

Press Hardening of Tubes with Additional Interior Spray Cooling

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Abstract—Press-hardened profiles are used e.g. for automotive applications in order to improve light weight construction due to the high reachable strength. The application of interior water-air spray cooling contributes to significantly reducing the cycle time in the production of heat-treated tubes. This paper describes a new manufacturing method for producing press-hardened hollow profiles by means of an additional interior cooling based on a water-air spray. Furthermore, this paper provides the results of thorough investigations on the properties of press-hardened tubes in dependence of varying spray parameters.

Keywords—22MnB5, hollow profiles, press hardening, tubes, water-air spray cooling.

I. INTRODUCTION

ONE possibility to manufacture high-strength components for automobile body constructions is press hardening. Due to the high attainable strengths of up to 1500 MPa, press hardening offers a great lightweight potential [1]-[3]. Press hardening combines hot forming and quenching in one process with closed forming tools [4]. First of all, the material has to be austenitised at temperatures of the austenitisation temperature and then transferred to the forming tool where the press-hardening process is carried out. The manganese-boron-steel 22MnB5 is typically used for press hardening. In order to ensure a complete transformation of the microstructure from austenite to martensite for the manganese-boron-steel 22MnB5, a cooling rate of 27 K/s or more is necessary [5] as illustrated in Fig. 1.

The technology of press hardening is well established for the sheet metal forming of structural components for the automotive sector. Press-hardened parts are mainly used for crash-relevant structural parts such as for instance A-pillar, B-pillar, reinforcements, bumpers, door beams, roof rails and other structural components [7]. In addition to highest

strength, further advantages of this technology are a high formability and a great forming accuracy due to the low springback behaviour [8].

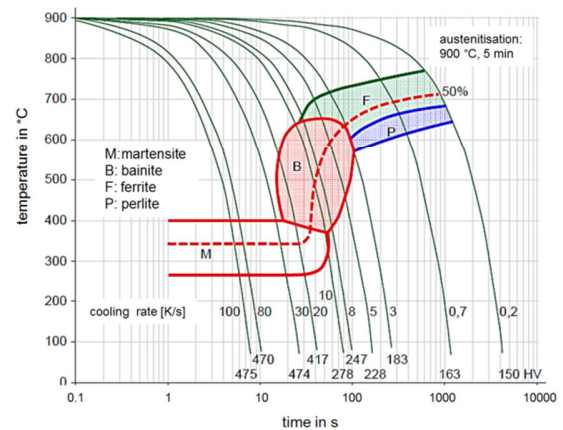


Fig. 1 Time-temperature transformation (TTT) diagram of 22MnB5 [6]

The number of press-hardened parts used in car manufacturing has been growing exponentially from the beginning of this technology in 1984 to about 200 million parts in 2013 [9]. Press hardening is well-established for sheet metal forming, but not common for hollow profiles.

The press hardening of sheets is characterized by a two-sided tool contact so that a sufficient cooling rate for the full martensite transformation is ensured. But when forming tubes, there is just a one-sided tool contact. In order to compensate for the missing cooling of the inside of the tube, the application of a water-air spray cooling is a suitable possibility.

Torque tubes assembled in chassis can be named as an example for the use of press-hardened hollow profiles as shown in Fig. 2.

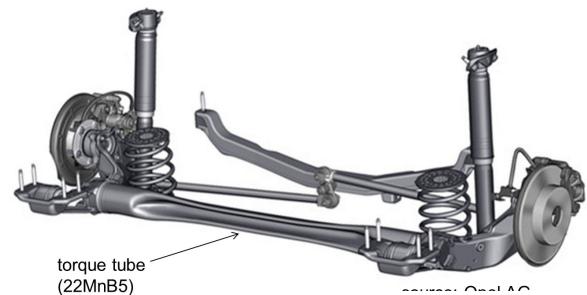


Fig. 2 Torque tube as an example for a heat-treated hollow profile used in chassis [10]

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The tubes used in chassis applications often have a wall thickness of 3-4 mm. Due to the high wall thickness an efficient interior cooling is required, especially for a full martensite transformation. Both aspects, the one-sided tool contact and the higher wall thickness of the tubes, lead to an inefficient process time for manufacturing press-hardened tubes [11].

The press hardening of hollow profiles is not common in industrial series production. The conventional process for manufacturing tempered profiles is combined of numerous process steps as illustrated in Fig. 3 (a). Furthermore, this conventional manufacturing process consists of cold forming followed by a heat treatment comprising heating, quenching and annealing [11].

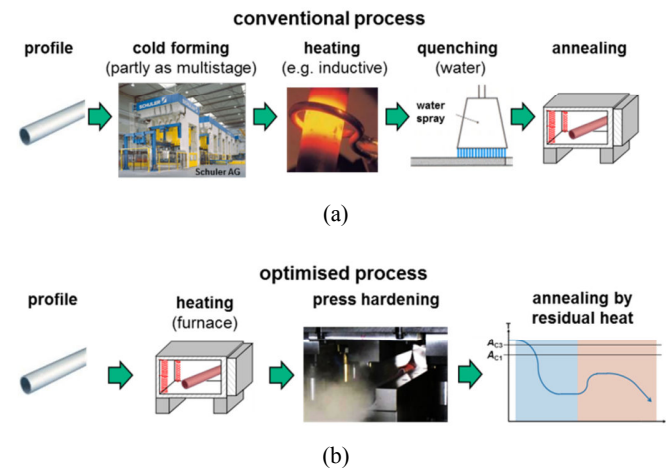


Fig. 3 Conventional process (a) and optimised process (b) for manufacturing of hollow profiles

Due to the numerous process steps the conventional process chain of heat-treated hollow profiles is extensive and expensive. Therefore, an optimised manufacturing process was investigated. The optimised and shortened manufacturing process is illustrated in Fig. 3 (b). After the austenitisation of the profiles, they are formed within the tool where the quenching from the outside occurs by tool contact. The

quenching from the inside follows directly after the forming by inserting a spray-lance into the tube and activating the water-air spray. The interior water-air spray cooling is necessary for a complete martensitic transformation. Compared to the conventional manufacturing process, a subsequent annealing process is not necessary because of the residual heat of the tubes as a consequence of the relatively high wall thickness.

II. EXPERIMENTAL SETUP

The experimental investigations were carried out on a part as shown in Fig. 4 (a). The forming tool was provided by the company *Kirchhoff Automotive Deutschland GmbH* and was mounted in a specially designed pillar guiding framework as depicted in Fig. 4 (b). By means of this forming tool, a part can be produced which is partly deformed and has a geometry similar to the half of the torque tube from Fig. 2. The chosen part is still a hollow profile so that the spraying device can be inserted in the profile tube. For the interior spray cooling, different types of nozzles were investigated. Fig. 5 (a) shows a nozzle with an impingement deflector. This type of nozzle deflects the spray from an axial into a radial direction so that the water drops will impact the interior wall of the tube perpendicularly [11]. The advantage of this type of nozzle is the opportunity of an exact positioning of the cooling zone.

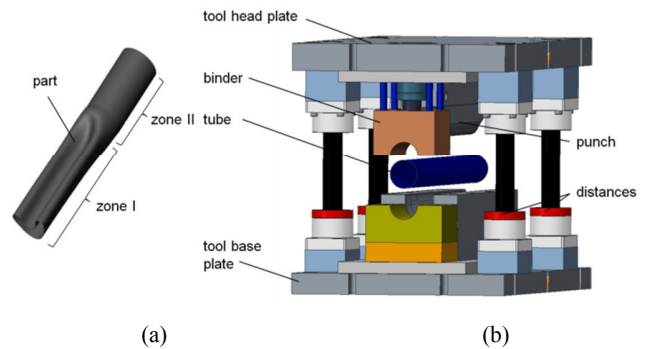


Fig. 4 Part (a) and the CAD model of the forming tool (b)

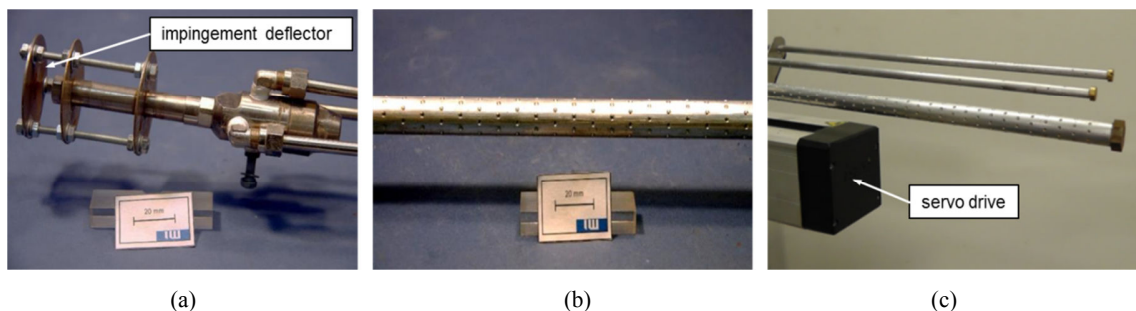


Fig. 5 Spray nozzle with an impingement deflector (a), simple spraying lance (b), triple spraying lance (c)

Furthermore, the cooling zone can be very accurately distinguished from areas which should not be quenched, e.g. soft areas for joining purposes. A disadvantage of this method is the punctual application of water inside the tube. As a result

of the accumulation of water at the bottom of the tube, an inhomogeneous cooling occurs. For this reason, the spray nozzle approach has not been investigated further.

Another nozzle type was investigated as shown in Fig. 5

(b). This spraying lance has a diameter of 15 mm and a spraying length of 550 mm. 55 rows of holes were placed in a distance of 10 mm to each other. Each row consists of 9 holes (\varnothing 0.5 mm) around the circumference. The spraying lance is driven by a servo drive and can perform oscillation movements during the spray cooling in order to ensure a homogeneous cooling rate.

In [11], the local cooling rates were investigated for a tube of a length of more than 500 mm. The tubes were austenitized at temperatures of 950 °C and quenched by using the simple spraying lance. A nearly homogeneous cooling rate all over the tube was observed. Furthermore, different cooling rates were generated by varying the medium pressures for air and water. Satisfactory cooling results could be achieved when cooling the unformed tube by the simple spraying lance. However, in order to achieve an effective cooling of the formed tube areas, for instance of the part (Fig. 4 (a)), a modification of the simple spraying lance is required. For this reason, the simple spraying lance was upgraded with two additional spraying lances for cooling the deformed zones. The triple spraying lance is depicted in Fig. 5 (c) and the lances' position within the formed zone of the tube is illustrated in Fig. 6. By means of the triple-lance, effective cooling of the formed zone of the part is feasible. Especially the upper area of the forming zone (Fig. 6) is hard to reach with the water-air spray when using the simple lance. Furthermore, the cooling rate is relatively low at this point due to the missing tool contact. At the center of the tube, the punch formed a special geometry. The outer areas of the forming zone have no contact with the punch or the die which leads to a low local cooling rate. Fig. 7 shows the measured temperature at one exemplary measurement point located in the forming zone.

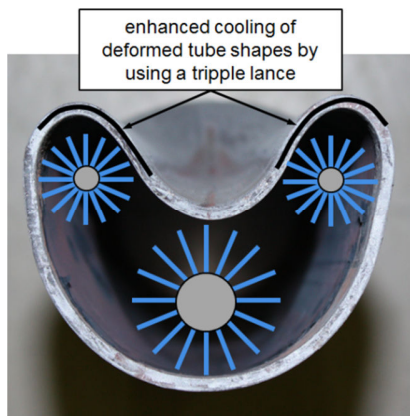


Fig. 6 Position of the triple lance in the formed zone of the part

III. EXPERIMENTS

The tubes for the tests were made of 22MnB5. The outer diameter was 90 mm and the wall thickness was 3.6 mm. Here, no Al-Si coating, which is often used as corrosion- and scale protection for 22MnB5 steels, was applied. Nano X-Tec, produced by the company NANO-X GmbH, was applied to the tube's exterior for scale prevention. The tubes were heated

up to a temperature of 950 °C in a chamber furnace for 8 minutes. A manual transfer of the hot tubes from the furnace into the forming tool was performed. After closing the forming tool, the spraying lance was driven into the tube and the spray cooling was immediately started by an electrical signal from a position sensor for a defined time. After the forming and quenching of the tubes, the forming tool opened directly and the quenched tube was manually removed from the tool. The residual cooling was carried out under simple ambient conditions outside the tool. The part temperature was measured during the entire process by thermo couples and IR-pyrometers at different points.

In the experiments, the spray duration was varied in order to analyse the effects of the different heat treatments on the mechanical properties. For the tests, the air pressure was set to a value of 0.3 MPa and the water pressure was adjusted to a value of 0.5 MPa. These settings were determined as suitable in initial attempts.

IV. RESULTS

The samples, produced with different spray cooling durations, were investigated regarding mechanical properties, e.g. tensile strength R_m , elongation at break A_5 and Vickers hardness. Additionally, the material's ductility was analysed by a three-point bending test.

A. Temperature Measurement

The local temperature was measured by a calibrated IR-pyrometer. With the simple lance, the cooling rate at the measured point is low in comparison to the triple-lance. A lower temperature is achieved in just 14 s at the measured point when using the triple-lance for spray cooling.

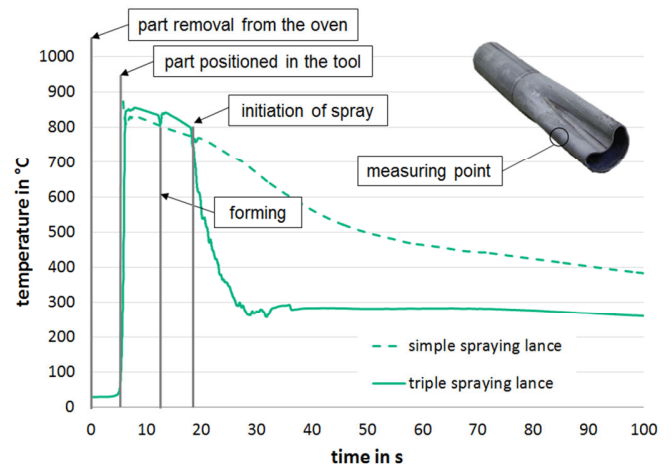


Fig. 7 Local cooling in dependence of the used lances

B. Tensile Tests

The tensile tests were performed on the basis of the standard DIN EN ISO 6892-1. Tensile specimens were taken from the formed zone (zone I) of the profile tube as well as from the unformed part (zone II) of the tube. The removal positions of the tensile specimens of the formed area of the tube are illustrated in the upper part of Fig. 8.

The diagram in Fig. 8 shows the achievable tensile strength R_m and the received elongation at break A_5 of four tubes which were cooled by water-air spray by means of the triple-lance for a duration of 10 s. Despite the high rate of cooling when using the triple-lance in the formed zone, a tensile strength R_m of about 860 MPa was determined. For higher values of tensile strength, tool contact on all sides is required. This was not given for the forming zone of the tube when using the forming tool as illustrated in Fig. 4 (b).

Furthermore, the average elongation at break A_5 was approximately 15 %. Press-hardened sheets with a thickness of 1.2 - 1.5 mm typically have an elongation at break of 5 - 7 %. The reason for the great elongation at break A_5 of the press-hardened tubes is the high tube wall thickness of 3.6 mm. Here, a different ratio of the loaded sample cross-section to surface is existing.

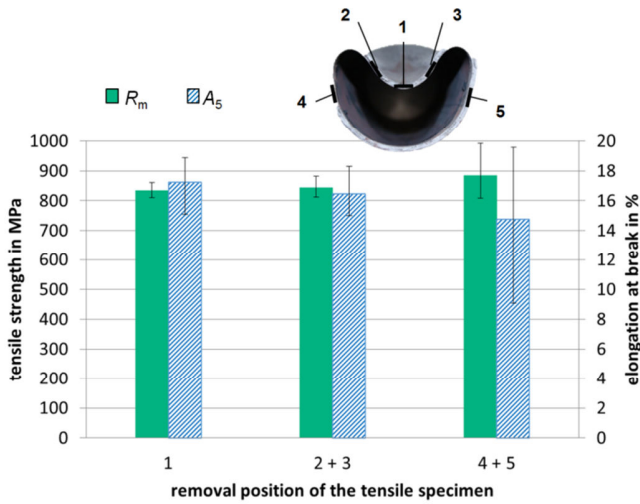


Fig. 8 Tensile strength and elongation at break for tubes cooled by the triple-lance by a 10 s spray cooling

In order to achieve higher values of the tensile strength, a water cooled forming tool is required which ensures an all-round tool contact for an addition heat extraction. For this reason, further tensile specimens were taken from the zone II of the tube in accordance with DIN 50125. In this area, an all-round tool contact is given. The test tubes were quenched by the simple spraying lance since the triple-lance is only required for the deformed part of the tube. Moreover, this part of the tube is in contact with the tool on all sides during the forming process and hence more heat is extracted from the tube. The removal positions of the tensile specimen from the zone II of the tube are depicted in Fig. 9. Two specimens were taken from the upper half of the tube and two further specimens from the lower half. Four tubes with four specimens each were tested for each spray cooling duration.

The tubes used for the tensile tests were cooled with different spray cooling durations. The cooling duration was varied between 2.5 s and 20 s. For each cooling duration, four tensile specimens were used. Fig. 10 shows the results of the tensile tests.

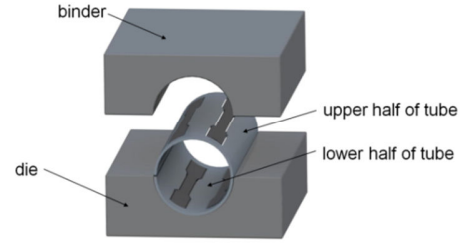


Fig. 9 Positions of the tensile specimens

The tensile strength increased from 933 MPa at 2.5 s of spray cooling up to 1600 MPa for samples of 20 s spray cooling. The elongation at break is reduced from 14 % to a value of about 10.5 % for more than 7.5 s of spray cooling. A longer cooling duration does not increase the achievable elongation at break.

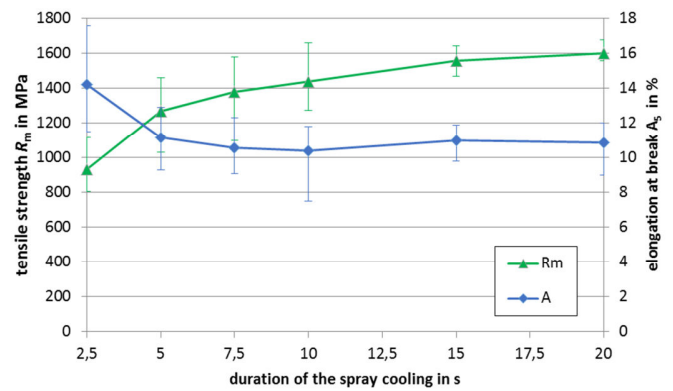


Fig. 10 Mechanical properties of the samples at different spray cooling durations

For some cooling durations, the divergence in the measured values is relatively significant. On the one hand, the reason may be the manual processing such as the manual transfer from the furnace to the forming tool and the manual removal from the forming tool. On the other hand, the divergence of the measurement values can be justified due to the high number of samples.

C. Hardness Tests

Further tubes were used for hardening tests in accordance with DIN EN ISO 6507-1. The hardness measurement was carried out at the center of the upper half of the tube. Fig. 11 displays the average of nine single measurements of hardness in HV10 for each of the five tested tubes which were subjected to different spray cooling durations. Here, low values were observed for the Vickers hardness for short durations of spray cooling. A hardness of 281 HV10 was observed for a sample which was quenched for 2.5 s by water-air spray cooling. 521 HV10 were measured for a sample which was quenched for 15 s.

Due to the fact that the tubes were cooled by tool contact on the outside and by spray cooling on the inside, different local cooling rates may occur. The different cooling rates can result in final microstructures. For this reason, further hardness measurements in order to analyze the distribution of the

hardness around the circumference of the investigated tubes were carried out. The results also show that longer spray times and longer tool contact lead to a greater hardness. Fig. 11 exemplarily shows the hardness around the circumference of a tube which was quenched with water-air spray cooling for 15 s.

For any position around the circumference of the tube the measured hardness is greater than 420 HV10. The lower half of the tube tends to higher values of hardness. The reason may be the longer dwell time in the forming tool. The tube must remain in the lower die until the upper tool has reached its basic position. Until then, the tube cannot be removed from the tool and receives an extended cooling by tool contact.

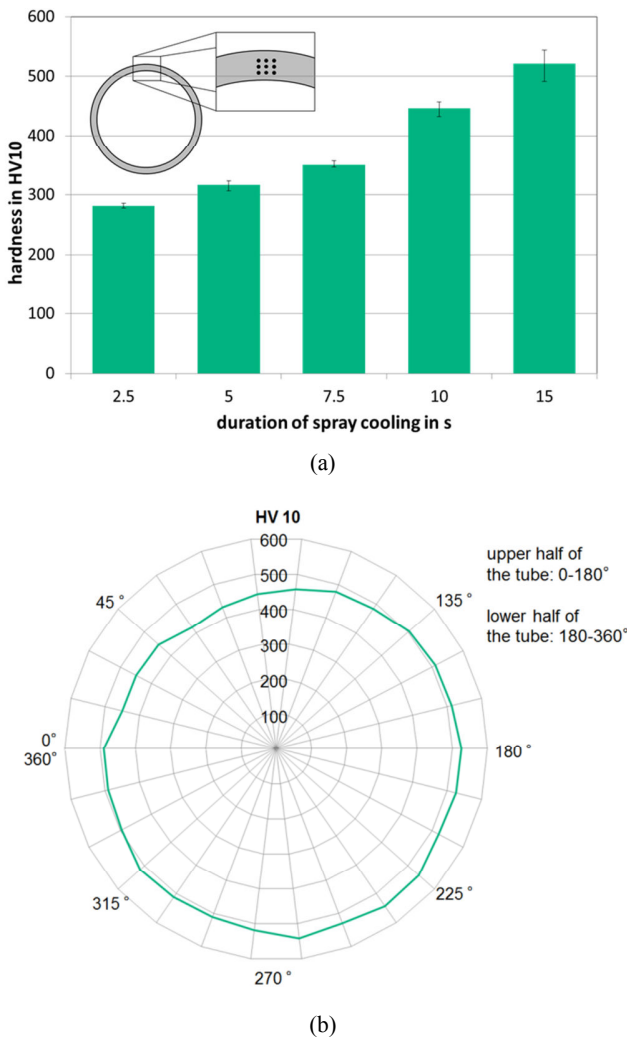


Fig. 11 Hardness in dependence of the spray cooling duration (a), hardness distribution around the circumference of the a tube treated with 15 s spray cooling (b)

In addition, the hardness was measured along the tube thickness due to the different cooling methods for the inside and outside of the tube. The outside of the hot tube was cooled by tool contact whereas the inside was cooled by the water-air spray. This may lead to different cooling rates and subsequently to different microstructures with corresponding

hardness values for the inside and outside of the tube. For this reason, the micro hardness was measured in HV0.1 from the inside ($x = 0 \mu\text{m}$) to the outside of the tube ($x = 3600 \mu\text{m}$). The results are depicted in Fig. 12.

As expected, higher hardness values were observed for longer spray cooling durations. Each curve is a mean of four rows of micro hardness measurements. The micro hardness measurement was carried out in the upper half of the tube. For each investigated cooling duration, a nearly constant hardness over the tube wall thickness was determined.

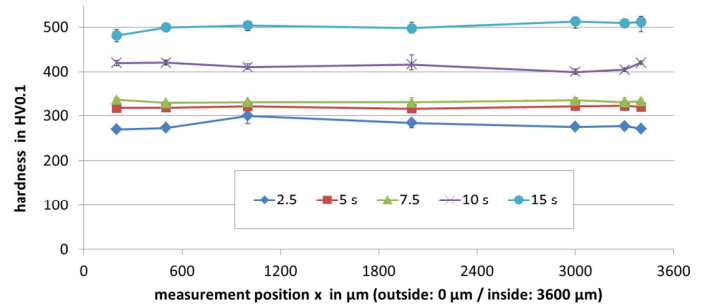


Fig. 12 Hardness measured across the wall thickness

D. Three-Point Bending Test

For an evaluation of the material ductility, some plate specimens were tested by means of the three-point bending test according to the VDA 238-100 test specification. The investigations were carried out on a test bench of the company Kirchhoff Automotive GmbH. Fig. 13 shows the experimental setup and Table I provides the test settings.

The test plates with dimensions of 30 mm x 60 mm were cut out of the upper half of the tubes by a waterjet cutting system. The test plates were taken from tubes quenched at varied spray cooling durations between 2.5 and 15 s. For each cooling duration, two tubes with two test plates each were investigated.

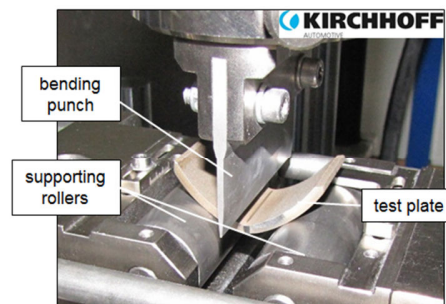


Fig. 13 Experimental setup of the three-point bending test

The material ductility was evaluated according to the force-displacement behaviour as well as the maximum reachable bending angle. Fig. 14 shows the result of the three-point bending test.

TABLE I
 TEST PARAMETERS OF THE THREE-POINT BENDING TEST

Setting	Value
radius of the supporting rollers:	15 mm
radius of the bending punch:	0.4 mm
distance between the rollers:	15 mm
pre-load:	100 N
testing velocity:	20 mm/min

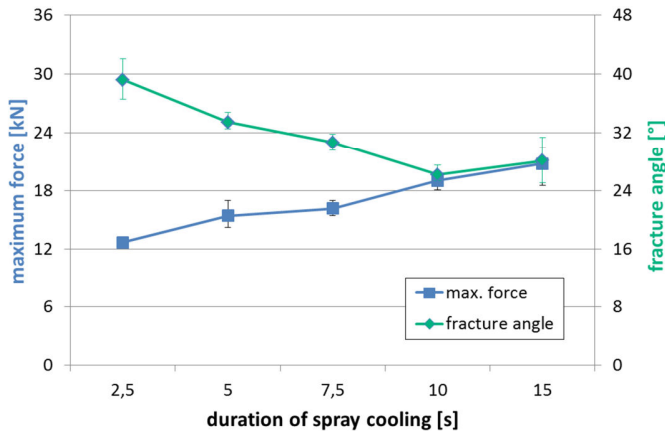


Fig. 14 Results of the three-point bending test

Test plates cooled by a 2.5 s spray cooling show a wide fracture angle of nearly 40°. For bending these samples, a force of just approximately 12 kN was needed due to the bainitic microstructure. The longer the duration of cooling by the water-air spray, the more force is required for bending the samples due to the increased proportion of martensite. The achievable fracture angle is accordingly reduced with an increasing spray cooling time from nearly 40° to a value of

28°. A minimum fracture angle was determined for a spray cooling duration of 10 s. The reason for this effect is probably the tempered martensite embrittlement occurring in a temperature range of 230 - 370°C [12].

E. Metallography

The tubes, which were heat-treated with different spray cooling durations, were investigated metallographically. For the metallographic analysis, the embedded samples were etched with a 4 % picric and 4 % nitric acid and were examined by using a light microscope with brightfield illumination. Fig. 15 depicts different micrographs of samples which were cooled at different spray cooling durations between 2.5 and 15 s. The samples were taken from a part of the tube cooled by outer tool contact and interior spray cooling. The micrographs were taken from the center of the tube wall. The microstructure of a sample which was cooled for 2.5 s has a Vickers hardness of 314 HV0.1 in contrast to a sample taken from a tube which was heat-treated by an intensive 15 s spray cooling with a hardness of 504 HV0.1. The composition of all microstructures is listed in Table II. The amount of martensite increases with a longer duration of the spray cooling.

V. CONCLUSION

The press hardening of tubes in combination with an interior spray cooling is a suitable approach to reducing the manufacturing time. By a variation of the spray cooling parameters, different properties and microstructures can be achieved.

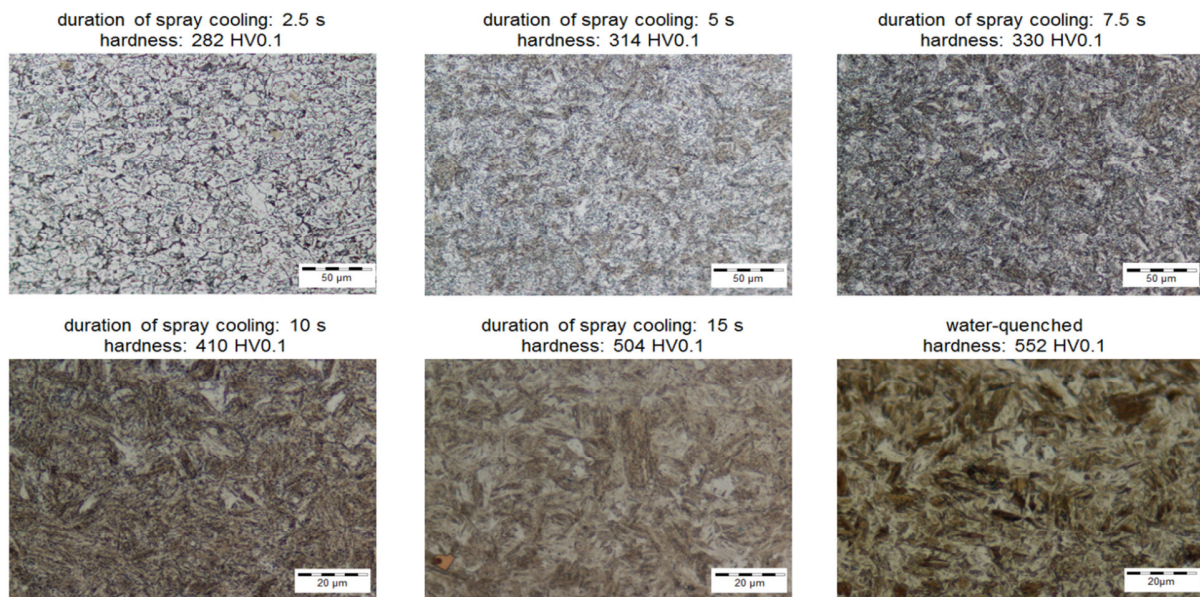


Fig. 15 Microstructure of samples with different cooling duration

TABLE II
COMPOSITION OF THE MICROSTRUCTURE

Duration of spray cooling	Composition of microstructure
2.5 s	ferrite, perlite, carbides and small proportions of martensite
5 s	martensite, bainite, ferrite, carbides and small proportions of perlite
7.5 s	martensite, bainite and traces of perlite
10 s	tempered martensite
15 s	slightly tempered martensite
water-quenched	martensite

A short duration of spray cooling and a short dwell time of the press-hardened tube in the tool leads to soft properties. Moreover, a cooling duration of 2.5 s leads to a tensile strength of 933 MPa and a Vickers hardness of 281 HV10. In contrast, a tensile strength of 1570 MPa and a Vickers hardness of 521 HV10 can be achieved by cooling the tube for 15 s. The fact that longer cooling leads to high strengths values was confirmed. The three-point bending test showed that in order to achieve a similar bending angle in the intensively cooled samples as well as in those samples with shorter cooling durations, considerably more force was required. The reason for this is the increased portion of martensite caused by an extended cooling duration, as revealed by the metallographic analysis.

In conclusion, it can be stated that the interior water-air spray cooling is a helpful tool in shortening and improving the conventional manufacturing process for heat-treated tubes.

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