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Ultrasonic press–fitting: A new assembly technique

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Abstract. The superposition of ultrasonic frequency vibrations to conventional machining techniques is known and practiced since the 1950s under the name of ultrasonic machining. Using ultrasound, many good properties appear including reduced thrust force, improved surface finish, reduced residual stress in machined material, etc… In this paper we present a new assembly technique based on the same principles: ultrasonic press–fitting. Feasibility and energy reduction are demonstrated through experiments under industrial production conditions.

Keywords: ultrasonic assembly, ultrasonic press–fitting, interference–fitting, thrust force reduction, hole–pin insertion energy reduction

1 Purpose of this paper

The vibrations assisted machining is an extension of conventional machining wherein a mechanical vibration is superposed on the tool movement. If the vibrations frequency exceeds 20 kHz, the expression mostly used in the literature is *ultrasound assisted machining*. This idea of assistance by ultrasound to the machining energy was also the starting point in the research conducted at EPFL – LPM. However, after several years of research, the authors came to the conclusion that the energy intake of ultrasound is higher by at least an order of magnitude than the one of the conventional machining or assembly techniques. Because the role of ultrasound surpasses the meaning of the word *assistance* usually used in the literature, the authors prefer the term of *ultrasonic machining* as well as *ultrasonic press–fitting* and will use them in this article instead of the usual expressions. Moreover, the mechanical behavior of the press–fitting as well as the hole–pin interactions are seen to be transformed in presence of ultrasound. Such a change in friction conditions and elastic–plastic characteristics have also been reported for other ultrasonic manufacturing processes [**1**].

The purpose of this paper is to present a new assembly technique: ultrasonic press–fitting. To achieve this goal, conventional press–fitting is introduced in section **2** and informations about ultrasonic equipment in section **3**. The description of the experimental setup of section **4** is followed by the measurement results in section **5** and their discussion in section **6**.

adfa, p. 1, 2011.

2 Conventional press–fitting

Process steps. Press–fitting is a common assembly technique which consists in a fastening achieved by introducing a pin into a hole with an interference. Even though this process appears as simple, it is not straightforward at (sub)millimetric scale.

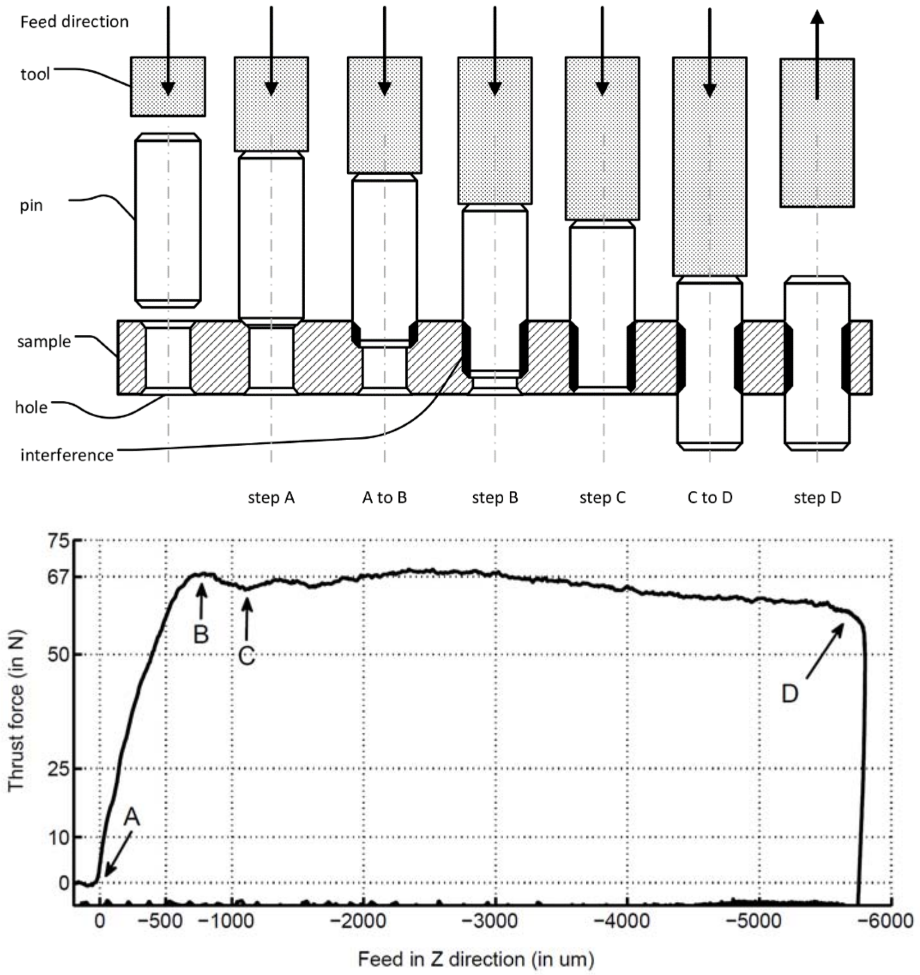

Fig. 1. Conventional press–fitting steps: **A** Beginning of the press–fitting with the contact between the tool and the pin resulting in an important thrust force increase **A to B** Feeding with growing pin–hole contact length resulting in a thrust force increase **B** Lower pin extremity reaches the minimal hole diameter **C** Lower pin extremity reaches the lower hole exit **C to D** Feeding with constant pin–hole contact length **D** Pin reaches its final position and tool moves back to its initial position **Process parameters.** $CuZn_{39}Pb_2$ brass sample, sample thickness 1000 µm, hole diameter 991 µm, 100Cr6 steel pin, pin diameter 998 µm, interference 7 µm, feed rate 10 mm/s

Functional analysis. Functions of the press–fitting are often observed to fail over the time. These cases have been studied especially through examples from the watchmaking industry by Bourgeois [**2**]. Some of the main functions expected from press–fitting are listed in **Table 1**.

Table 1. Result of a functional analysis modified from [**3**]

Nr.	Function	Acceptation criteria	Acceptation level
1	Withstand axial load	Min. sliding load (F)	10 N < F
2	Withstand torque	Min. sliding torque (T)	5 N·mm < T
3	Position in axial direction	Max. position error (e)	e < 2 µm

Process variability. The lack of quality, i.e. the variability in process output, is due to the difficulty to maintain the hole diameter within tolerances of 1 µm to 2 µm during manufacturing. These extremely thin tolerances are necessary to control the interference and thus the thrust force during press–fitting. This statement is based on the Lamé–Clapeyron model which predicts thrust force to be proportional to interference and to contact length between parts. Hence, the thrust force used to run and control the press–fitting varies of 10 N to 50 N for a change in interference of 1 µm [**2**]. This represents a variability of 15 % to 75 % of the maximal thrust force.

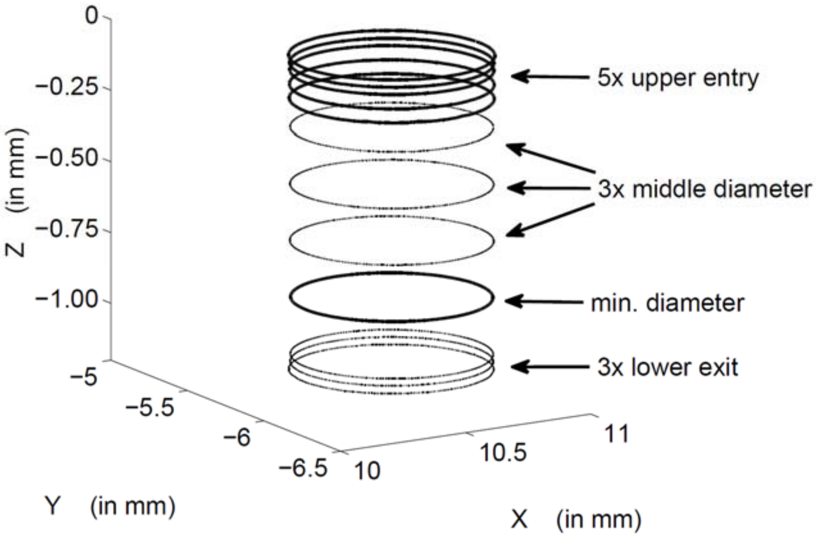

Fig. 2. Typical example of a hole diameter measurement by micro–CMM. The results showed that drilled–bored holes are not cylindrical as usually modeled and that a tightening of 1–4 µm exists at 50–100 µm above the lower hole exit. **Measure parameters.** 52 runs, probe diameter 302 µm, nominal hole diameter 990 µm

Model of a hole. To get a better understanding of the interference variability, the most accurate possible profile of 52 typical drilled–bored holes were measured at the Swiss Federal Institute of Metrology (*METAS*) on an enhanced micro–CMM on which a spherical probe with a diameter of 302 µm was mounted [**4**]. A representative result is plotted in **Fig. 2**. Each hole was measured at 12 different depth with more than 400 points per depth. The uncertainty of measurement in the three dimensions lies under 50 nm. The analysis of these measurements showed that drilled–bored holes are not cylindrical as usually modeled and that there is a tightening of 1 µm to 4 µm at 50 µm to 100 µm above the lower hole exit.

Diameter measurement. Since all the samples cannot be sent for a micro–CMM measurement, the authors investigated the most common method used in watchmaking industry: gauges. An R&R test with 3 experienced operators, 2 measurements per hole and 13 holes was performed [**5**]. This test gave a repeatability σ_1 of 0.29 µm while the reproducibility σ_2 was 0.81 µm. The authors were not surprised to find out that as usually at (sub)millimetric scale the dispersion of the measuring instruments $\sigma_m = 0.85$ µm, was of the same order of magnitude that the dispersion of the hole manufacturing $\sigma_p = 0.89$ µm. Hence, the interference values should be taken with precautions.

3 Ultrasonic equipment

Ultrasound generation. Since the first ultrasonic experiments in the 1950s, the principle of operation of ultrasonic machining or ultrasonic welding systems remained identical [**6**, **7**]. The ultrasonic press–fitting system is no different. A high frequency voltage generator converts a network supply voltage of 220 V at 50 Hz into a 1 kV voltage adjusted in frequency to the resonance frequency of the system. A second stage converts the electrical energy into longitudinal compression–tension mechanical vibrations by means of a piezoelectric transducer.

Ultrasound amplification. The sonotrode, sometimes also designated by *horn*, *booster* or *acoustic coupler*, is mounted between the electro–mechanical transducer and the tool. The vibrations amplitude at the output of the converter being about 1 nm to 100 nm [**8**], an amplification is necessary to obtain enough amplitude at the tool–tip workpiece interface. Therefore the sonotrode amplifies and transmits the vibrations from the transducer to the tool. Its geometry and dimensions are set to ensure the adjustment of its natural frequency to the generators excitation frequency.

For exponential flare of the sonotrode taper, the amplification is proportional to the ratio of the areas of the upper and lower faces of the sonotrode [**9**]. Machining tools or pin holding grippers can be screwed into this transducer. So a typical tool tip amplitude of 20 µm to 50 µm within a frequency range of 18 kHz to 70 kHz can be achieved.

4 Experimental setup

The press–fitting, should it be conventional or ultrasonic, is characterized by its thrust force against feed curve as shown in **Fig. 1**. Therefore one needs to be able to drive the tool in the feeding direction and measure its displacement as well as measure the thrust force seen by the sample. For this reason the authors have designed, realized and mounted the semi-industrial ultrasonic press–fitting setup described here.

Vertical movement. This setup consists of a *BOSCH REXROTH 3.842.993.178* rigid frame which carries a vertical linear guideway and two joined carriages. A *FANUC powerMotion i–A* numerically controlled NC axis drives a *PROMESS 64002–2201* ball screw to move these carriages. The nodal point of a 40 kHz *BRANSON GE101–135–67R* resonator unit is fixed to the carriages. The sonotrode is aligned on the same axis than the pin, the hole and the *KISTLER 9213B* force sensor. As shown in **Fig. 3**, this axis is also orthogonal to the samples upper face. The tool displacement is measured by a *HEIDENHAIN LS–487* linear encoder allowing an accuracy of less than 1 µm.

Force measurement. Using a force sensor with a high cutoff frequency which is placed directly under the sample, it is possible to measure two components of the force view by the sample: the low frequency component due to the insertion movement and the high frequency component due to ultrasonic vibrations.

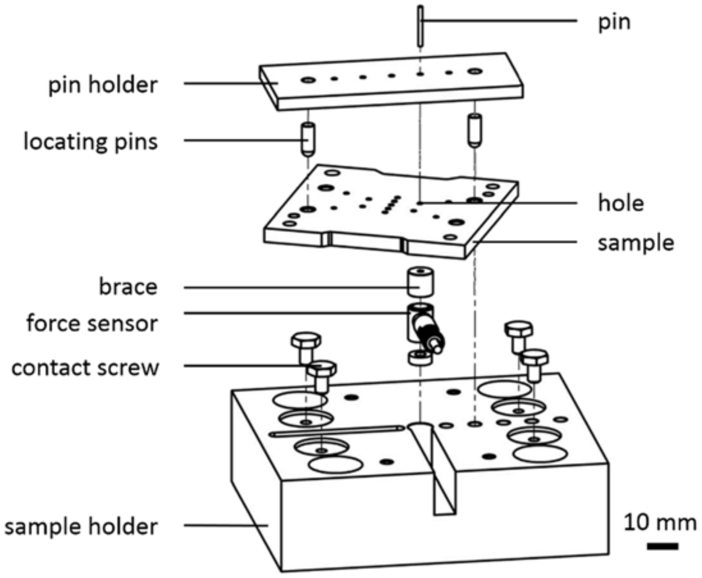

Fig. 3. The experimental setup includes a sample holder allowing a pre–positioning of the pins in the pin holder as well as a three point contact between the samples lower face and the sample holder using two of the four contact screws and the brace above the force sensor.

Holes. Due to the variability in hole diameters, and thus in interference, each experiment should be ran at least three times under the same conditions. Therefore the authors have bought sixty *B50* $CuZn_{39}Pb_2$ brass samples from *EMP* in Tramelan (Switzerland). Each of them contains 13 holes machined at EPFL – LPM with a special *Sphinx 51200* drilling–boring bit mounted on an industrial *Mikron HSM–400U* NC machine. The sample thickness is 1000 µm ± 10 µm. The nominal hole diameter is 990 µm ± 2 µm. Each hole has a 0.2 mm x 45° chamfer at both extremities to smooth the pin insertion into the hole.

Pins. To study the ultrasonic press–fitting at different interference values, three batches of pins have also been bought from *Adax*, in Bevaix (Switzerland). The pins are in 100Cr6 steel with a hardness of 60 HRC and a roughness of Ra 0.1. The nominal pin diameters are 997 µm ± 2 µm, 1000 µm ± 2 µm and 1020 µm ± 2 µm. Their length is 10 mm ± 100 µm with a 0.1 mm x 45° chamfer at each extremity.

5 Experimental results

For this article the authors have executed the same experiment 16 times with success and good repeatability in the thrust force against feed curve shape. A typical result is shown in **Fig. 4**.

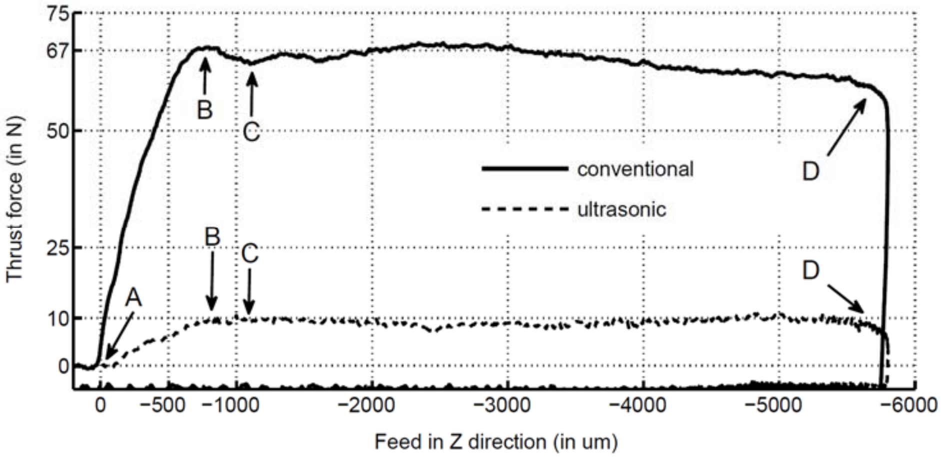

Fig. 4. The same steps as in conventional press–fitting are taking place: **A** Pin–hole chamfer contact **A to B** Feeding **B** Pin reaches minimal hole diameter **C** Pin reaches hole exit **C to D** Feeding **D** Pin reaches its final position **Comment.** The thrust force drops of 68 N to 11 N when ultrasound are used during press–fitting **Process parameters.** 16 runs, $CuZn_{39}Pb_2$ brass sample, sample thickness 1000 µm, mean hole diameter 991 µm, 100Cr6 steel pin, mean pin diameter 998 µm, pin roughness Ra 0.1, mean interference 7 µm, feed rate 10 mm/s

Experimental procedure. For both conventional and ultrasonic press–fitting, each run is executed with the same procedure described here.

1. The sample is placed on the sample holder and the pin is pre–positioned in contact with the sample. Locating pins on the pin holder guarantee alignment of the pin with both hole and force sensor as shown in **Fig. 3**.

2. Press–fitting operation runs according to the NC program: tool approaches up to 0.5 mm above the upper extremity of the pin and then moves down by 6 mm at a constant feed rate of 10 mm/s.

3. After reaching the lowest position, corresponding to **D** in **Fig. 4**, tool stops during 50 ms before moving off.

4. For runs carried out with ultrasound, the ultrasound generator is on during the whole press–fitting operation.

After each press–fitting, the maximal axial load before fastening failure is measured by turning over the sample and running the same NC program at a feed rate of 0.5 mm/s. The maximum axial load before sliding of the pin in the hole corresponds to the maximal axial load before the press–fit failure.

6 Discussion and future work

Discussion. As shown in **Fig. 4**, the typical thrust force against feed curve shape of a conventional press–fitting is also to be recognized in ultrasonic press–fitting. However, there is under the exact same experimental conditions a drastic drop in the thrust force in presence of ultrasound. This could be explained by a change in the friction conditions between the pin and the hole. Further experiments are needed in that field to confirm this hypothesis and build a reliable model.

Table 2. Comparison between conventional and ultrasonic press–fitting characteristics

	Conventional	**Ultrasonic**	**Gain**
Maximal thrust force	67.75 N	10.56 N	> 6x
Press–fitting energy	51.48 mJ	6.61 mJ	> 7x
Maximal axial load before sliding	64.91 N	46.94 N	≈ 0.7

Looking at **Table 2**, one can also observe a serious reduction in the mechanical energy needed to achieve the insertion. This could specially be interesting in industrial cases where the pin length to pin diameter ratio is high. Indeed, for such components a buckling is often observed. Reducing the thrust force and the press–fitting energy could overcome this buckling problem and extend the suitability of press–fitting for even smaller diameter pins.

Future work. As the presented assembly technique is a novel one, there is still a certain amount of work to achieve in order to fully understand the influence of ultrasound on the press–fitting. The authors will continue to study this promising field of research and undertake the following actions:

1. Run a screening design of experiments to point out most influential process parameters which could be the sample material, hole depth, hole diameter, interference, feed direction, feed rate, vibrations amplitude, etc…

2. Run a second design of experiments to study the effect of the previously identified process parameters

3. Continue their study on the effect that manufacturing techniques have on the hole shape and hole diameter

4. Investigate for an alternative measurement system to gauges which would present a lower measuring instrument dispersion σ_m than 1 μm for (sub)millimetric holes

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