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Development of an alternative joining technique for balers

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Like many other sectors, agriculture is facing the challenge of finding new solutions for dealing with traditional plastics like polypropylene (PP). In Germany, around 7,800 tons of bale twine made from PP are consumed every year. However, PP will be in limited supply in the future and is a non-biodegradable plastic. One solution is to save material. The objective of this research is the development of an alternative joining technique for balers based on magnetic bicomponent fibers. These bicocomponent fibers can be welded by means of induction. The process for producing the magnetic bicomponent fibers is explained in detail. First results of induction welding on a laboratory scale are also presented. This form of adhesion bonding results in efficiencies of up to 97.6 % and thus much higher than the efficiencies of knotting bale twines (47 to 72 %). Accordingly, material can be saved with this solution approach.

Keywords
Balers, joining technique, sustainability, sheath-core bicomponent fibers, induction welding

Over the last few decades, plastics have found their way into all areas of industrial production (Baur et al. 2018). Thus, plastics are also used in agriculture, with German agriculture consuming more than one million tons of plastics annually (Bertling et al. 2021). Figure 1 shows four examples of plastic usage in agriculture: Foil for silage and round bales, bale twine for straw bales, bale net for round bales.

Figure 1: Four examples of plastic usage in agriculture (© Bertling et al. 2021)

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Typically, standard plastics such as polypropylene (PP) or polyethylene terephthalate (PET) are used (Kalberer et al. 2019). PP is used for the production of bale twines for balers for square and round bales (Kreyenhagen 2017). PP is easy to process, meets the mechanical requirements and is one of the cheapest plastics (Fourné 1999). When processed to bale twines, PP is film extruded, stretched and finally fibrillated before winding as shown in Figure 2.

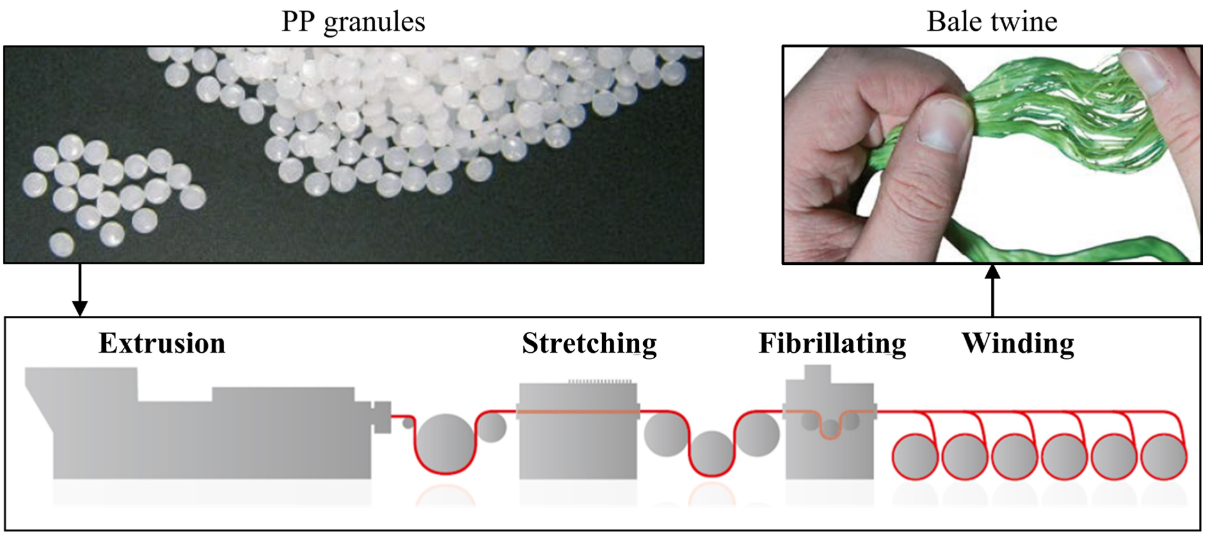

Figure 2: Bale twine production (Pictures from Krone 2018)

About 7,800 tons of bale twine are consumed annually in Germany (Bertling et al. 2021). However, PP is derived from petroleum, which means its availability may be limited in the future. In addition, PP is a non-biodegradable plastic (Endres and Siebert-Raths 2011). The research into alternatives is very important (BMEL 2016) and is also demanded by politics among others, as demonstrated by initiatives such as the European Green Deal (European Commission 2024). Recycling used bale twines is one solution (Claas 2023). In this case, the used bale twine is collected and new products can be made after reprocessing.

Another approach is to reduce material usage in bale twine. Since the bale twine is knotted during the bale manufacturing process, the knot represents the weakest link in the chain. Cormick and Deering knot are the established knots in balers (Kreyenhagen 2017). Table 1 shows with data taken from Kreyenhagen 2017 the strengths of the pure bale twines and the efficiencies of the knotted bale twines depending on fineness. The fineness does not have a significant effect on strength. However, it can be observed that the efficiency improves with higher fineness. The Cormick knot tends to have a higher efficiency than Deering knot. Overall, efficiency varies between 47 and 72 %. One way to save material in bale twine would therefore be to increase the efficiency of the knots. However, this approach has already been investigated (Kreyenhagen 2017) and did not result in higher efficiencies.

Table 1: Different joining techniques and their properties (data from Kreyenhagen 2017)

Method	T in m/kg	σ in MPa	η in %	
Knotting bale twines	85	363	59	(Cormick)
			47	(Deering)
	115	336	72	(Cormick)
			62	(Deering)
Friction welding strapping bands	69	364	98	
	80	285	83	
T, σ and η refer to fineness, strength and efficiency, respectively.				

Higher efficiency could be achieved by using a different joining technique. PET strapping bands have been joined by using friction welding (Kreyenhagen 2017, Table 1). The fineness of the strapping bands is less than that of the bale twines. The strengths are in a similar value range. Due to the fact that this type of joining is an adhesion bonding, efficiencies of 83 to 98 % could be achieved. This approach was developed to the point of integration into a square baler.

In this article, another researched technique to join bale twine ends is proposed. The joining technique being considered is induction welding based on magnetic bicomponent fibers. The basic principle of the production of the bicomponent fibers is explained in detail. Results from induction welding on a laboratory scale also are presented and compared to the knotting systems. The values show that the efficiency of the joint is similar to that of friction welding. Thus, the joining technique in form of induction welding has the potential to save material in bale twines and to replace the current knotting system.

Experimental setup

Basic principle

The basic principle of induction welding by using magnetic bicomponent fibers has been presented in Marx et al. (2023a) and can be seen in Figure 3. Polymer granules and technical oxide are mixed by compounding (Kohlgrüber et al. 2022). The magnetic compound (sheath) and the pure polymer granules (core) are further processed in melt spinning (Fourné 1999) to generate a magnetic bicomponent fiber for the following reasons: Only the polymer in the sheaths melts during induction welding and allows bonding with surrounding fibers; the cores' crystalline structure remains intact, preserving the strength of the fibers. Thus fiber ends can be joined together as an alternative to knotting or friction welding.

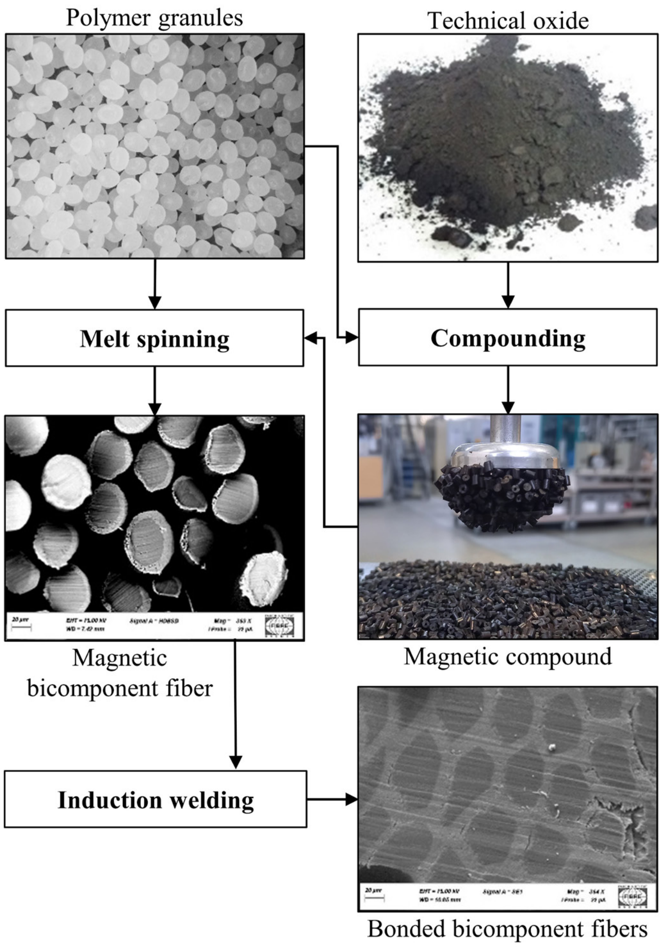

Figure 3: Basic principle of induction welding by using magnetic bicomponent fibers

Materials

Polyetheretherketon (PEEK), density (ρ) = 1.33 g/cm^3, in granular form is used as polymer. The glass transition temperature (T_G) is 135 °C and the melting temperature (T_M) is 340 °C. Technical oxide (Fe_3O_4) (ρ = 4.6 g/cm^3) in powder form is used to generate magnetism. The medium particle size is 0.3 µm.

Compound and bicomponent fiber formation

PEEK and Fe_3O_4 are feeded to a twin-screw extruder (Leistritz Extrusionstechnik GmbH) with twelve heating zones by two feeders (Coperion GmbH). The mixture is extruded on technical scale at a temperature above T_M of PEEK. After exiting the nozzle, the extruded monofilament passes through a cooled water bath and is granulated.

For bicomponent fiber formation, the magnetic compound (sheath) and pure PEEK (core) are processed on technical scale on two different extruders (Fourné Maschinenbau). As with compounding, both materials are extruded above T_M of PEEK. After exiting the nozzle, the magnetic bicomponent fibers are formed, drawn off and then stretched before being wound up. The fineness of the tested bicomponent fiber is 2,040 dtex that means 4,900 m/kg.

Induction welding

Before induction welding, the fiber ends are overlapped manually, swirled by compressed air and passed through an induction coil. The inner diameter of the water-cooled coil is 6 mm and the length 25 mm. The induction is generated with a unit Sinus S52 (Himmelwerk Hoch- und Mittelfrequenzanlagen GmbH). The frequency is 1,597 kHz and the power is 3.42 kW. The fiber ends are induction welded for varying durations (1.5 s, 2.0 s, 2.5 s, 3.0 s, 3.5 s and 4.0 s, Table 2). In Figure 4 left can be seen the experimental setup with the induction coil and the bicomponent fiber ends. Figure 4 right shows the heated magnetic bicomponent fiber within the induction coil using a thermal imaging camera. The unit of the displayed temperature is °C.

Table 2: Properties of induction welded magnetic bicomponent fibers

Method	**T in m/kg**	**σ in MPa**	**η in %**
Induction welding magnetic bicomponent fibers	4,900	452	54.5 ± 30.0 after 1.5 s
			81.7 ± 20.9 after 2.0 s
			97.6 ± 16.5 after 2.5 s
			89.2 ± 18.2 after 3.0 s
			83.4 ± 18.7 after 3.5 s
			41.5 ± 18.9 after 4.0 s

T, σ and η refers to fineness, strength and efficiency, respectively.

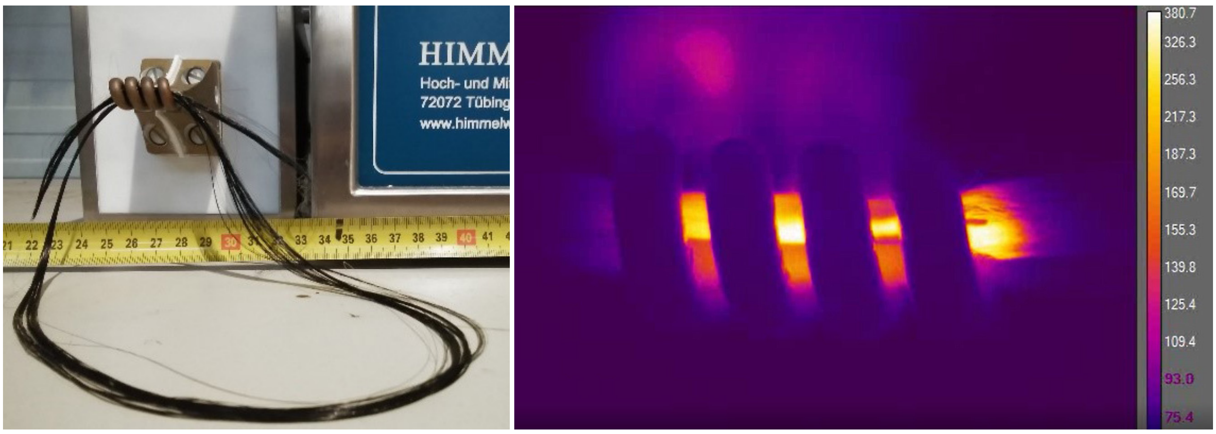

Figure 4: Experimental setup (left) and heated magnetic bicomponent fiber (right)

Measurements

The temperature during induction welding is measured with a thermal camera SC600 (FLIR Inc.). The associated software is Research IR (FLIR Inc.). The temperature measurement is calibrated in relation to emissivity of the magnetic bicomponent fiber before the experiment is carried out.

The strength of the bicomponent fiber and the joinings of the fiber ends are determined with the Statimat 4U (Textechno, Mönchengladbach, Germany) according to DIN EN ISO 2062: The test length is 250 mm and the test speed is 250 mm/min. The preload force is 0.5 cN/tex. The fineness of the fiber is measured automatically.

Results and discussion

When comparing finenesses and strengths in Table 1 and Table 2, it can be seen that magnetic bicomponent fiber is much thinner than bale twine or strapping band. However, the strength is higher due to the stretching of the bicomponent fiber. The reason is the fiber form, because a material has the highest strength as a multifilament compared to the same material in a different form (Schürmann 2007).

Figure 5 above depicts the measured temperature depending on the time during induction welding. It can be seen that after about 0.7 s, TG of PEEK is reached and the state of the polymer becomes soft and rubbery. The temperature subsequently increases and eventually reaches TM after approx. 4 s. After 4 s the temperature decreases because the bicomponent fiber is completely melted. The melt is flowing. This leads to the conclusion that induction welding is possible for this bicomponent fiber after 0.7 s for a period of 3.3 s.

In Figure 5 below, the efficiency of the joining using induction welding is compared to the tensile strength of the pure magnetic bicomponent fiber. Table 2 shows the corresponding values. Six different measuring points and a second degree polynomial compensating curve are shown. The authors interpret the results as follows: First of all, the reaction time of the system can be seen, which is about 0.9 s for the used bicomponent fiber. Thereafter, when T_G is crossed, the temperature increases, the sheath components begin to melt and the fibers start to bond. This increases efficiency accordingly. The sheath melting time lasts for about 1.8 s and the efficiency reaches a maximum of 97.6 % at 2.5 s due to the adhesion bonding. When the maximum is reached, the cores of the fibers also start to melt and the efficiency decreases. It takes about 4.5 s to melt the complete magnetic bicomponent fiber. At the bottom right of Figure 3, the bonded bicomponent fiber can be clearly seen: The sheaths are bonded while the cores are still intact.

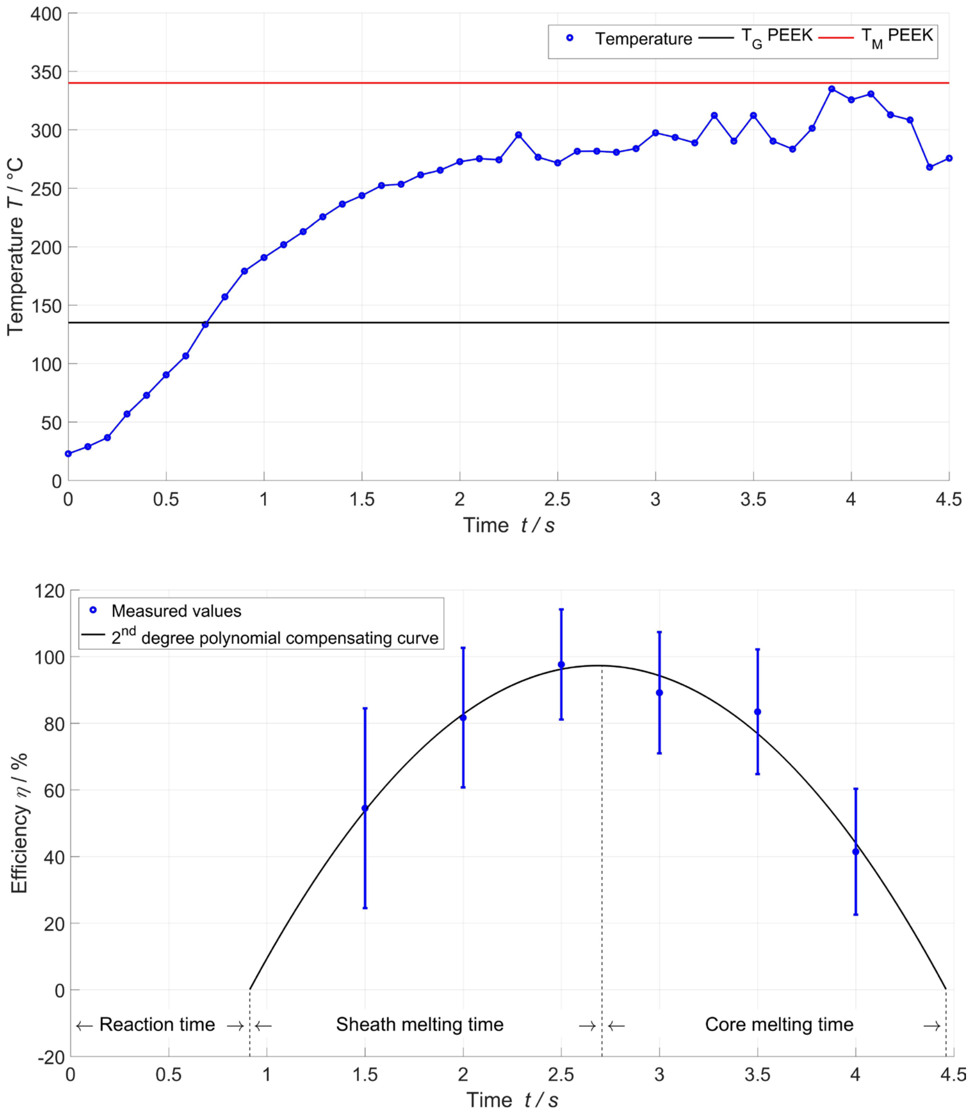

Figure 5: Temperature curve during induction welding (above) and efficiency of the joining (below)

The authors assume that with further process optimizations and automatization, induction welding can be homogenized and thus standard deviation reduced. The curve of efficiency in Figure 5 below and thus reaction time, sheath melting time and core melting time can be influenced in four main ways:

- Choice of the polymer: Polymers with lower melting temperatures than PEEK, such as PP (T_M = 165 °C (Fourné 1999)), can be welded faster.
- Content of technical oxides within the sheath: The more particles oscillate, the faster the melting temperature is reached (Bostan and Schiebel 2014).
- Sheath-core ratio of the magnetic bicomponent fiber: The melting temperature is reached more rapidly with a higher sheath fraction and thus a higher number of technical oxides.
- Power and design of the induction unit: With a higher frequency or a higher power of the induction unit or an optimized coil design the melting temperature is reached more rapidly (Bostan and Schiebel 2014).

Practical considerations

This article is about fundamental research, and a technical implementation of an induction welding process is associated with further development. This includes:

- The authors are not aware that factors such as dust, dirt and moisture have an influence on knot strength. However, it is necessary to investigate the impact of these factors on induction welding and efficiency.
- The different ignition temperatures of hay and straw, min. 250 °C (Kreyenhagen 2017) need to be considered when the polymer is melted for bonding.
- The time required for induction welding needs to be adapted to the time required for knotting in balers, less than 1.5 s (Kreyenhagen 2017).
- Multiple bale twines are currently used in balers and knotted simultaneously (Kreyenhagen 2017). The power needed for several simultaneous induction welding processes and also the energy demand must be calculated.
- The stretching of the bale yarn leads to a loss of density in square and round bales (Kreyenhagen 2017). This effect must be taken into account in induction welding joining technology.
- The incompatibility of the technical oxide embedded in the polymer when consumed by animals must be examined.

Conclusions

The present report discusses the development of an alternative joining technique for balers using induction welding. The process is based on magnetic bicomponent fibers with a sheath-core structure. During induction welding, the sheaths as a mixture of polymer and technical oxide can be bonded, while the cores with pure polymer maintain the strength of the fibers. Laboratory-scale tests show that an efficiency of approximately 98 % can be achieved. The results are in the same range as using friction welding with an efficiency of 83 to 98 % (Kreyenhagen 2017). Due to the higher efficiencies compared to knots, the experiments show the potential for material savings through induction welding.

The effort needed to melt-spin the bicomponent fiber can be compared with the effort required to produce bale twine by means of film extrusion. The production of the magnetic compound of polymer and technical oxide is an additional process which causes additional costs. It can be said that a technical implementation of induction welding is associated with an enormous development effort and thus costs for bale twine and baler manufacturers.

Other approaches are conceivable to save material in bale twine: For example, PP material could be used as a multifilament instead of the fibrillated film. As mentioned above, this could save material because fiber form generates the best mechanical properties of a material (Schürmann 2007). More environmentally friendly polymers could also be used (Endres and Siebert-Raths 2011). These include bio-based polymers such as bio-PP (Siracusa and Blanco 2020). On the other hand, bio-based and degradable polymers could be used, such as polylactide (PLA) (Marx et al. 2023b).

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