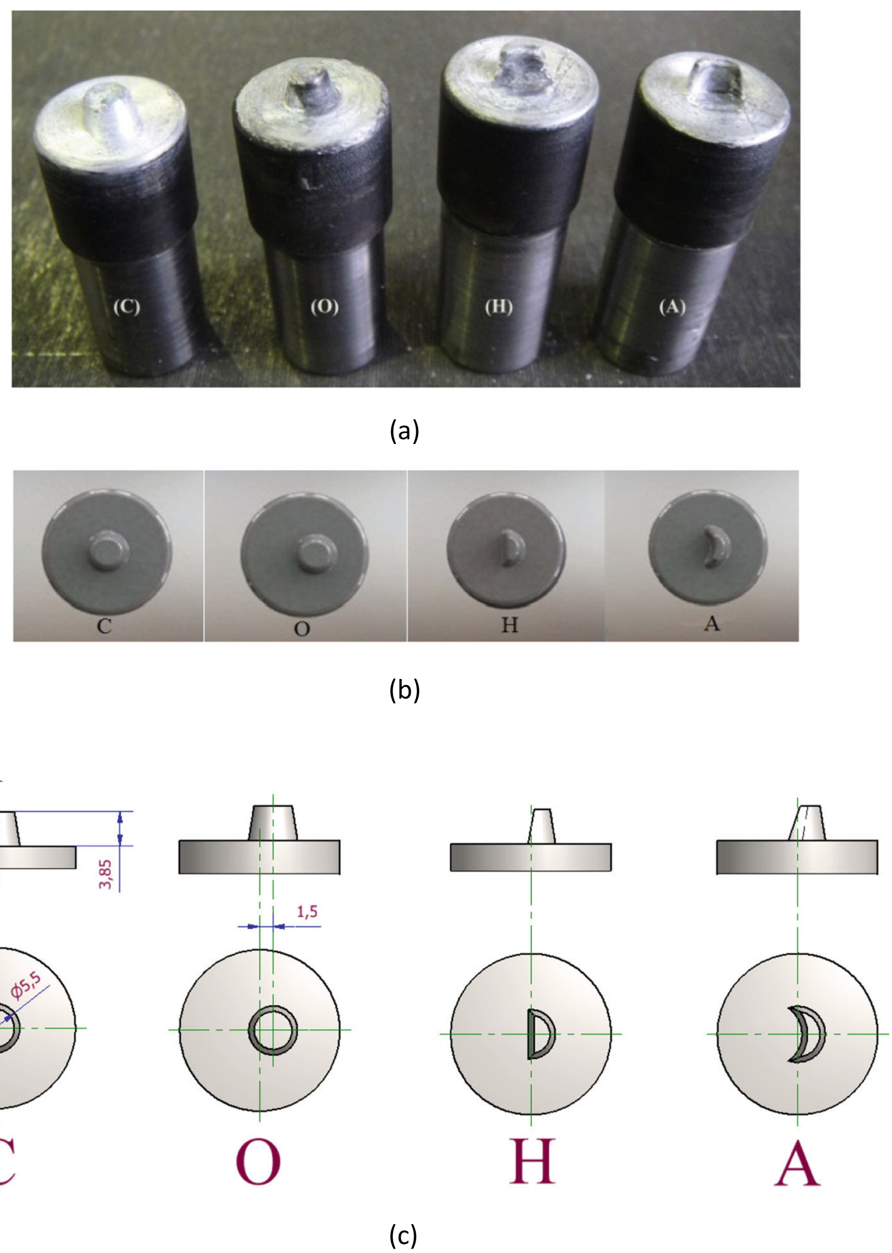


Fig. 1 Different shapes of tool pin and their positions. *C* concentric cone-shaped pin with tool shoulder, *O* offset cone-shaped pin relative to tool shoulder, *H* tool with half cone-shaped pin, *A* tool with cone-shaped arched pin. **a** Madden tools, **b** pin tip, and **c** dimension of pin tip

pin made of concentric pin with tool shoulder (Fig. 1(H)), and tool with arched pin made of concentric pin with tool shoulder (Fig. 1(A)). These tools have been machined with good precision and then they have been hardened at the rate of 48 RC.

The workpiece of the tests is from plates AA5083 with dimensions of 120 mm×60 mm×4 mm. The chosen welding parameters are shown in Table 1.

As Table 1 displays, tests are performed with different rotational speeds, and the effects of these parameters of FSW are considered for different tools. A dynamometer (9257B, Kistler Co.) has been used for the measurement of welding forces. The dynamometer is located under welding fixture so that its axis *Z* is in the direction of tool axis and its axis *Y* is in the direction of the welding, and process forces can be measured in vertical direction (tool axis) and welding direction (travel). Necessary fixture of workpieces is designed so that it can reduce the transfer of welding head to the dynamometer. Figure 2 shows a view of test preparation for friction stir welding process.

After the preparation of the process and necessary equipment, tests were performed on the workpieces of aluminum. Workpieces were tested with four rotational speeds and two translational speeds for each tool, and in total, 32 tests were performed. The parameters of rotational speed and translational speed were adjusted and the tool was installed on spindle and the workpiece was placed on fixture and dynamometer for the performance of the test. When welding process started, force changes were shown and saved by the dynamometer. Figure 3 shows the workpieces that resulted from the FSW process.

Fig. 2 A view of the preparation of friction stir welding process

3 Test results and discussion

The dimensions of the pin and the shoulder and the profile of tool pin are very important in the FSW process [12]. Therefore, effective pin dimensions in FSW process can be changed by the change of the position of the axis of tool pin relative to tool shoulder. Figure 5 shows effective pin dimensions in the tools.

According to Fig. 4a, the part of the pin that is concentric with the axis of tool shoulder in rotation state is shown with black color. This part of the pin is not deviated from the center of tool axis and it is symmetric. The part of the pin that is offset (eccentric) is shown in gray color (light and dark). So, when the pin rotates around tool axis, its position changes moment by moment. As shown in Fig. 4a, the lines on top view show pin position in a moment. It is necessary to offset the pin from the center of tool axis in order to make small effective pin dimensions. The pin cannot be offset completely because the diameter of tool shoulder is constant in this research. In this state, complete rotation of the pin around the axis causes the occupation of much space and less surface of the shoulder remains. Therefore, a small area of the shoulder has contact with the surface of the workpiece. In order to avoid excessive enlargement of rotational space of the pin,

Table 1 process parameters

Rotational speed (rpm)	Translational speed (mm/min)		Tool tilt angle (°)
560	63	100	1.5
900	63	100	1.5
1120	63	100	1.5
1400	63	100	1.5

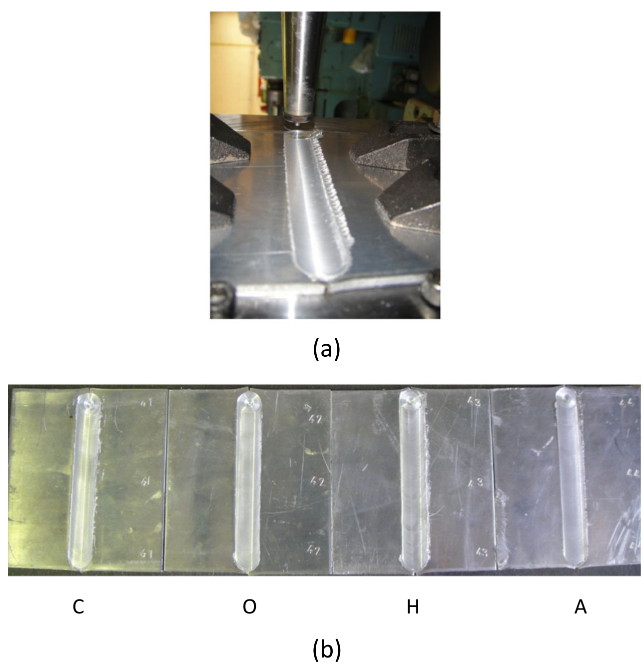
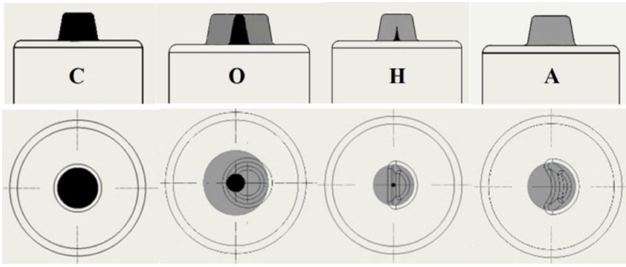
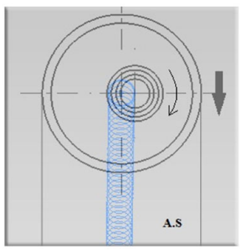


Fig. 3 Specimen of welded workpieces in FSW process **a** in process and **b** for four tools



(a)



(b)

Fig. 4 **a** A view of effective pin dimensions in the tools: concentric pin with tool shoulder (tool C), offset pin relative to tool shoulder (tool O), tool with half pin (tool H), tool with arched pin (tool A). **b** A view of pin movement rotating in tool O

tool H is considered as half, tool A as arched, tool O as offset spherical, and tool C as concentric spherical. Effective pin dimensions and the surface of tool shoulder on tool O is less than in tool C, effective pin dimensions in tool H is less than in tool O, and the surface of tool shoulder on tool H is more than in tool O. In tool A, pin is completely offset and effective pin dimensions are zero and shoulder surface is bigger than in tool O. The hole created by rotating tool C in immersion phase has the same size as pin dimensions. In tools O and H and A, this hole is bigger than the pin dimensions. Therefore, rotating pin occupies just a part of the hole each moment and the remaining space is empty as shown in Fig. 4a with dark gray color.

Pin movement in tool C is continuous along with a straight direction during rotating and moving in joint direction because pin is coaxial with tool axis and materials face much compaction when they are transferred from the front to the back of pin. According to Fig. 4b, in tool O, rotating pin moves in a spiral direction because of offsetting of the pin relative to shoulder axis during advancing phase. In this way, we face very good conditions of materials transfer. So, in each rotation of the tool, little materials use empty space of the pin and they are transferred to the back of the pin. The pin repeats it alternatively because the tool has rotational movement. Tools H and A benefit from spiral and alternative movement like tool C and they have better conditions of materials transfer compared with tool C, but they are not so strong compared with tool O because the empty space of pin margin in the hole is small in immersion phase.

Measured forces are vertical force (in the direction of tool axis) and welding force (in the direction of travel) in this research. The maximum vertical force and maximum welding force after tool penetration along welding direction for four tools are shown in graphs. Figure 5 shows the graphs of vertical force with two translational speeds (63 and 100 (mm/min)) and the change of rotational speed.

With regard to the graphs of Fig. 5, offsetting the axis of tool pin relative to the axis of tool shoulder (tool O) reduces the vertical force considerably about 50–70 % compared with the tool with concentric pin with tool shoulder (tool C). Vertical forces decreased in tool H and tool A by about 10–20 % compared with tool C. In tool O, with regard to offset tool pin, at the beginning of the welding when the tool is in immersion phase, the hole created by the pin is bigger than that in tool C and the pin occupies just half of the hole and another half is empty and just effective surface of tool shoulder contacts with workpiece. In tool C, the hole size is the same as pin dimensions in immersion phase and the surface of tool shoulder contacts with the surface of workpiece completely. In tool C, when the tool begins advancing movement in order to pass joint direction, material transfer from the front of the pin to the back exerts much pressure and force on the tool because of material forging. In tool O, the pin rotates in a big hole in immersion state, and at the beginning of the movement in joint direction, material transfer from the front of the pin to the back exerts less pressure and force because there is enough empty space around the pin, and materials face less compaction and tool shoulder exerts less force as forging. During the rotation of tool O, the area of shoulder surface involved with the workpiece decreases. In other words, effective surface of tool shoulder decreases and this leads to the decrease of vertical force. In addition, that part of the shoulder occupied by the pin instantly does not have fixed position and it cannot exert much force from the tool to the workpiece and forging force from that part of the shoulder that is not in rotation region is exerted on the workpiece. The decrease of total pin volume and of effective pin volume has decreased forces. So, shoulder area of tool H and tool A are approximately equal to tool C and forces have decreased about 20 %. In tools A and H, holes created in immersion phase are bigger than pin dimensions. So, the pin occupies just half of the hole and less pressure is exerted on it during advancing materials compared with tool C. As a result, less force is exerted on tool shoulder. In addition, when the surface of tool shoulder is big, friction force and forging are exerted on bigger part of workpiece surface and force reduction is less in comparison with tool O.

Vertical force in Fig. 5b with translational speed of 100 mm/min has decreased compared with vertical force in Fig. 5a with translational speed of 63 mm/min, and the increase of rotational speed has decreased vertical force in tool C but it does not have a significant effect on other tools.

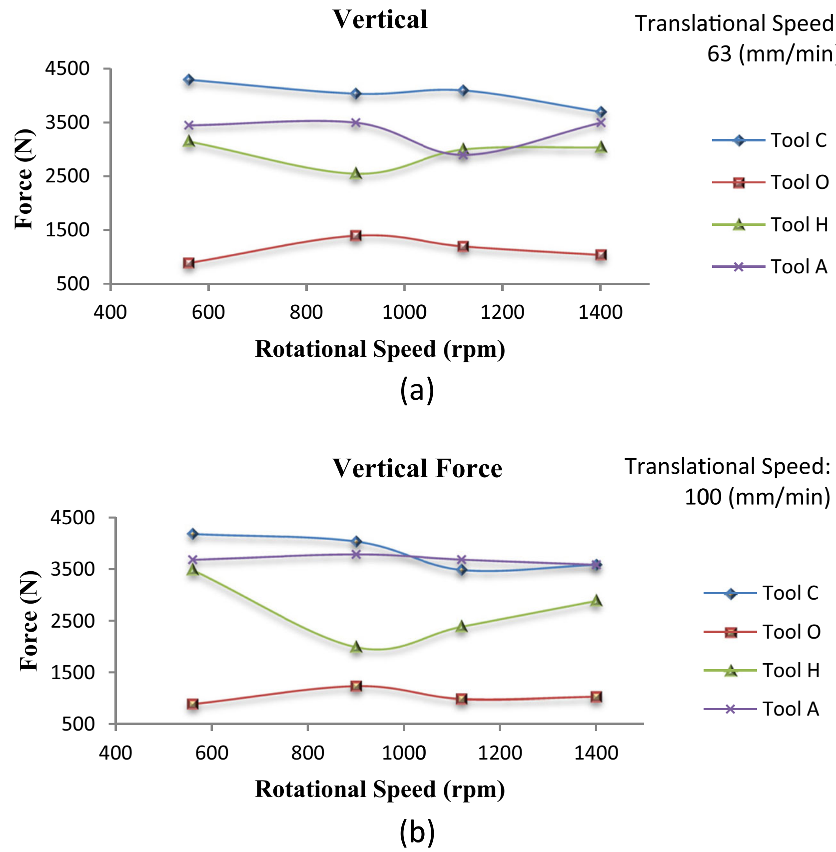
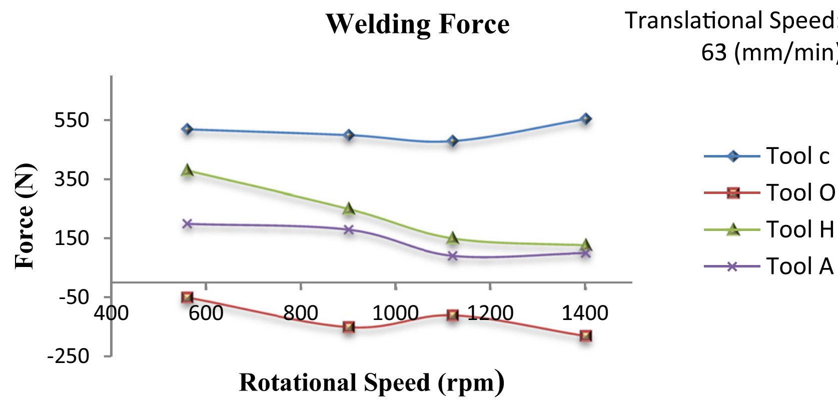


Fig. 5 The effect of rotational speed on vertical force. **a** Translational speed 63 mm/min and **b** translational speed of 100 mm/min in the FSW process with tools: concentric pin with tool shoulder (tool C), offset pin relative to tool shoulder (tool O), tool with half pin (tool H), and tool with arched pin (tool A)

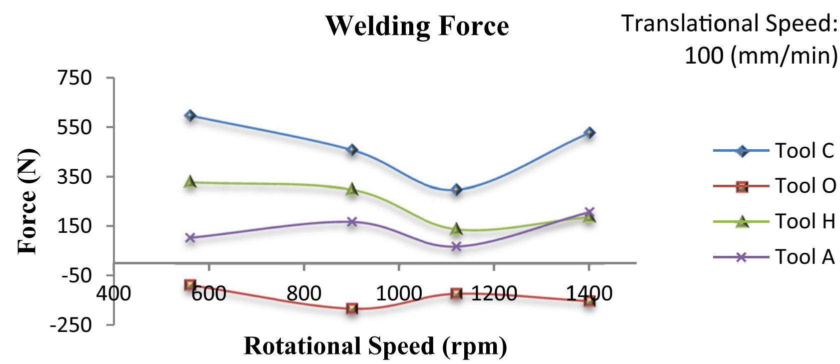
Figure 6 shows the graphs of welding force in the direction of tool advancing with two translational speeds of 63 and 100 mm/min for four tools and the change of rotational speed.

Shoulder diameter and tool pin are effective critical parameters on forces in FSW process [11]. With regard to the results of Figs. 5 and 6 and the analysis in Fig. 4, the results are interpreted in this way: when tool with concentric pin with shoulder axis rotates (tool C), whole pin rotates around itself, and whole pin dimensions are effective in this state. But with offsetting tool pin relative to tool shoulder (tool O), that part of the pin rotating continually around itself creates effective pin dimensions that have constant volume in rotation state and it is smaller compared with tool C, because whole pin rotates around itself on tool C but offset part of the pin rotates around the axis of tool shoulder in tool O and it does not have fixed position in rotation state and effective pin becomes small. In addition, effective area of tool shoulder decreases with offset pin and because axial force depends on shoulder area, the decrease of effective area of tool shoulder causes the decrease of axial force. With regard to high speed of rotations, materials under tool shoulder with offset pin are in forging state and they do not have exit way and are transferred from the front of the pin to the back. Offset part of the pin causes better mixing of the materials and the transfer from the front of the pin to the back. Occupied space is big in rotation state in tool O because effective pin is small. Therefore, welded space is bigger than other tools and better welding is produced. The only disadvantage of this tool (tool O) is the remaining big hole in the late pass of the welding.

According to Fig. 6, tool C has the maximum welding force. Because of concentric pin with shoulder axis, whole pin of tool C is effective in welding process. But forces decrease with offsetting the pin and the smallness of effective pin. There is a decrease of welding force in tools H and A (about 40 %) because the pins are offset and they have edge shape and they split the materials as sharp edges and forces decrease with these tools. The decrease of welding force in tool A is more than that of tool H, because its pin has an arched shape. In tool O, forces are negative. It shows the pin tends to draw plates toward it. So, when tool pin is offset, the pin has higher linear speed compared with other tools and it occupies bigger place and creates much torque and transfers materials from the front of the pin to the back with more power. During transferring, materials use empty space around the pin without any resistance and they are transferred to the back of the pin. They are compressed under pin pressure and forged by the shoulder that leads to much force. Compaction force of the materials from the back of the pin is higher than exerted force from the front of the pin. As a result, forces measured by dynamometer are negative. The power of tools H and A in the reduction of axial force is less than that of tool O because of the smallness of pins offset and edge shape.



(a)



(b)

Fig. 6 The effect of rotational speed on welding force. **a** Translational speed of 63 mm/min and **b** translational speed of 100 mm/min in FSW process with tools: concentric pin with tool shoulder (tool C), offset pin relative to tool shoulder (tool O), tool with half pin (tool H), and tool with arched pin (tool A)

4 Conclusion

In this research, tool shape is considered in the FSW process on workpiece AA5083. Measured parameters include vertical force (in the direction of tool axis) and welding force (along the direction of welding). The effects of tool shape on the above-mentioned parameters along with the changes of rotational speed have been considered in this research and results are as follows: The effect of the tool with offset pin on the decrease of vertical force and welding force (between 50 and 70 %) is more than the effect of the tool with concentric pin with the axis of tool shoulder on these forces. Tools with half pin and arched pin have more exerted forces than tool with offset pin and they have less exerted forces than tool with concentric pin.

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