Key Engineering Materials *Submitted: 2021-11-30*
ISSN: 1662-9795, Vol. 926, pp 663-673 *Revised: 2022-01-31*
doi:10.4028/p-x5s54x *Accepted: 2022-02-08*
 Online: 2022-07-22

Hot Spinning of Cutting Blades for Food Industry

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Keywords: Cutting blades, Flow-forming, Incremental forming, Hot Forming, High strength steels

Abstract. The spinning process is a flexible incremental forming process for the manufacturing of axially-symmetric sheet metal or tubular components with functionally graded properties. It is characterized by the utilization of universal tooling geometries and quite low forming forces. The process has a high potential to reduce material waste, to extend the forming limits and to achieve more complex geometries as well as favorable part properties [1]. Current research work at the Chair of Forming Technology (LUF) is focused on innovative flow-turning processes that have a high potential for producing flat components with excellent geometrical and mechanical properties while keeping process times short [2]. In combination with process-integrated local heat treatment, the new spinning process is predestined for the efficient forming of ultra-high-strength steel or tailored materials. Due to the desired field of food industry only food-safe materials such as special stainless steels are being investigated. This paper presents an innovative machine layout as well as an adequate process design for the production of high-performance circular knives with optimized mechanical hardness. In this context, particular attention is paid to various areas of temperature control as well as process-related challenges during the process.

Introduction

Knives and cutting tools are used in a wide range of domestic, handcraft and for example industrial sectors. The food industry mostly uses circular knives for portioning frozen and non-frozen goods.

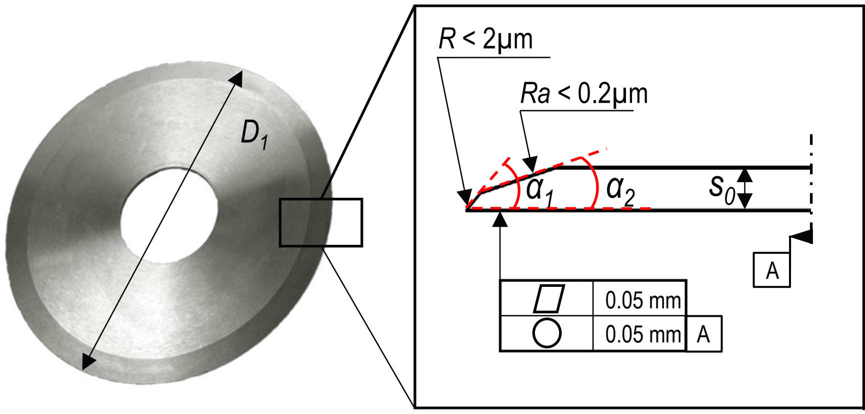
The focus of the research work concentrates on circular and sickle knives in the food industry. The applications result in various requirements for the respective circular knives, which have sheet thicknesses of between 0.6 and 5 mm for diameters of 100 to 580 mm. These include specific knife and cutting-edge geometries, high abrasion resistance, low surface roughness, good corrosion resistance and food safety. Since circular knives are under strong heavy loads and abrasion is unavoidable, manufacturing costs play another significant role. Low service life in combination with a regular change of blades and high wear causes expensive circular blades [3].

From a microbiological point of view, surfaces that come into contact with foodstuffs require a high surface quality.

The resulting contamination of the foodstuffs is also prevented, which is in addition to personal damage also an economically significant problem. [4] In addition to the antibacterial properties of the knife material, a particularly smooth surface prevents bacteria from sticking to the cutting tool. Finally, a typical target value here is a roughness of preferably $Ra = 0.2$ µm and maximum $Ra = 0.8$ µm [5].

As a result of the high manufacturing costs of food-safe circular knives there is a desire for a long service life. In order to keep this as long as possible, the mechanical properties of the circular knives and primarily those of the blade tip are essential. First of all, good abrasion resistance is favored by high hardness and strength of the blade material. Consequently, the target hardness of industrial knives is between 54 (580 HV) and 62 (740HV) HRC, depending on the application [6, 7]. The strength is linked to the hardness of the material and reach about 2,000 MPa [8].

Furthermore, the shape of the blade tip defines the sharpness and the associated cutting ability. In addition to the blade geometry, described by the angles α_1 and α_2, one characteristic for determining this property is the blade radius R [9]. By investigating an example blade from the company Marel, which is made of the material 1.4112 (AISI 440B), it can be seen that blade radii in the range of 2 µm ensure suitable cutting ability. The flatness and roundness of the cutting areas have a tolerance of 0.05 mm [10]. In summary, the most important properties of a blade are shown in Figure 1.



Material 1.4112	
Hardness	Min. 580HV
UTS Strength	2000 MPa
Diameter D_1	100-580 mm
Thickness s_0	0.6-5 mm

Figure 1: Properties of a circular knife for the food industry. Example of an industrial blade.

The circular knives are conventionally produced by a sequence of laser or waterjet cutting followed by surface and cylindrical grinding operations. Due to the different procedures of grinding a suitable roughness of the countered and non-contoured part of the blade is possible. Depending on the process, maximum feed rates of 0.01 to 0.05 mm/ infeed can be achieved. Thus, depending on the material thickness and surface quality a machining time of 1 to 1.5 hours (at 4 mm thickness or more) is necessary for the grinding of the blade. The machining of the circular blade results in a material loss of about 10 %. Likewise, the grinding tools suffer heavily at such machining depths. Long grinding operations generate large quantities of grinding dust, which can only partially be collected by the cooling lubricant. This has to be cleaned at great expense. Not in the cooling circuit bound dust evaporates into the air and pollutes the environment. To adjust the mechanical properties, the circular knives are subjected to a prior heat treatment before grinding. These separate and particularly time-intensive operations are reflected in considerable component costs with low average tool lifetimes [11].

With the focus of an innovative approach to circular knife production, the Chair of Forming Technology (LUF) is researching a modular technology system with an associated production process focusing on the food industry. The aim is to maximize material utilization and minimize process time by means of a spinning process. A significant increase (decreased tensile strength) in forming capacity is possible through process-integrated local heat treatment. At the same time, the necessary process forces are reduced, so that process times are further reduced. Due to a significantly lower grinding effort and the local heat treatment, energy- and resource-saving work is possible.

Conception

Flow-forming is one of the incremental pressure forming processes used in sheet metal forming. The use of geometrically simple and universal useful spinning tools enables a cheap production of complex component geometries. Thin to medium wall thicknesses are realizable. In addition to very good material utilization the high dimensional accuracy is a further benefit. Rotationally symmetrical components can be mentioned as an essential component spectrum of the flow-forming process [12]. In a flow-forming process, the semi-finished product is formed over a die and thus receives the final workpiece geometry.

In the following investigations, the basic concept of flow-forming is optimized for the application of circular knife production for the food industry. A universal mandrel is used. The semi-finished product is formed against this.

The roller has an asymmetrical design and is provided with a radius. The primary target is to enable process-integrated heat treatment in the optimized process variants in order to increase the forming capacity of high-strength and ultrahigh-strength materials. Local process-integrated heat treatment makes it possible to save a separate process step, which is usually placed prior the grinding process. This optimization makes the entire manufacturing process more time- and energy efficient. The shaped blade only needs to be regrinded and polished, so that material utilization increases while the grinding effort decreases. This enables an innovative manufacturing chain. In the following three different test principles will be explained.

Partially Kinematic Principle. Figure 2 shows the partially kinematic test principle.

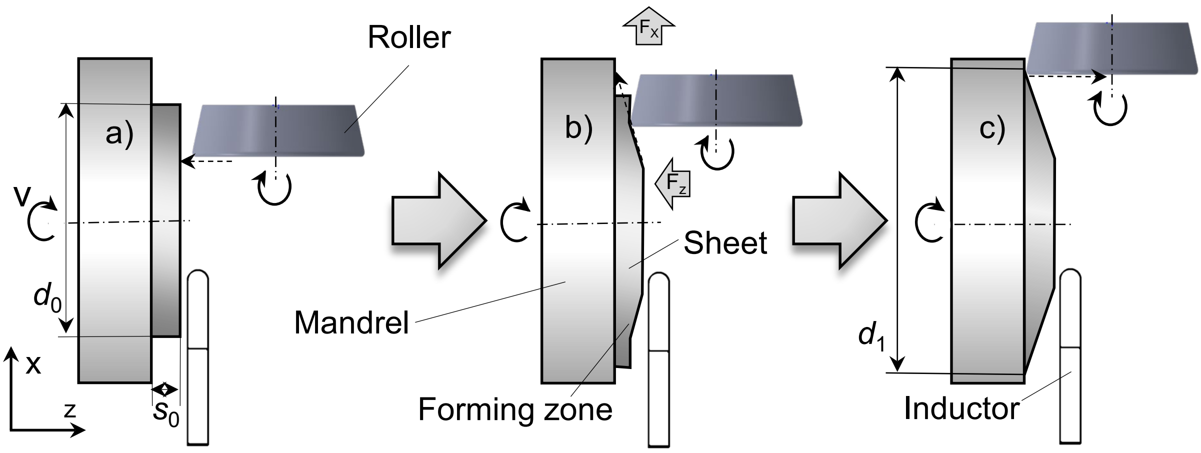


Figure 2: Partially kinematic process design

In this partially kinematic process design, the semi-finished product is mounted and clamped in the front of the mandrel. The spindle sets the semi-finished product in rotation. Neither the counter-holder itself nor the spindle has any relative movement to the subsequent circular knife. Only the spinning roller has a relative movement and forms the final blade geometry on the semi-finished product by a two-axis movement (x and z direction). This results in the term partial kinematics. In order to be able to carry out an integrated heat treatment, the inductor can optionally be positioned on the side facing away from the roller. However, due to the one-sided accessibility to the sheet, the heating efficiency is limited. Therefore, further process optimization is being developed and investigated.

Fully Kinematic Principle with Plane Counter-Holder. Figure 3 shows the fully kinematic test principle with a plane counter-holder roller. Analogous to the partially kinematic process design, a plane counter-holder instead of the mandrel is used in this variant.

However, this is not permanently connected to the spindle, but is supplied in the form of another spinning roller (Roller 2) that acts like a counter roller. This brings the advantage that the counter-holder is applied in the forming zone only temporary.

In combination with a thinner spindle, a two-sided accessibility is realized which significantly increases the effectiveness of the process-integrated heat treatment. Due to forming forces of roller 1 additional attention must be paid to the stiffness of the mounting and bearing of spinning roller 2. Increased elastic deformations lead to undesired deviating forming results.

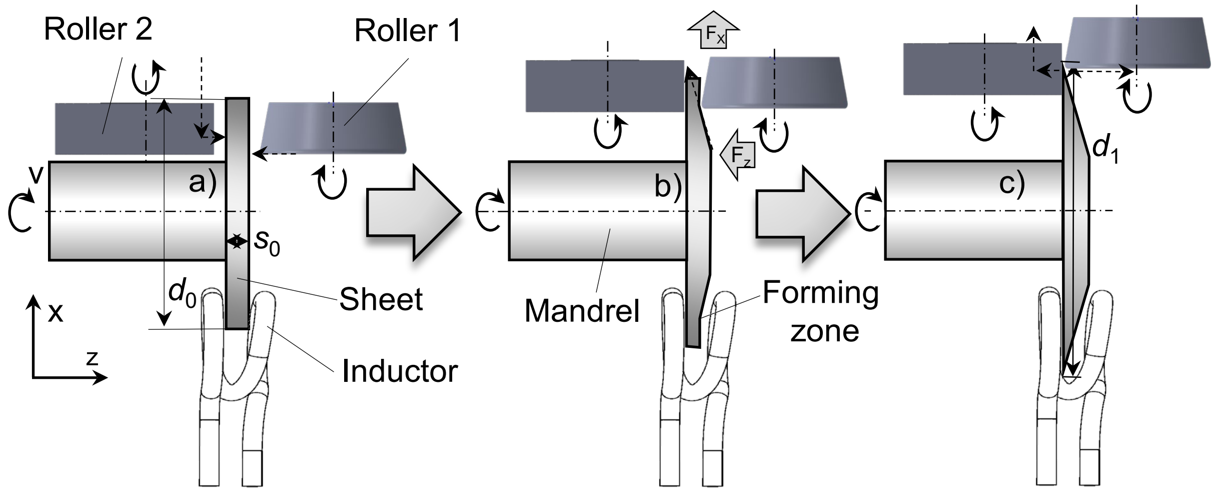


Figure 3: Fully kinematic process design with a second plane roller

As a result of different applications of circular knives in the food industry, knives with a blade contoured on both sides are frequently used. The fully kinematic process design is particularly well suited for this type of components.

Fully Kinematic Principle With Conical Roller. Compared to the fully kinematic process design with a plane counter-holder, the plane counter-holder roller can be exchanged for another contoured spinning roller (Roller 3), as shown in Figure 4. This makes two-sided forming possible. Both spinning rollers can form the blade by a two-axis movement in x- and z- directions, resulting in a symmetrical blade geometry.

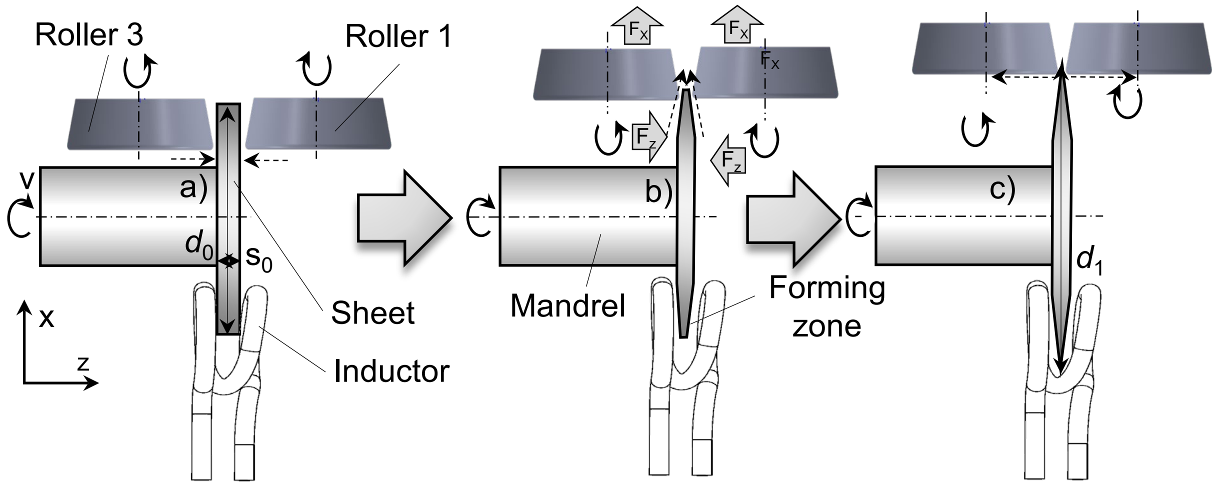


Figure 4: Fully kinematic process design with a second contured roller

In that case, the counter-holder takes either place on only one side of the spindle. Thus, supplying the inductor on both sides of the metal sheet and local heat treatment on the opposite side of the forming rollers are also possible with high efficiency. Primarily, the heat input results from induction due to Joule losses, which are strongly dependent on the coupling distance between the material and the inductor. Due to self-induction in the magnetic field of the inductor and the electrical resistance of the material losses in the form of heat occur.

In ferromagnetic materials, this heat generation is further enhanced by frequency-dependent hysteresis losses during magnetization and demagnetization [13].

Experimental Setup

The concept will be shown in the following. Hereby the main focus is put on the experimental setup as well as the measurement and control technology. Figure 5 details the final setup.

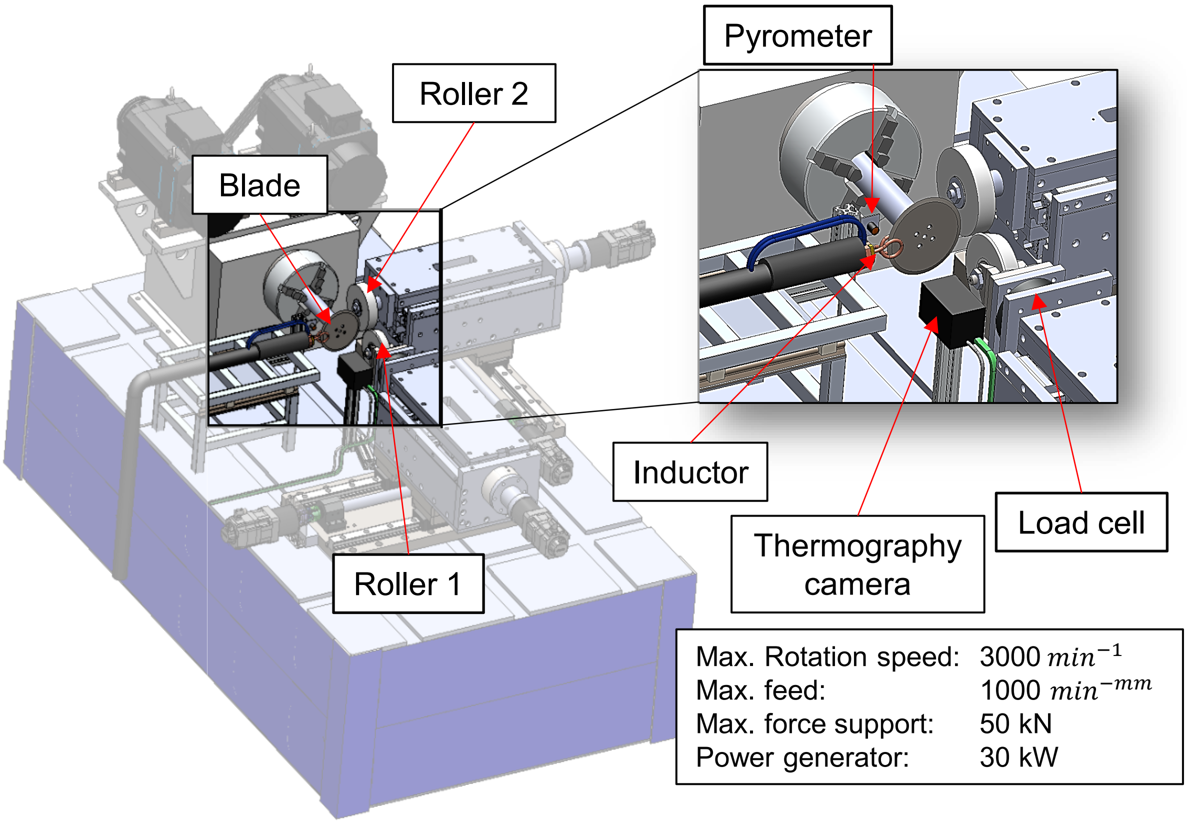


Figure 5: Experimental test setup

A machine bed acts as the basis of the experimental test setup, which is used to fix and align the components and to absorb forces and moments. A shaft is clamped in a three-jaw chuck of the spindle, on which the blank is fixed as a semi-finished product. To ensure the highest possible concentricity, the spindle shaft has a centrally positioned centring pin. The semi-finished product ($d_0 = 200$ mm, $s_0 = 3.5$ mm), which has been pre-machined with a 12 H7 fitting hole, can be mounted on this pin. Four screws (M12) provide the clamping force. The rollers required for the forming operations (Roller 1 ($d_{Roller1} = 190$ mm, $R_{Roller1} = 2, 4, 6$ mm) and Roller 2 ($d_{Roller2} = 190$ mm, $R_{Roller2} = 2, 4, 6$ mm or without radius)) are mounted on supports. Depending on the knife geometry, this radius can be varied between 2, 4 and 6 mm. While Roller 1 is mounted parallel to the spindle, Roller 2 is positioned vertically. Both supports have two axes and are freely programmable by use of a Siemens CNC control system. The axes are driven by recirculating ball spindles. Analogous to the spinning roller (Roller 1), a load cell is also mounted to support 1. This 6-axis load cell (*producer:ME, type: K6D175)* records all forces and torques during the forming process. At the beginning of the process, the inductor, which is designed as a cylindrically wound tube, can be positioned around the circumference of the sheet using a linear guide. The inductor is powered by a 30 kW medium-frequency generator (*producer:ELDEC/EMAG, type: MFG 30/30 twin)*.
The current temperature of the sheet is measured by an infrared pyrometer (*producer:MAURER, type*: *VL-VA-T)* positioned on the rear side of the sheet. This pyrometer is connected to the generator via an evaluation unit (*producer:MAURER, type*: *KTRD 1465-1)* and controls the temperature of the rotating component based on measured temperature gradients.
To ensure the function of the pyrometer and at the same time to be able to record the temperature curves of the components, a thermographic camera (*producer: INFRATEC, type*: *VARIOcamGIGE)* based on infrared is placed with a disatance of 150 mm on the front side of the sheet.

It's tolerance is about ± 20 °C at a temperature of 1000 °C. This records the heating, holding and cooling phases at three different points in the forming zone. After forming process is finished the final blade is cooled down by air pressure.

Results

With the presented experimental setup, circular knives with specifically adjusted mechanical properties can be produced. The process-integrated heat treatment enables optimized values to be achieved. Particularly for the target parameter of material hardness. The following section deals with the determination of a suitable process window for the heat treatment. All investigations are carried out for the material 1.4112.

Oven Hardening. Oven hardening is chosen as a reference test to investigate the ideal parameters of holding time and hardening temperature of the used material (1.4112). In this way, consistent conditions can be ensured for all specimens. To determine the process window, different hardening temperatures and the holding times are checked. Hardening temperatures of 825 °C, 970 °C, 1000 °C, 1100 °C and 1200 °C are investigated. This temperature range is limited by the beginning of austenitization (830 °C) and the maximum capacity of the oven (1200 °C). Furthermore, holding times of 50 to 600 seconds are tested. For each hardening temperature, four specimens equipped with a thermocouple are placed in the oven. Due to an additional performed tactile temperature measurement, measurement inaccuracies less than ±5 °C are ensured . First, the material is heated up to the desired hardening temperature. When this is reached, the time is stopped and the respective specimen is removed from the oven after holding time has elapsed. After that the specimen is cooled down by compressed air cooling (20 °C/s). Figure 6 shows the resulting hardness curves as a function of the curing temperature and the holding time.

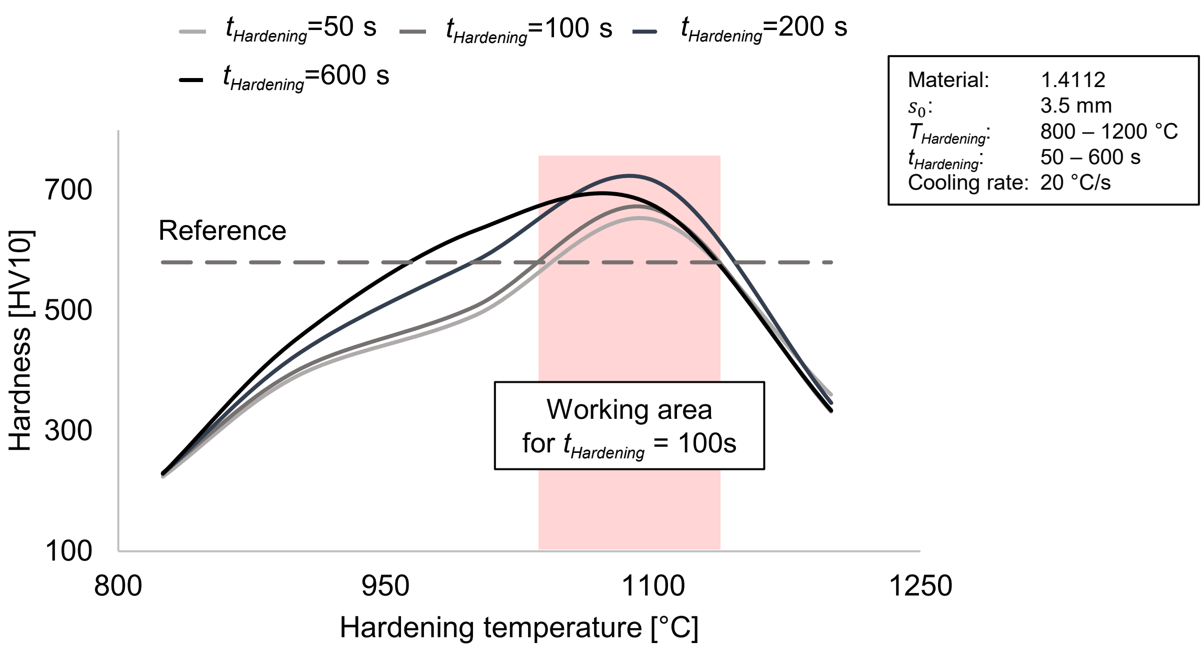


Figure 6: Impact of holding time and hardening temperature on mechanical properties of 1.4112 specimen

Since the temperature of 825 °C is below the annealing temperature of 830°C, a hardness of about 230 HV results for this temperature range irrespective of the holding time.
This hardness corresponds to the soft-annealed material state. The maximum hardness results between 1050 °C and 1100 °C at 600 to 740 HV, regardless of the holding time.
Thus, this target temperature range should be aimed for the local heat treatment of the optimized flow-forming process.

In particular, long holding times of 200 and 600 seconds can ensure high material hardness. At 50 seconds holding time, the hardness is lowest at 600 HV but still above the permissible minimum of 580 HV.
As a compromise between the shortest possible holding time and a sufficient hardness, a holding time of 100 seconds is consequently selected for the optimized process. The red area indicates the permissible temperature range for achieving the target value with a holding time of 100 seconds. If a temperature of 1150 °C is exceeded, an enormous drop in hardness follows. This may be due to increased grain growth.

Induction Hardening While Forming. Furthermore, it must be ensured that these results of a heat treatment in the oven can also be reproduced by a local heat treatment. This can be realized by adjusting the frequency of the generator, the coupling distance between the inductor and the sheet and of course a correct temperature measurement.

Consequently, the same hardening temperatures (825 °C, 970 °C, 1000 °C, 1100 °C and 1200 °C) at a holding time of 100 s are also tested for samples from the test setup. The blades of the formed and simultaneously heat-treated circular knives are subsequently cut out and also tested for hardness. Figure 7 illustrates the position of the measuring points.

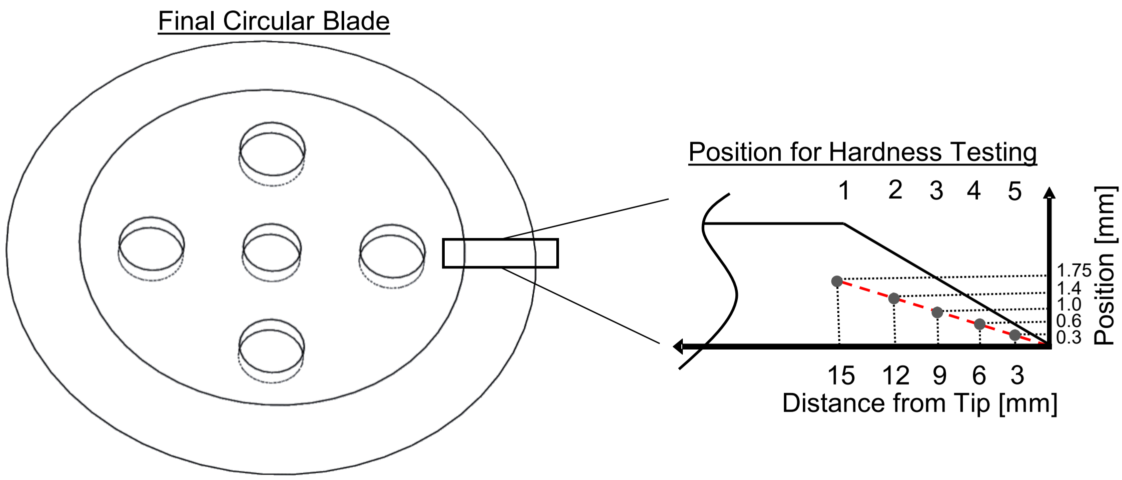


Figure 7: Principle for hardness measuring of produced circular blades

To evaluate the blade hardness, the minimum hardness should be determined. Due to the higher duration until complete heating, this is in the core area of the blade. Therefore, the measuring points are distributed at equal intervals on the diagonal (shown in red).

Analogous to the heat treatment in the oven, the specimens of the test setup are also first heated up to the target temperature. A measuring point located 5 mm from the edge of the blank in the direction of the blank center serves as the reference measuring point. This is the beginning of the forming zone. When the target temperature is reached, it is held for 100 seconds while the blank rotates. The forming process starts. During forming, the temperature is still controlled to the target temperature. The duration of the forming process is considered to be short (< 40 s). After finishing the forming process, the still rotating blank is directly cooled by compressed air (cooling rate of 20 °C/S). The results are shown in Figure 8.

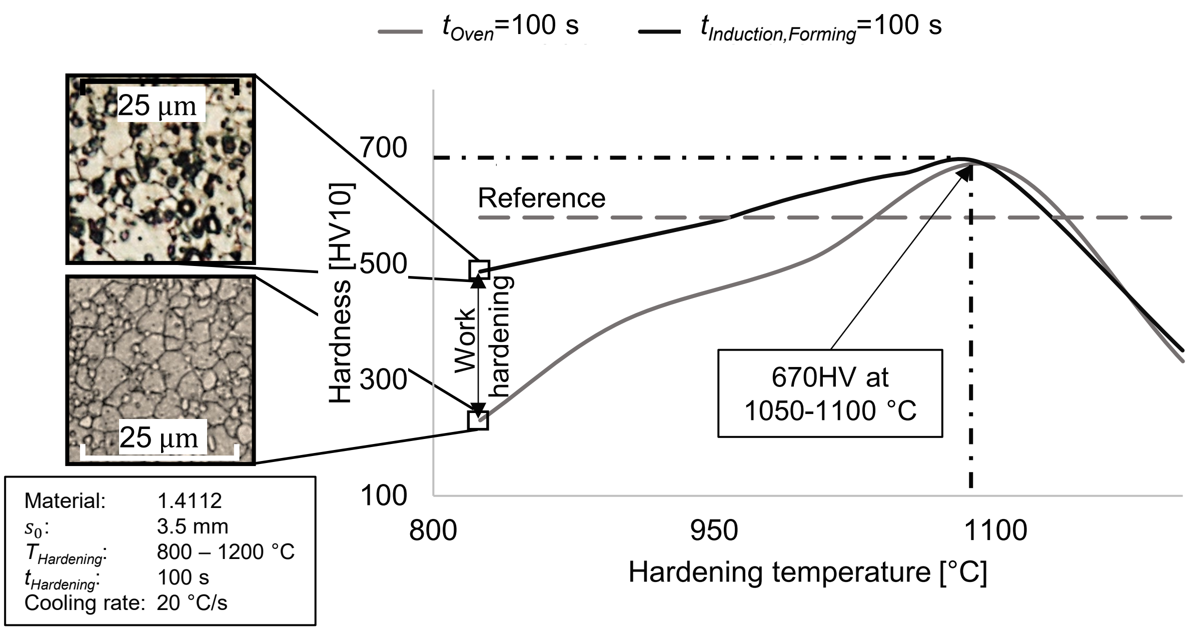


Figure 8: Work hardening increases the final hardness compared to oven hardening

Especially for the target temperature of 1050 °C, the process curves of both variants are identical. Also, for temperatures higher than the target temperature, the hardness curves are very similar. At such high temperatures, the influence of grain growth predominates and work hardening by forming is omitted. Only for the temperature range below 1050 °C the two curves deviate from each other. The hardness of the local heat treatment with simultaneous forming is higher than the hardness of the oven treatment. As shown for the temperature at 825 °C, this is mainly due to work hardening as a result of forming and grain refinement as a result of heat treatment. Since 825 °C is below the austenitization temperature, no martensitic hardening of the material is to be expected. This is different from all temperature ranges above 830 °C. For this reason, an increase in hardness can result from the finer grain structure and effects of work hardening. Thus, the hardness of the formed sample at 825 °C is twice that of the oven sample. The grain size shrinks from an average of 7 µm to less than 4 µm. This effect is exceeded by increasing martensitic hardening in the temperature range from 825 °C to 1050 °C, so that both hardness curves converge [14].

Process Control Strategies. In the following, two different process control strategies are presented analogous to the pictogram in Figure 9. The influence of the holding time t_{H2} on the hardness is investigated.

Since the temperature can only be controlled at one point, the heat distribution over the blade is not permanently constant. In particular, as the blade is increasingly shaped, the edge region becomes thinner and the diameter larger. For this reason, the coupling distance between the blade tip and the inductor is greatly reduced. Figure 9 shows the influence of a holding time t_{H2} on the hardness distribution of the knife blade. If the heat supply is stopped directly after forming ($t_{H2} = 0$), the result is a high hardness of the blade tip (700 HV). In this case the hardness at the beginning of the forming zone is close to the reference. If the generator continues to supply energy after finishing the forming process with a reduced coupling distance between the blade tip and the inductor, the blade tip overheats and a reduced hardness is to be expected. For this case, the hardness increases to 660 HV at the beginning of the forming zone, since the blade is uniformly annealed and rapidly cooled after forming.

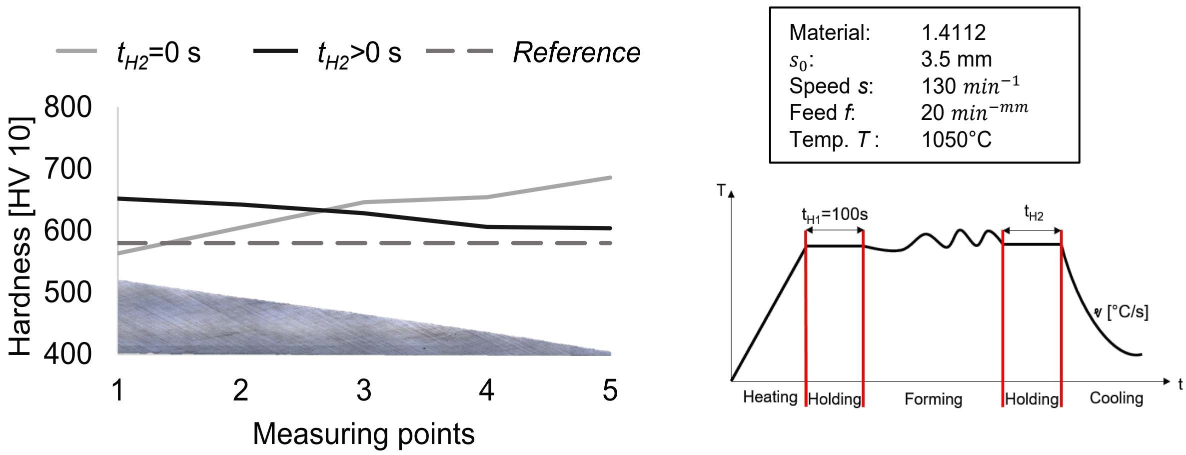
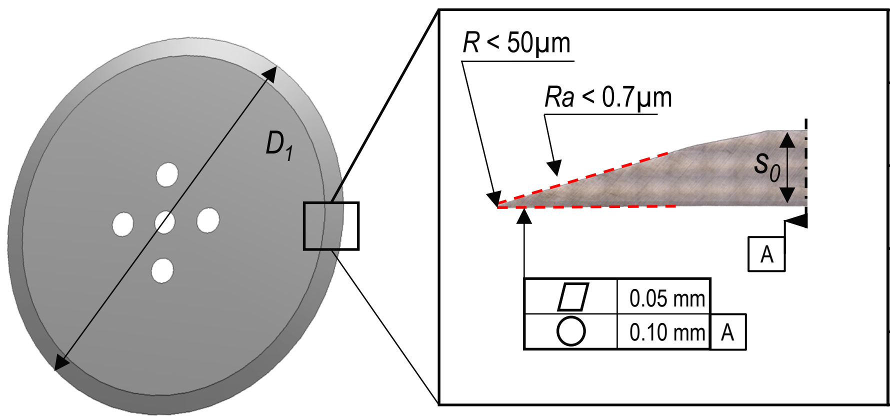


Figure 9: Hardness profile of two different process strategies

As a result of these hardening curves, a holding time of $t_{H2} = 0$ is proven to be favorable for this boundary conditions considered. This contributes an increased hardness of the knife tip and at the same time the lowest process duration. On the one hand, this reduces the overall manufacturing process time. On the other hand, a high edge hardness is desirable for the reduction of wear. As an additional effect, a reduced hardness in the core of the knife which enhances and balances residual tensile strength, and lowers the risk of fracture during service.

Figure 10 shows the summarized properties of a formed blade. Due to process-related oxides released by the heat treatment, a subsequent grinding process must be provided. The blade radius after forming does not yet meet the minimum requirement of 0.002 mm. Thus, this dimension is also optimized by a grinding process. The investigations show that the material can tear off when a blade radius of 0.05 mm or smaller is formed. So the final sharpness should be given by a grinding process. The stress caused by forming between two rollers is too high. The core hardness of the blade material is significantly higher than the minimum requirement.



Material 1.4112	
Hardness (at tip)	665 HV10
Strength	2000 MPa
Diameter D_1	200 mm
s_0	3 - 4 mm

Figure 10: Properties of a circular blade tip manufactured at LUF

Conclusion

High wear and low tool lifetimes combined with high component costs are the main problems associated with the use of circular knives. In this paper, the high claims placed on circular knives in the food industry were highlighted. In addition to geometric requirements such as concentricity, blade radius and surface quality, the hardness of the blade is the main focus. A modified spinning process was presented as an innovative solution. A suitable work range for hardening temperature as well as the holding time was identified.

A temperature range of 1050 °C to 1100 °C was determined for optimum heat treatment of the material 1.4112. The holding time at austenitization temperature was determined to be sufficient at 100 seconds. This can be realized by using induction technology for heating the metal sheets. For the blade tip area, a hardness of up to 665 HV10 can be achieved. These exceed the minimum requirements by 15 %. The fully kinematic test setup was determined to be the optimum and allows increased accessibility of the inductor. This increases the efficiency of the heat input and reduces the necessary energy requirement. Due to forming the material instead of grinding the loss of material can be reduced by 10%. In addition, the production of the blade geometry is made more flexible. Depending on the blade geometry, conventional production takes more than an hour. An innovative process layout with process integrated heat treatment reduces the manufacturing time. Including heating, forming and cooling, the process time without grinding is currently 3 minutes. The duration of the subsequent grinding process is reduced to a minimum.

Acknowledgements

This research and development project is being funded by the European Union and managed by the Project Management Agency Jülich (PTJ). The authors are responsible for the contents of this publication. The Research project was carried out at the Department for Metal Forming Technology (LUF), Paderborn University, in cooperation with Hermann Jennert GmbH & Co. KG, Wilnsdorf, Matplus GmbH, Wuppertal, DynaWeld GmbH & Co. G, Kamen, Friedr. Lohmann GmbH, Witten-Herbede, Marel Poultry B.V., Boxmeer.

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