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ORIGINAL ARTICLE

Sensitivity of process signals to deviations in material distribution and material properties of hybrid workpieces

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Abstract
Hybrid components, made of multiple materials, can meet the increasing demands for lightweight construction and functional integration in the automotive and aircraft industry. Hybrid semi-finished components are produced by applying a high-alloy cladding to a low-alloy base material before hot-forming and machining the workpiece. Throughout this process chain, workpiece deviations in the form of material distribution and material properties can occur that influence the component's lifetime. This paper investigates whether such workpiece deviations can be detected within the process chain by analyzing process signals obtained from subsequent process steps. For this purpose, artificial workpiece deviations were introduced to hybrid semi-finished workpieces made of C22.8/X45CrSi9-3. Then, process signals during forming and machining were analyzed to determine their sensitivity to the artificial deviations. The results revealed that deviations in cladding size can be effectively monitored using signals from both forming and machining. Cladding position deviations can only be detected during machining, while forming signals are more responsive to detecting the introduced hardness deviations of approx. 100 HV0.1.

Keywords Laser hot-wire cladding · Cross-wedge rolling · Machining · Monitoring · Workpiece deviations

1 Introduction

Increasing demands for lightweight design, miniaturization, and function integration in the automotive and aircraft industries can be met with hybrid components made of multiple materials [1]. The local variation of materials allows for the mechanical, chemical, and physical adaption of a component's material properties. By applying high-quality materials in certain areas, components can be manufactured more resource-efficiently [2]. The Collaborative Research Center 1153 has been developing and investigating a continuous process chain for the manufacturing of hybrid shafts. These hybrid shafts can be used in gearbox assemblies. This leads to an increased lifetime since materials with high mechanical strength, and consequently increased abrasive resistance, are applied locally to the centrally integrated bearing surface. The process chain is shown in Fig. 1. First, the high-quality material X45CrSi9-3 is applied to the surface of C22.8 base shaft in the area of the later bearing seat by laser hot-wire cladding (A). Laser hot-wire cladding can increase the mechanical strength of the shaft surface, while the core of the shaft remains ductile. The result is a hybrid semi-finished workpiece. Subsequently, the semi-finished shafts are cross-wedge rolled (B) and machined (C). These process steps are discussed in more detail in the following.

A: In the investigated process chain, laser hot-wire cladding (LHWC) is used as a deposition welding process. LHWC is applicable to various alloys, including steel, aluminum, titanium, and nickel-based alloys [2, 3]. This deposition welding process is suitable for manufacturing high-quality claddings with diverse geometries while minimizing heat input into the component. Previous studies have demonstrated the suitability of LHWC for manufacturing hybrid shafts [4–6]. LHWC allows the production of various cladding geometries without additional machining. This is an advantage over plasma powder transferred arc welding,

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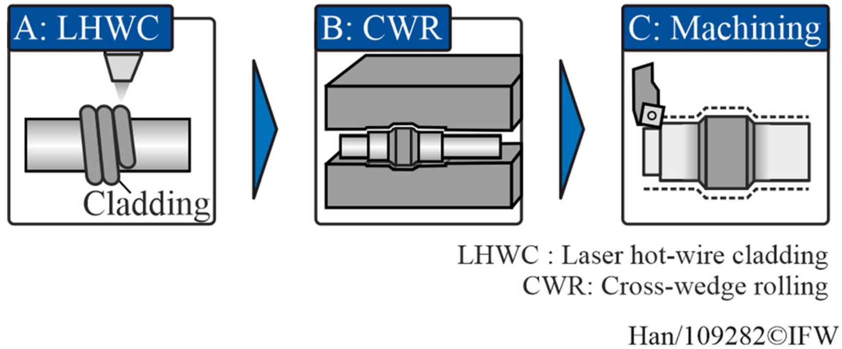

Fig. 1 Process chain for the manufacturing of hybrid components

which requires machining for achieving desired cladding geometries due to lower precision [4]. The cladding material is supplied in wire form. The wire is heated via resistive heating and melted by laser radiation. Preheating the wire reduces the required laser power [7], enabling more precise control over heat input and distribution. Moreover, preheating helps avoid incomplete fusion [8] and increases the deposition rate [3].

B: After cladding, the semi-finished components are hot-formed through cross-wedge rolling (CWR) to achieve a near net-shaped geometry. Current research on the CWR of mono-material components primarily focuses on identifying the causes of the Mannesmann effect, which is undesirable void formation in the rolled part, during the rolling of steel alloys [9–11]. Pater et al. [12, 13] utilized simulations to predict the Mannesmann effect. Alternatively, it can be measured by ultrasonic or X-rays.

C: After cross-wedge rolling, the hybrid components are machined. A cutting process is necessary to finalize the geometry and to adjust the surface properties. Machining of hybrid components requires the adaption of process parameters, e.g., feed and cutting speed, based on the material being cut [14–16]. This adaption reduces diameter deviations in the final workpiece geometry caused by displacements. To adapt the process parameters, it is essential to have knowledge about the position of the material transition. This position can be identified by monitoring the process forces [17].

During the production of hybrid components, disturbances can occur in each process step. Such disturbances can be due to factors like varying thermal conditions or errors in the manual loading of a machine. In the case of the considered hybrid shafts, these disturbances result in deviations in cladding distribution and material properties, significantly reducing the component's lifetime. Usually, material distribution and properties of randomly selected components are directly measured in destructive tests at the end of the line. Therefore, there is no assurance that all components will later achieve the desired lifetime.

A non-destructive approach for identifying such workpiece deviations is the monitoring of process signals. Existing studies focus on detecting diameter deviations in mono-material components through process signals. In [18], it was shown that the pressure curves of CWR are sensitive to the resulting diameter of shafts and, thus, can be utilized to predict the diameter when manufacturing with varying roll gaps. In machining, process forces are used to detect various process errors [19, 20]. A recent study by Denkena et al. [21] has demonstrated that cutting force is sensitive to initial deviations in the depth of cut during face turning. For friction-welded hybrid components, Ullah [22] investigated the corresponding process forces of various material combinations to identify optimal machining parameters and direction. In summary, the literature indicates that diameter deviations during CWR and machining of mono-material workpieces can be detected from corresponding process signals. For hybrid workpieces, it is currently unknown if deviations in material distribution and material properties of hybrid semi-finished workpieces can be detected from process signals. A prerequisite for such monitoring is that process signals are sensitive to the monitored deviations, which has not yet been investigated.

This paper focuses on analyzing the sensitivity of process signals from cross-wedge rolling and machining to deviations in material distribution and material properties in hybrid workpieces. The investigations were conducted using the initially described process chain. To ensure the reproducibility of the results, the investigation is performed on samples with artificially induced deviations. Therefore, the cladding size and position, as well as the hardness of the samples, are adjusted by varying specific process parameters in LHWC and CWR. In Section 2, the preparation and characterization of these specimens, as well as the experimental setup, are described. In Section 3, the sensitivity of subsequent process signals to the artificially induced deviations is investigated.

2 Experiments

To analyze the sensitivity of process signals from CWR and machining to deviations in material distribution and

Table 1 Parameters for reference process and process variations

	Process	Deviation	Parameter	Reference (Ref.)	Variation
Var. 1	LHWC	Mat. properties	Base material	C22.8	20MnCr5
Var. 2	LHWC	Mat. distribution	Cladding width	11 Seams	6 Seams
Var. 3	LHWC	Mat. distribution	No. of cladding layers	2	4
Var. 4	LHWC	Mat. distribution	Cladding displacement	0 mm	+5 mm
Var. 5	CWR	Mat. properties	Temperature	1,270 °C	1,170 °C
Var. 6	CWR	Mat. distribution	Roll gap	28.0 mm	27.5 mm
Var. 7	CWR	Mat. properties	Cooling method	Air-cooled	Quenched in water

properties, the deviations were artificially induced along the process chain. Section 2.1 describes the preparation of specimens with artificial deviations in material distribution and properties and the characterization of the induced deviations. The experimental setup for process signal acquisition is outlined in Section 2.2.

2.1 Prepared specimens

For the preparation of specimens with similar deviations, parameters of LHWC and CWR were varied, as the material distribution and properties of the semi-finished components can be significantly influenced by these processes. In addition to the specimens with deviations, specimens with reference parameters were also prepared. The reference parameters (Ref.) and the variations (Var.) are listed in Table 1 and described in the following.

For the specimens, simple shafts of unalloyed mild steel C22.8 [23] were used as the base material. To simulate a deviation in the material properties, 20MnCr5 [24] was used as the alternative base material (Var. 1). In the LHWC process, martensitic valve steel X45CrSi9-3 [25] was applied to the bearing surface area using a coaxial deposition welding head in spirally overlapping weld seams. The applicability of the tailored forming process chain for manufacturing hybrid shafts with these material combinations has already been demonstrated in previous studies [4–6].

The material distribution was adapted in three dimensions: the cladding width (Var. 2) through a variation in the number of weld seams next to each other, the cladding height (Var. 3) through a variation in the number of cladding layers above each other, and the local position of the cladding (Var. 4) in the axial direction through a simple offset. Since it is not known whether deviations in cladding size affect the subsequent processes and whether they can be monitored with process signals, major changes to the reference values were chosen. For each parameter set, seven specimens were prepared by LHWC with varied process parameters, then cross-wedge rolled and finished without further variation of the process parameters. After LHWC and CWR, one specimen from each parameter set was used for the preparation of cross-sections and the measurement of hardness to identify the induced deviations in material distribution and properties. All hardness measurements were carried out with an INNOVATEST NEXUS 4303 with a test force of 0.98 N and a test force uncertainty of less than 1%.

The material distribution after LHWC for the manufactured specimens is depicted in Fig. 2. As the adapted base material (Var. 1) and the cladding displacement (Var. 4) do not influence the cladding's size in height or width, they are not shown in Fig. 2. The impact of these deviations on the material distribution after CWR is illustrated in Fig. 3. If the cladding width after LHWC is smaller than the reference (Var. 2), the bearing surface after CWR is no longer entirely covered. This lack of coverage could potentially result in a significantly shorter component lifetime and needs to be detected during manufacturing. In the case of the displaced cladding, the bearing seat is covered, but the material distribution is asymmetric. However, because material is removed during machining, the height of the cladding will be reduced, potentially leaving the bearing seat of the finished component uncovered.

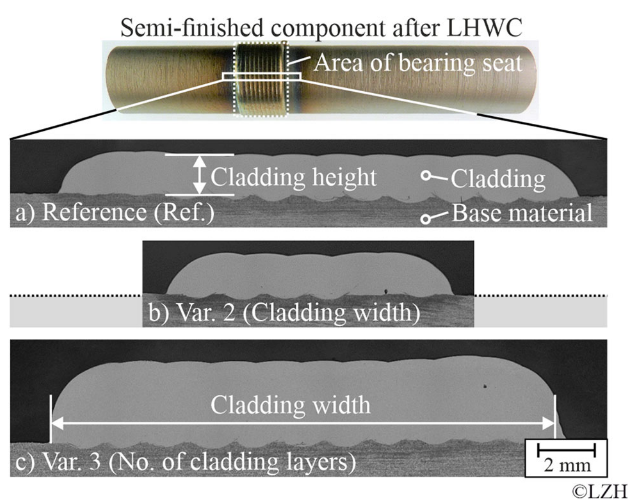

Fig. 2 Cross-sections of welded specimens

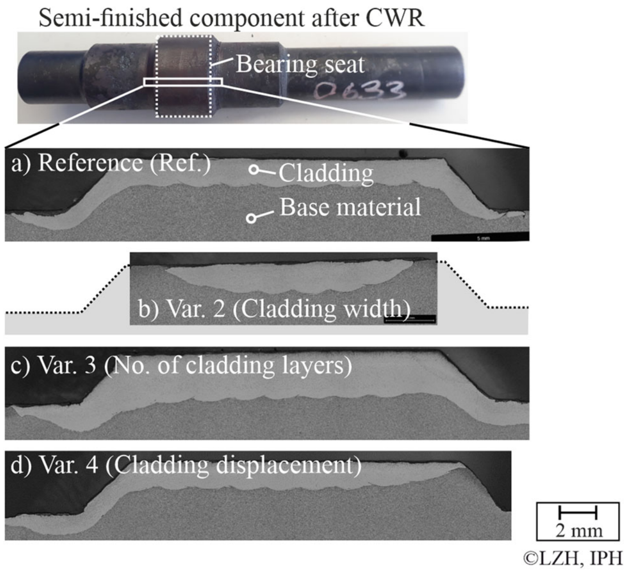

Fig. 3 Cross-sections of formed specimens

The hardness profiles of the cladding with all variations induced by LHWC are presented in Fig. 4a. For each parameter set, a series of 45 measurements were taken from the cladding in the direction of the base material. The hardness of the reference cladding (Ref.) falls between 700 HV0.1 and 760 HV0.1, which aligns well with the results of previous studies [5, 6]. Specimens with a higher number of cladding layers (Var. 3) exhibit slightly decreased hardness in the lower layers due to the higher heat input during LHWC. The hardness of the C22.8 base material is 160 HV0.1, while the hardness of the 20MnCr5 base material (Var. 1) is slightly higher. This difference becomes more pronouned after CWR (Fig. 4b) due to the heat treatment and the distinct effects on both C22.8 and 20MnCr5.

In addition to specimens with deviations caused by the LHWC process, specimens with deviations resulting from changes in the CWR process were prepared. For this purpose, specimens without previous deviations were used and cross-wedge rolled with varying process parameters. Subsequently, they were finished without further variation in the process parameters. Deviations in material properties were induced by lowering the temperature of the workpieces at the process start (Var. 5) and by adapting the cooling method after the process (Var. 7). Additionally, the roll gap (Var. 6) was modified to alter the workpiece geometry and, thereby, the material distribution in the radial direction. In the axial direction, the change in the roll gap had only a minor influence on the position of the material transition. The cross-section, therefore, does not differ from the reference and is not depicted in Fig. 5. The hardness profiles in Fig. 5 show that the modified temperature (Var. 5) had no significant influence on the hardness of the cladding or the base material. Instead, the cooling method had a significant influence on both the hardness of the cladding and the base material. If the specimens are quenched (Var. 7), then the hardness of the cladding increases up to a range between 720 HV0.1 and 810 HV0.1 while the fluctuation decreases. The measured hardness values correspond well with the results obtained in [5]. The hardness of the base material, however, increases to over 400 HV0.1 if quenched. This is due to the higher cooling rates during quenching, which suppress grain growth and result in a finer microstructure.

2.2 Experimental setup

For the CWR, a self-built module was used, consisting of an upper and a lower tool in a flat jaw design. These tools move in opposite directions through hydraulic cylinders at a speed of 150 mm/s (Fig. 6). Cartridge heaters, inserted into an aluminum plate, heat the tools to a temperature of 150 °C. Before the process, the workpieces were heated to 1,350 °C

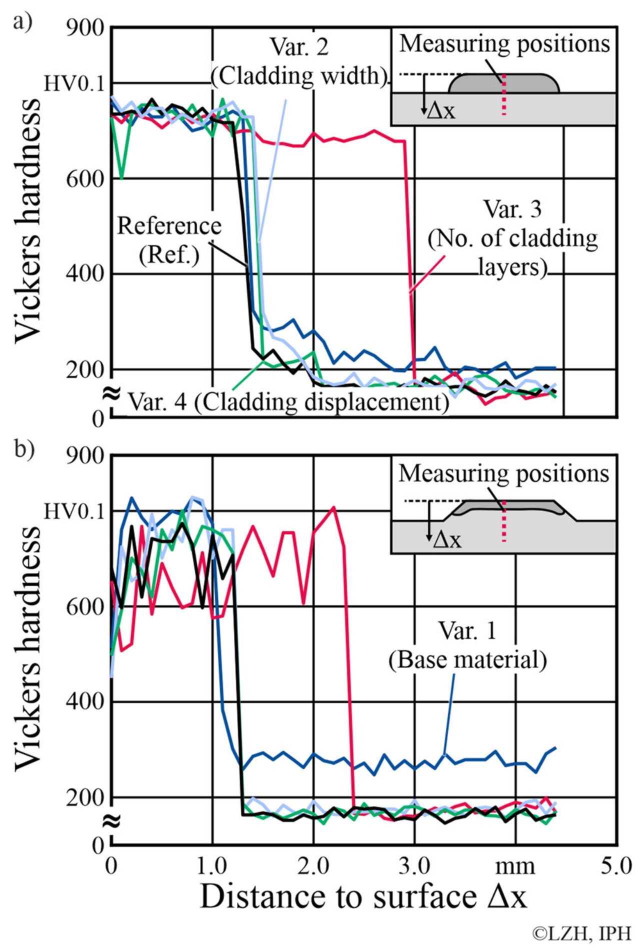

Fig. 4 Hardness for parameter variations in LHWC: a) after LHWC, and b) after CWR

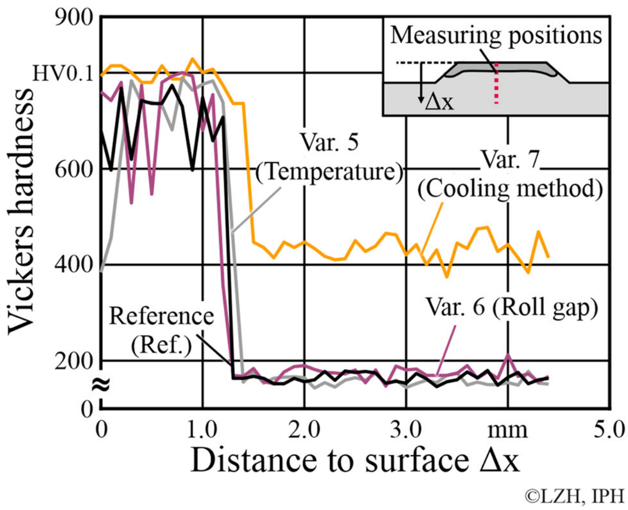

Fig. 5 Hardness for parameter variations in CWR

using an induction heating system from EMA-TEC GmbH (Type EBS 10 - SSK 20/200). After manual positioning of a specimen and the lowering of the upper tool, the forming process began with a workpiece temperature of 1,250 °C. During the CWR, the pressure of the hydraulic cylinders and the position of both tools were continuously monitored using a universal measuring amplifier (type: QuantumX MX840B), a glass-scale distance measuring system, and force transducers inside the hydraulic cylinders. Additionally, a pyrometer was used to measure the temperature of the hybrid workpiece during the process. The measurement frequency was set to 30 Hz, ensuring accurate detection of deviations while minimizing the data requirements.

In the final stage, the semi-finished workpieces underwent turning on a Gildemeister CTX420 linear lathe. An industrial personal computer (IPC) was used to capture the process forces from a Kistler 9129A piezoelectric multicomponent dynamometer, operating at a sampling frequency of 1 kHz, and to record the axis positions from the numerical control unit (NCU) of the lathe at a sampling frequency of 83 Hz. Kistler 5011 charge amplifiers with a low-pass filter of 300 Hz were used to process the piezoelectric signals of the dynamometer. The machining setup is depicted in Fig. 7. CBN indexable inserts with a DNGA150608

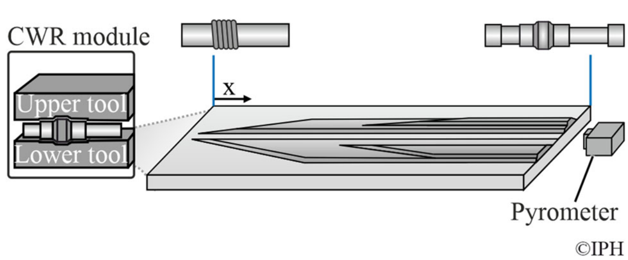

Fig. 6 Lower tool for CWR

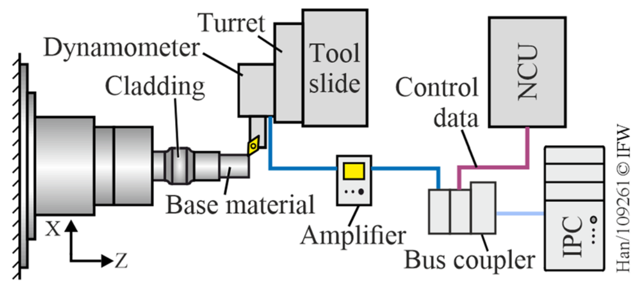

Fig. 7 Experimental setup for turning

geometry, combined with a PDJNL 2525 M15 clamp holder, were used. The workpieces were machined with a cutting speed of v_c = 120 m/min, a feed rate of f = 0.15 mm, and a depth of cut of a_p = 0.3 mm, using cooling lubricant and a rotary centering tip. The parameters were selected based on manufacturer specifications. The workpieces were securely clamped in the position shown in Fig. 7, using a clamping head SK 42 with a round profile.

3 Results

To evaluate the suitability of different features for monitoring, the sensitivity of process signals from CWR process (Section 3.1) and machining (Section 3.2) to the induced workpiece deviations is analyzed.

3.1 Monitoring of workpiece deviations by process signals of cross-wedge rolling

In CWR, the measured pressure of the hydraulic cylinders was analyzed based on the position of the tools. Figure 8 illustrates an exemplary pressure curve of the CWR process for a reference specimen. The curve exhibits two local maxima and an intermediate local minimum. The first half of the curve, up to the local minimum around position x = 700 mm,

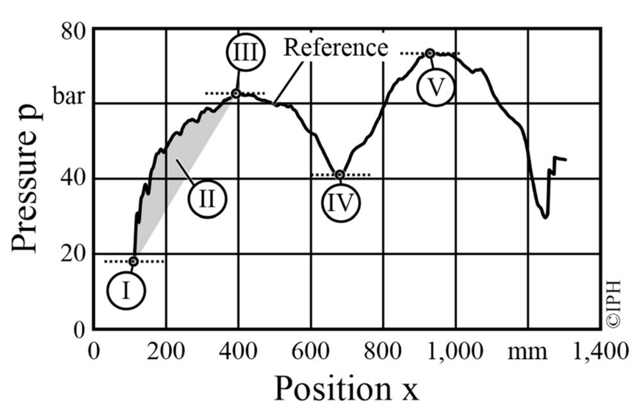

Fig. 8 Pressure curve of CWR with characteristic points

represents the formation of the bearing surface, while the second half represents the shaping of the adjacent shaft sections. A commonly used strategy for monitoring various manufacturing processes is determining and analyzing characteristic features of the process, such as maxima or minima. For this process, five characteristic features were defined, as depicted in Fig. 8. Point I is the starting point of the curve and is constant for all measurements. Point III is the first local maximum of the curve, and Area II refers to the area between the pressure curve and the straight line from I to III. The size of this area was analyzed to evaluate the curve's shape and, thus, the slope of the first area, in a standardized manner. Point IV is the minimal turning point between the two maxima of the curve, while Point V marks the second maximum of the curve.

The mean pressure curves for all parameter sets are displayed in Fig. 9. It can be observed, that certain process variations have a significant influence on the characteristic shape of the pressure curve (e.g. Var. 2). Other variations, however, only affect the height of the pressure curve, with the shape remaining similar (e.g. Var. 1). To determine the impact of each variation on the process signals, the previously described characteristic features were calculated for all variations. The mean features III, IV, and V, along with their standard deviation, are presented in Fig. 10a, while feature II is depicted in Fig. 10c. The measured temperature of

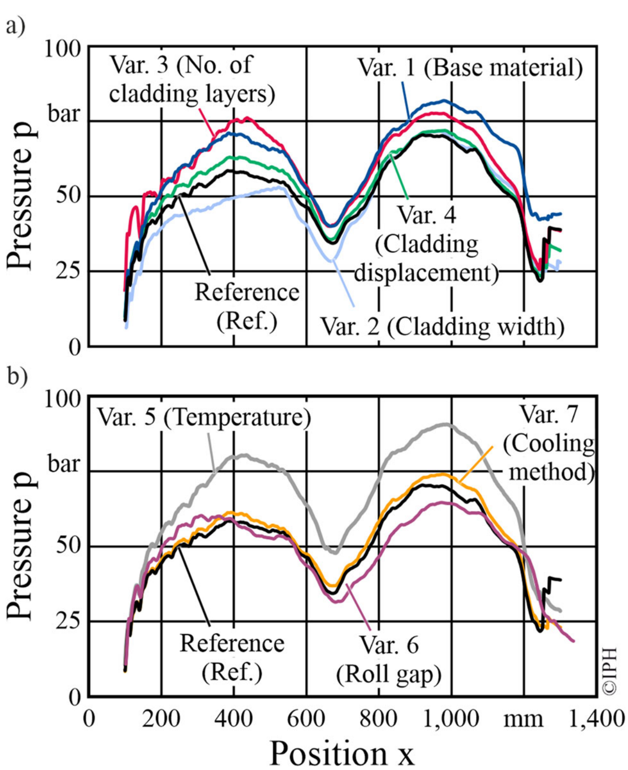

Fig. 9 Pressure curves of CWR: a) parameter variations of LHWC and b) parameter variations of CWR

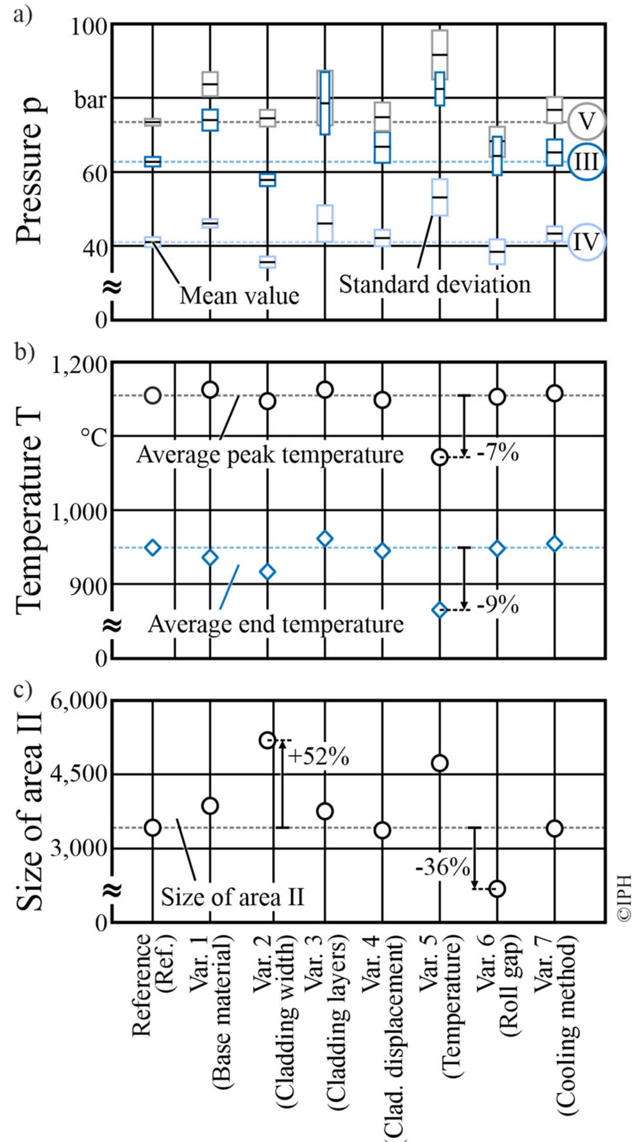

Fig. 10 a) Pressure values of characteristic points III, IV and V, b) temperature curves, c) size of the area II

the workpieces is shown in Fig. 10b. The changes in CWR process signals due to the induced process variations are described below.

In the case of a variation in base material (Var. 1), a more highly alloyed material was used. 20MnCr5 requires more force for forming than C22.8, as illustrated in Fig. 9a. The shape of the pressure curve is qualitatively similar to that of the reference curve (Ref.), but the pressure values are consistently higher. Thus, the difference between III and V for Var. 1 is similar to the difference between them for the reference set (Fig. 10a).

For a reduction in cladding width (Var. 2), a 52% larger Area II than the reference was calculated. Also, an 8% lower maximum force III, as well as a 13% lower minimum force

IV, were determined (Fig. 10a). The lower force values result from the fact that the shape filling of the bearing seat, which occurs in the first part of the process (between I and IV), requires less force when less material is present. In the second part of the process (between IV and the end of the process), the other areas of the workpiece were formed. These were not influenced by less cladding, thus leading to values in Point V similar to the reference specimens (Ref.).

With an increased number of cladding layers (Var. 3), the slope of the pressure between I and III was significantly higher than that of the reference (Fig. 9a). The maximum III was established to be 25% higher than for the reference set (Fig. 10a), resulting in a 10% larger Area II (Fig. 10c). Point V is similar to III, meaning that forces in the first and the second half of the process are alike. The overall higher pressure in III and V, compared to the reference, is caused by the larger amount of cladding material in the bearing seat area. Additionally, the temperature values indicate that the greater amount of applied material resulted in less energy input by induction heating. Thus, the initial temperature of the workpieces in the forming process was lower than the reference.

In the case of cladding displacement (Var. 4), the value of III is 6% higher than the reference, as seen in Fig 10a. Since the cladding was positioned in a different area of the tool, the forming degree of the cladding material and, thus, the pressure values are higher. As with the cladding width variation (Var. 2), the value for V is not significantly affected by the displacement of the cladding. The deviations of Point V from the reference pressure are minimal. Due to the high standard deviations of Point III, the cladding displacement cannot be robustly identified through pressure signals.

For a reduced forming temperature (Var. 5), very high values for II to V were determined. Compared to the reference, the size of Area II increased by 38%, the maximum force III increased by 31%, and V by 25%. The minimum force IV grew by 30%. At lower temperatures, higher yield stresses were required for forming. From the pyrometer data in Fig. 10b, it can be observed that the temperature of the bearing seat was approx. 100 °C lower throughout the process than that of the reference (Ref.).

The reduced roll gap (Var. 6) resulted in a high slope at the beginning of the process, between I and III (Fig. 9b), causing Area II to be 36% smaller than the reference (Fig. 10c). In the subsequent process section, the forces were lower compared to the reference curve (Fig. 9b).

Since the cooling is carried out after the CWR, the variation of the cooling method (Var. 7) has no influence on the process signals during the CWR.

It can be concluded that detecting workpiece deviations in material distribution and properties during CWR is possible by analyzing pressure and temperature measurements. Features II to V and the measured temperature from the pyrometer can distinguish deviations. Due to high standard deviation in the pressure measurements of Var. 3, 4 and 5, it is not possible to completely discern the specific causes of deviations. However, the occurrence of a deviation from the reference process can be identified. Moreover, since the pressure is measured for specific sections of the workpiece, a precise local identification of the deviations is not possible. For example, the exact position of the cladding and whether it is displaced to the left or right cannot be determined by process signals from CWR.

3.2 Monitoring of workpiece deviations by process signals of machining

To investigate the sensitivity of machining process signals to initial workpiece deviations in material properties and distribution, the process forces were measured. Figure 11 displays the feed force F_f in two relevant areas of the hybrid shafts (the bearing surface in green and the adjacent shaft shoulder in blue). The analysis of the feed force allows for the determination of the material transition position between the base material and the cladding, as the material transition is characterized by a significant increase in feed force resulting from different material properties. Thus, in contrast to CWR, the cladding distribution can be determined during machining. The achievable resolution of the material transition position

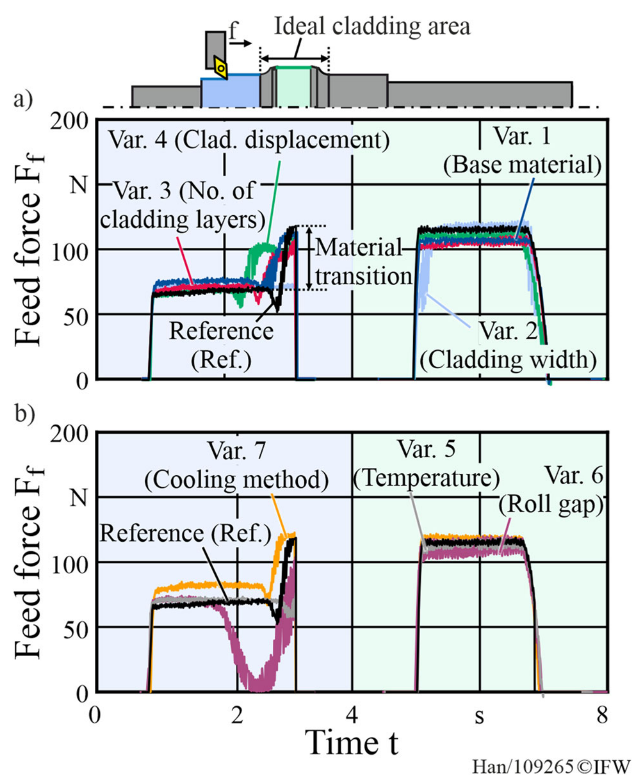

Fig. 11 Feed forces in machining a) variation of LHWC and b) variation of CWR

is dependent on the feed rate and the sampling frequency of the axis positions. For the selected feed rate, the axial resolution of the material transition is around 0.05 mm.

Examining the position of material transition on the left side of the cladding area reveals that the reference specimens' cladding typically begins, on average, 1.6 mm before the ideal cladding area in the feed direction. In the case of cladding displacement (Var. 4), the cladding begins, on average, 6.1 mm before the ideal cladding area indicating a consistent displacement of the cladding in LHWC by 5 mm throughout the process chain. For specimens with more cladding layers (Var. 3), the material transition occurs, on average, 2.9 mm before the ideal position, while specimens with smaller cladding width (Var. 2) exhibit a transition, on average, 6.8 mm after the ideal position. Other variations in process parameters do not significantly affect the position of the material transition, resulting in outcomes similar to the reference parameters.

In addition to cladding distribution, material properties also influence the feed force. The slightly higher hardness of the 20MnCr5 base material (Var. 1) results in up to a 12% higher feed force in the base material compared to the reference (Fig. 11a). Thus, the deviation is not as significant in the feed force as it is in the pressure signal during CWR. The quenched specimens (Var. 7) also exhibit a higher feed force in the base material, up to 20% compared to the reference specimens (Fig. 11b). Since cooling takes place after the CWR, it can only be identified during the machining. The smaller roll gap (Var. 6) leads to material defects in the adjacent shaft shoulder, causing a significant, local decrease in the feed force for the area of the material defect. The lower temperature during CWR (Var. 5) has a significant influence on the pressure during CWR. However, as it does not affect the material transition or properties, the feed force during turning is similar to the feed force of the reference specimens.

4 Conclusion

The results demonstrate that each of the different workpiece deviations introduced influences at least one of the evaluated process signals. However, the influence varies in terms of the local spread of a deviation and the sensitivity of signals to a deviation. The deviations in cladding width (Var. 2), cladding height (Var. 3), or cladding displacement (Var. 4) are locally limited, while the altered base material (Var. 1), temperature (Var. 5), roll gap (Var. 6), and cooling method (Var. 7) affect the signals over the entire process. Localizing deviations in the cladding (Var. 2-4) is easier using the signals of the machining process, as the tool engages only in a small area of the workpiece. However, the small contact area between the tool and the workpiece during machining is disadvantageous when monitoring hardness deviations (Var. 1, 7), as they only slightly increase the process forces. A large contact area, as is the case with CWR, is therefore advantageous for monitoring hardness deviations. This results in deviations in the material properties having a significant influence on the process signals.

Table 2 Summary of sensitivity regarding workpiece variations

	Parameter	CWR	Machining
Var. 1	Base material	+	o
Var. 2	Cladding width	+	+
Var. 3	Cladding layers	+	+
Var. 4	Clad. displacement	-	+
Var. 5	Temperature	+	-
Var. 6	Roll gap	o	+
Var. 7	Cooling method		o

[+] High monitorability [o] Moderate monitorability [-] Not monitorable

The monitorability of the investigated workpiece deviations by process signals is summarized in Table 2 based on the results of Section 3. The monitorability of the workpiece deviations is evaluated in three categories: not monitorable, moderately monitorable, and highly monitorable. For CWR, the monitorability was classified as high if the mean value of a characteristic point deviates significantly from the reference, and the standard deviations do not overlap. Moderate monitorability is determined if the mean value of a characteristic point deviates significantly from the reference, but the standard deviations overlap.

For machining, the deviations in cladding size were determined to have a high monitorability because the position of the cladding can be determined with high resolution of around 0.05 mm in axial direction. Thus, even small axial deviations in cladding distribution can be measured. In contrast, the monitorability of hardness deviations (Var. 1, 7) is only moderate, as the process forces only slightly deviate from the reference. Additional process errors, such as tool wear, can lead to an even lower monitorability, as they could overlay the effects of the hardness deviation on the process forces. A reduced forming temperature (Var. 5) could not be monitored by process forces during turning, as it did not influence the resulting material properties. Since the two processes, CWR and machining, react differently to workpiece deviations, they are differently well-suited for identifying different workpiece deviations. Therefore, it is necessary to combine information from both processes to holistically monitor faulty workpiece deviations.

The investigations also showed that different workpiece deviations can have a similar effect on signals. This is demonstrated, for example, in CWR, where a varied base material

(Var. 1) and an incorrect workpiece input temperature (Var. 5) during rolling cause a similar increase in the characteristic points. It is not always possible to conclusively determine the cause of the process signal deviation from the data.

5 Summary and outlook

Hybrid components are advantageous for lightweight design and function integration. They are manufactured in a process chain using laser hot-wire cladding (LHWC), cross-wedge rolling (CWR), and machining. High-alloy material is deposited on a low-alloy base material as cladding. Deviations in the cladding distribution and material properties that occur during single process steps of the process chain can lead to defects such as faulty material distribution. Typically, these defects are detected through destructive tests conducted on a random basis. To identify these defects without resorting to destructive tests, process signals of the individual process steps are monitored.

This paper investigated the sensitivity of process signals in CWR and machining to workpiece deviations in material distribution and properties caused during LHWC and CWR. Deviations in material distribution and material properties were artificially introduced into the semi-finished workpieces. In CWR, hydraulic pressure data and temperature measurements were analyzed, while in machining, the process forces were analyzed. The core findings are summarized as follows:

- Deviations in the hardness of the base material of approximately 100 HV0.1 are most effectively detected using the hydraulic pressure in CWR.
- The displacement of the cladding by 5 mm cannot be reliably monitored using process signals from CWR.
- Deviations in material distribution can be determined with an axial resolution of 0.05 mm by process forces during machining.
- Combining data from CWR and machining processes is likely to enhance the monitoring of faulty workpiece deviations, as these processes provide different information.

It has been demonstrated that process signals can serve as a non-destructive testing method to detect initial workpiece deviations in cladding distribution and material properties. The monitoring results can then be used to adjust process parameters, preventing subsequent workpieces from inheriting the same defects. This requires a deep understanding of the various processes. Only then can suitable countermeasures be identified and implemented. For instance, if machining reveals insufficient cladding coverage on the bearing seat, the cladding width prepared by LHWC can be adapted for the subsequent components. Similarly, compensating for faulty material properties can be achieved by adapting the temperature of the workpieces or adjusting the contact duration between the workpiece and the tool during CWR.

In the future, the focus of investigations will be on applying the new knowledge to the process chain to minimize defects. The analysis will include assessing the sensitivity of the process signals to smaller workpiece deviations and exploring the possibility of predicting workpiece quality using process signals. Furthermore, a control approach will be developed to ensure the quality of hybrid workpieces throughout the entire process chain by adapting process parameters.

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Data Availability Datasets related to this article can be found at https://data.uni-hannover.de/dataset/monitoring-of-hybrid-workpiece-deviations-by-process-signals, hosted at Institutional Repository of Leibniz Universität Hannover [26].

Declarations

Competing of interest The authors have no relevant financial or non-financial interests to disclose.

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