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Composition of some metallic fragments found in food that are undetectable by magnetic or eddy currents equipment: A case study

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A B S T R A C T

Contamination of food with metallic fragments implies a serious risk to the end consumer. Therefore, that metallic waste must be detected and removed before that contaminated food arrives to the market. One of the cheapest and most common ways of dealing with this problem is the use of magnetic separators for ferromagnetic waste. If the waste has a non-ferromagnetic character eddy current metal detectors are a good alternative. However, depending on the composition and shape of the metallic fragments, its detection can be very difficult.

This paper presents a study on the composition of some metal fragments, a hypodermic needle used during veterinary treatments and metallic wire, that were not detected by the magnetic separator nor by the eddy current sensors of a meat processing line. The composition of the fragments was analyzed by EDX Spectroscopy and compared with the results of a plain magnetic attraction test. The results show the non-detected fragments were made of stainless austenitic steels, which have a non-ferromagnetic character and a relatively low electric conductivity, making this material difficult to detect using magnetic means. To avoid this problem and guarantee the detectability, austenitic steels should, when possible, be substituted by ferritic or duplex stainless steels.

1. Introduction

The food industry must take as many actions as necessary to assure food safety and avoid any possible hazards to consumers, hazards that the Codex Alimentarius Commission defines as any “biological, chemical or physical agent in, or condition of, food with the potential to cause an adverse health effect” (World Health Organization-FAO, 2009).

Food security cannot be guaranteed by an approach based on the withdrawal of potentially harmful products or foods from the market, but by ensuring food safety from primary production to the consumer’s table, throughout all the length of the supply chain. The HACCP quality control system considers three types of hazards in food processing: physical, chemical and biological. The physical hazard consists in foreign objects that can cause a physical extraversion or any type of injury in a digestive system. These types of hazards are the most visual proof of contamination in a food and the most likely to be reported by the end consumers, the ones that will consume the product, through complaint (Haff & Toyofuku, 2008). So, it is one of the main concerns for the food industry.

Some of these contaminants consists of metallic waste that can enter the processing chain due to the detachment of equipment pieces or as a result of defective practices at various stages of the production chain, from the producer of the primary resource to the end consumer (Luning, Devlieghere, & Verhé, 2005). Fortunately, ingested foreign bodies usually do not cause complications and the vast majority of them pass through the gastrointestinal tract without surgical assistance (Ambe, Weber, Schauer, & Knoefel, 2012; Trafialek, Kaczmarek, & Kolanowski, 2016). Nevertheless, that is not always the case and between 10 and 20% of he cases can need an endoscopy and 1% of them can need surgery. As examples, Kim and also Conrado reported cases of acute appendicitis caused by metallic foreign objects (Jiménez, Martínez-Montalvo, Maduro, González, & Suaza, 2019; J. H.; Kim, Lee, & Kim, 2015). In fact, contamination of food with petal fragments is not so rare. Bowler reported 19 out of 123 injuries caused by ingested foreign objects were caused by metal fragments in food (Bowler, 2019) and Edwards reported 170 out of 2347 incidents of contamination were caused by metal fragments (Edwards & Stringer, 2007).

Another problem relates to the inevitable important economic losses caused to the industry due to product recalls (Mitchell, 2015) and the loss of customers trust (Wowak, Craighead, Ketchen, & Connelly, 2021). Thus, it is important for the food industry to install systems capable of detecting metallic waste.

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The usage of separators and detectors based on the use of magnetic fields is one of the most common automatized methods (Barbut, 2020) to remove metal waste from food. Magnetic separators consist of permanent magnets or electromagnets that attract ferromagnetic waste and separate it from food. Eddy current detectors rely on a high frequency alternating magnetic field (known as the primary magnetic field) generated by a coil. This magnetic field creates electric eddy currents in any conductive material in its range. These electric currents, in turn, generates a secondary magnetic field that opposes the primary one. The detection of this secondary field serves to know if a metallic fragment is present and can also be used to separate them from food. The problem is that although all metals are in theory detectable, the magnitude of the secondary magnetic field and, thus, the detectability of the metallic waste, depends on its size, electrical conductivity and magnetic permeability (Bowler, 2019). The higher the size, the magnetic permeability and the conductivity (both related to the metal chemical composition), the more detectable is the metal waste. This means the composition of the metal fragments can make them difficult to detect (Lenz & Edelstein, 2006; Smetana, Capova, Behun, Palcek, & Orsulova, 2018). Although this non-detection failure rarely occurs and the incident is classified as a lower risk incident (World Health Organization-FAO, 1998), that possibility should be considered when deciding the composition of the stainless steels used in the manufacturing of equipment for the food industry, something that is not always done.

To illustrate this problem, the aim of this work was to study the composition of some metallic fragments provided by a meat processing company that were not detected by the installed detectors. The definition of the composition that these metal fragments should have had to be detectable in the 100% of the cases is another objective of the paper. Knowing that composition would help to avoid contamination of the final product. The results provide a word of caution about the composition of the stainless steels used in the manufacturing of metallic elements that could lead to food contamination. These results need to be passed on the meat suppliers, manufacturers of industrial equipment, veterinarians and other agents of the food industry.

2. Materials and methods

2.1. Samples

The metallic samples were provided by a Spanish meat processing company. As can be seen in Fig. 1, sample number 1 corresponds to a hypodermic needle (Fig. 1a). This sample was detected by the eddy current detection tunnel and was provided for comparison purposes. Sample number 2 (Fig. 1a) is another hypodermic needle, but in this case it was not detected by the eddy current sensors nor eliminated by the magnetic separators. The third sample (Fig. 1b) corresponds to two pieces of steel wire that were, also, not detected by the eddy current sensors or the magnetic separators. Regarding the non-detected samples numbers 2 and 3, no information was received with regard to how they were finally detected or if they were found by a customer outside the company's facilities.

3. Methods

12 verification additional passes were made for each one of the samples at the facilities of the company using the eddy-current detector (Inmagalsa, model Esosia, Madrid, Spain).

After the execution of the aforementioned verification test in the metal detection tunnel, a simple magnetic attraction tests using small permanent magnets was carried out in order to quickly check the ferromagnetic nature of the metal fragments. The use of a permanent magnet is a simple and fast test used in metal workshops to determine if a steel is an austenitic stainless steel. If so, there will be no attraction between the material and the magnet.

Finally, the chemical composition of the samples was analyzed using a scanning electron microscope (JEOL, model JSM- 6300, Peabody, USA) with the Energy Dispersive X-ray Spectroscopy (EDX) attachment (Oxford Instruments, High Wycombe, UK). Therefore, samples number 1 and 2 were transversely cut and analyzed without further polishing (Fig. 2). Sample 3 was only cleaned, as its size was small enough for the microscope chamber.

A measurement of microhardness was also carried out for samples 1 and 2 on the transversal surface of the needles using an Innovatest 400A Vickers microhardness tester (Maastricht, The Netherlands) with a load of 35.6 N (300 g) and a dwell time of 10 s. These measures were used to estimate the mechanical characteristics of these materials (there is an almost linear relationship between hardness and the ultimate strength of steels), which in the case of the needles have proven insufficient to prevent their breakage. The needless were firmly held using a small vise to avoid movements during the tests.

4. Results and discussion

The results of the verification passes of the samples through the eddy current detection tunnel are consistent with the initial data provided by the company. They are also consistent with the permanent magnet test, as samples 2 and 3 were very difficult to detect (3 out of 12 passes and 1 out of 12 passes respectively), while sample 1 was detected every time without any problem.

In all cases, the visual aspect of the surface of the samples and the absence of corrosion indicate that these elements were made of stainless steel, the most used metallic material in the food industry. The presence of needles as foreign objects in meat seems odd, but it has to be taken into account the common use of needles in livestock during veterinary practices. That use forces the food industry to consider the probability of

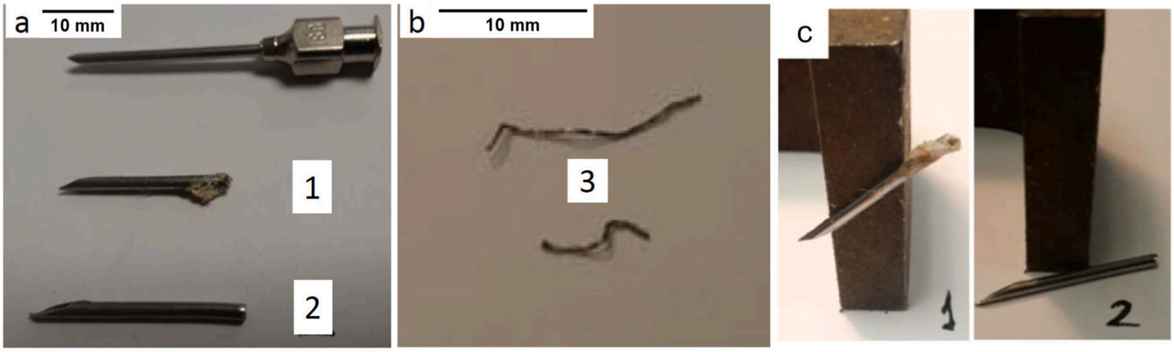

Fig. 1. a) Samples 1 and 2: Hypodermic needles found in food. Sample 1 (25.23 mm length) was detected by the eddy current detector, but sample 2 (30.1 mm length) was not detected. b) Pieces of wire (14.3 and 6.3 mm length) not detected by the magnetic separators nor the eddy current detectors. c) Sample number 1 is attracted by a magnet but sample 2 is no attracted. This indicates a different composition of the needles.

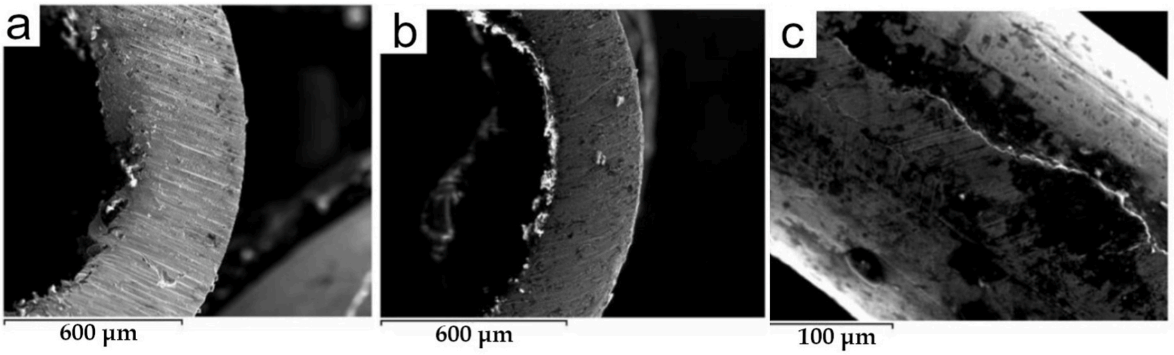

Fig. 2. Scanning electrom microscopy image (SEM) of the cross-sections of a) sample 1 and b) sample 2. c) SEM image of one of the wires of sample 3. The EDX analysis was performed on these surfaces.

the presence of needle fragments in the slaughtered animal because, occasionally, during the shot the needle breaks and the remains of it, or even the whole needle, stays inside the animal. The origin of the stainless steel wire is unknown, but it could come from an undetected wound caused by a broken metallic fence, from maintenance labors done during working hours or from any other activity susceptible of causing food contamination.

In fact, the number of possible steels that can be used in the food industry is reduced to the stainless steels family due to their high chromium content, that provides an excellent resistance against corrosion. There are, basically, four types of stainless steels, all of them with a content of Chromium higher than 13% and a low electrical conductivity:

- Austenitic: These steels are composed mainly of austenite (a face-centered allotropic form of iron stable at room temperature due to the addition of more than 8% of Nickel). They are the only ones that are non-ferromagnetic (has a low magnetic permeability, around 1.02) and a conductivity around 1.37 $(\mu\Omega\cdot m)^{-1}$ for AISI-304 and AISI316. Unfortunately, conductivity is not high enough to properly compensate for a so low value of permeability. Thus, these steels will not be attracted by magnets and their detection can't be guaranteed by using the eddy currents technique. This type of steel is, by far, the most common in the industry due to its good weldability and formability, corrosion resistance and price.
- Ferritic: Composed of ferrite (a body centered allotropic form of iron). They are available in many formats, but their formability and weldability are worse than that of austenitic steels and their corrosion resistance is not as good. They are used in the food industry, but only for moderately corrosive environments. They are ferromagnetic, with a relative magnetic permeability over 1000, and have a conductivity of around 1.67 $(\mu\Omega\cdot m)^{-1}$, so, even if some fragments scape the magnetic separators, they should be detected by the eddy current sensors.
- Martensitic: Used only to manufacture knives or cutting blades, tools that require a very high hardness. They are ferromagnetic, but require a heat treatment, have a higher price and can't be welded or deformed plastically.
- Duplex: Composed of ferrite and austenite, they are the main alternative to austenitic stainless steels. They are weldable with ease, have a good formability and a higher resistance to corrosion than austenitic steels and both magnetic separators and eddy current detectors could be used to eliminate metal fragments. Their only disadvantage is their higher price, although their uses increase every year, what should lead to a price decrease.

Fig. 1.c shows how sample number 2 (the same happens with sample number 3) is not magnetically attracted, what indicates the material is possibly an austenitic stainless steel. On the other hand, sample number 1 is attracted by the magnet, what indicates, it's made of another type of steel.

In order to deepen on the study of the composition of these materials and assure the conclusions provided by these simple tests, the samples were studied through EDX to obtain their chemical composition. In these analyses the percentage of carbon has not been included due to the limitations of the equipment to detect low atomic mass elements, but the error that this inconvenience can cause is very low as typical stainless steels have a very low content of carbon. The chemical compositions can be seen in Table 1.

The composition of sample 1, matches that of an austenitic-ferritic stainless steel (also known as duplex stainless steel), since the mass percentages of Chromium and Nickel are 23% and 5,5% respectively. The high Chromium content provides resistance against corrosion while the medium content in Nickel is not high enough to promote a full austenitic microstructure, which remains within the austenitic-ferritic range. This composition justifies the existence of enough quantity of the ferromagnetic phase ferrite in the microstructure of the steel and, therefore, the possibility of detection using eddy currents.

The composition of sample 2 matches quite well with an austenitic steel and is very similar to that of AISI 304N steel, although the Si content obtained is much higher than expected. In its annealed state, AISI 304N is austenitic and so it is non-ferromagnetic, which hinders its detection. This sample contains a certain proportion of martensite due to the manufacturing process based on plastic deformation, but even in that case the detection does not offer any security, and much less the separation using magnets.

The percentages of Cr, Ni and other alloying elements in sample 3 also matches with an austenitic stainless steel. This is again coherent with the fact that sample number 3 was detected only in less than 10% of cases during the tests performed using the magnetic detectors of the company. They are also consistent with the results obtained from the attraction tests performed with a permanent magnet.

Regarding the fact that samples 2 and 3 were detected sometimes, austenitic steels are (on paper) composed 100% of austenite and, thus, are supposed to be fully non-ferromagnetic materials. That said, in reality, these alloys can form some ferromagnetic ferrite when they are welded or during a casting process. They also form martensite if they are cold worked (plastically deformed, as during the manufacturing of hypodermic needles or wire) (Fu & Yang, 2013; S. H.; Kim, Moon, Kang, & Lee, 2003; Padilha, Tavares, & Martorano, 2012; Saeidi, Gao, Lofaj, Kvetková, & Shen, 2015; Shakhova, Dudko, Belyakov, Tsuzaki, & Kaibyshev, 2012). Ferrite content can sometimes reach 20% and make the steel detectable by eddy-current methods, although perhaps not enough to be separated by magnetic separators. Martensite can appear in higher proportion than ferrite (>70% for very high deformations), although despite this high percentage it leads to a much lower increase in magnetic permeability than ferrite (Kobayashi, Kikuchi, Takahashi, Kamada, & Kikuchi, 2010; Post & Eberly, 1947). So, ferrite is the main component that can give austenitic steels a mild ferromagnetic behavior and make

Table 1
Composition of samples in %weight according to the EDX analysis.

Element	Sample 1			Sample 2			Sample 3		
	Weight %	Wt% σ	Atomic %	Weight %	Wt% σ	Atomic %	Weight %	Wt% σ	Atomic %
Fe	64.25	0.35	63.64	67.34	0.42	64.56	67.34	0.30	67.03
Cr	23.51	0.12	25.01	18.74	0.16	19.29	17.86	0.16	19.09
Ni	5.48	0.06	5.16	8.33	0.12	7.60	10.44	0.11	9.88
Mo	3.99	0.07	2.30	0.27	0.11	0.15	2.26	0.06	1.31
Mn	1.55	0.09	1.56	1.76	0.06	1.72	1.54	0.04	1.56
Al	0.21	0.03	0.44	–	–	–	–	–	–
Si	0.91	0.07	1.79	3.43	0.04	6.54	0.57	0.07	1.13
V	0.10	0.03	0.11	0.12	0.04	0.13	–	–	–

the samples detectable if their size and orientation is propitious.

Regarding hardness, the average hardness obtained for sample number 1 was 340HV (hardness values correspond to the mean value of 5 indentations), which according to the hardness-tensile strength conversion tables for steels, corresponds to, approximately, a tensile strength of 1150 MPa, a value a lot higher than the one expected for a typical austenitic or duplex stainless steel. Sample number 2 had a 345HV hardness, which means that its ultimate strength is approximately 1170 MPa, a value similar to the previous one.

This increase in mechanical properties of the material is due, to the martensitic transformation that undergo austenitic stainless steels during the manufacturing process of needles. This high hardness, necessary to ensure the sharpness of the tip of the needle, is associated with a significant ductility loss and therefore, a higher risk of fragile breakage during a sudden movement of the animal.

To summarize, all results show that if magnetic separators or eddy current detectors are to be used in the food industry special care must be taken in the selection of the materials used for maintenance processes, requiring all steels to have ferromagnetic characteristics. Thisimplies avoiding austenitic steels if there is a chance of food contamination.

For the time being not all elements manufactured using austenitic stainless steels can be easily substituted by ferromagnetic stainless steels due to their characteristics and price. Ferritic stainless steels could be used in farms or for non-demanding corrosive environments, but duplex stainless steels will be the best alternative in many cases if their price is reduced.

5. Conclusions

The analysis of the composition of some metallic fragments found in meat that were not detected by magnetic separators nor by eddy current detectors show these systems are not reliable to detect austenitic stainless steels. Although this type of steel is the most common in the food industry, itsrelatively low conductivity and non-ferromagnetic behavior, what makes them difficult to detect even when they contain some ferrite or strain-induced martensite.

Austenitic stainless steels should be substituted when possible by ferritic or duplex stainless steels to assure their detectability if the chances of food contamination are not negligible. This recommendation includes the selection of hypodermic needles in animal treatments as the relatively high hardness of the needles induced by the manufacturing process makes them less ductile and more breakable than a common stainless steel.

Author contributions

In this investigation, J.C–C. and M.P-G. conceived and designed the experiments; J.C–C. and F.S–V. performed the experiments; J.C–C., F. S–V. and M.P-G analyzed the data and contributed materials/analysis tools; J.C–C and F.S–V. wrote the paper.

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Data availability statement

Not applicable.

CRediT authorship contribution statement

Javier Cárcel-Carrasco: Conceptualization, Methodology, Formal analysis, Writing – original draft, Writing – review & editing. **Manuel Pascual-Guillamón:** Conceptualization, Methodology, Software, Validation, Data curation, Supervision, Project administration, Writing – original draft, Writing – review & editing, Visualization, Investigation, Resources.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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