Influence of the Plastic Deformation on Magnetic Properties of Austenitic Steels

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Abstract. Austenitic stainless biomaterials are worldwide used in biomedical practice. Electromagnetic nondestructive evaluation allows their contactless investigation in terms of magnetic field mapping. Intrinsic magnetic field directly reflects changes in their mechanical properties. This article presents investigation of concrete austenitic biomaterials by use of fluxgate sensor. Pre-defined plastic deformation levels of the cylindrical specimens are evaluated. Three-dimensional scanning procedure has been performed.

Keywords. Austenitic stainless steel, magnetic field mapping, nondestructive evaluation.

1. Introduction

Since society first realized the fallibility of people and their machines, they have recognized a need to inspect these machines in order to prevent failures. A wide variety of test schemes exist both destructive and the nondestructive. The practical benefits of nondestructive inspection are obvious, as long as the results are reliable and the inspection cost-effective. Load conditions, material properties and flaw size will determine if a flaw is likely to affect the serviceability of the part. NDE, however, is essential in locating and sizing of the flaw. NDE evaluation can be also beneficial to reducing the frequency of unscheduled maintenance which usually is more expensive than regularly scheduled maintenance, [1].

Inspection of conductive materials is however extremely important to the field of biomedical engineering. Biomaterial implants that have the same function as the bones (implants which replace failed hard tissue, artificial hip joints, bone plates and dental implants) are usually used under severe cyclic loading conditions. Therefore, metallic materials that typically exhibit high strength, ductility and toughness are the main candidates for the structural biomaterials of these implants. These implants must exhibit high biocompatibility, high performance and reliability for long-term use. The reliability of the implants after implantations is determined by their failure after the
critical period of infection. Therefore, the mechanical properties of structural biomaterials in a living body environment (fatigue, toughness, wear resistance) need to be evaluated in order to confidently use the implants for a long period of time. Some metals and alloys that combine high strength with reasonable corrosion resistance are favorite biomaterials for the fabrication of orthopedic implants, which are subjected to severe mechanical loading into the human body. The metallic biomaterials most commonly used for orthopedic applications are the austenitic stainless steels [2], [3], [4], [5].

This article will deal with the three-dimensional analysis of the conductive austenitic biomaterials after a previous defined plastic deformation. An intrinsic magnetic field of the specimens is analyzed, displayed and discussed. Because the magnetic field strength is comparable with the Earth’s magnetic field strength a commercial sensor (fluxgate type) is used for the measurements. The main aim is to reveal a correlation between the deformation structure and its influence on resulting magnetic field of the biomaterials. The originality of this study lies in 3D visualization of the intrinsic magnetic field of inspected biomaterials. Individual components of the field are sensed to bring new information about the behaviour of the field after plastic deformation.

2. Austenitic biomaterials properties

Biomaterials are the materials that usefully interact with biological systems. They are often used or adapted for a medical application, and thus comprise whole or part of a living structure or biomedical device which performs, augments, or replaces a natural function. One of the primary reasons for which biomaterials are used is to replace hard or soft tissues that have become damaged or destroyed through some pathological processes. Although the tissues and structures of the body which operate for an extended period of time in most people, they do suffer from a variety of destructive processes, including fracture, infection, and cancer that cause pain, disfigurement, or loss of function. Under these circumstances, it may be possible to remove the diseased tissue and replace it with some suitable synthetic material. One of the main application areas for biomaterials is for orthopedic implant devices. Both osteoarthritis and rheumatoid arthritis affect the structure of freely movable (synovial) joints, such as the hip, knee, shoulder, ankle, and elbow. The conductive biomaterials are the most widely used for load-bearing implants. For instance, some of the most common orthopedic surgeries involve the implantation of metallic implants. These range from simple wires and screws to fracture fixation plates and total joint prostheses (artificial joints) for hips, knees, shoulders, ankles etc., [5], [6], [7], [8]. In addition to orthopedics, the metallic implants are used in maxillofacial surgery, cardiovascular surgery, and as dental materials. Although many metals and alloys are used for medical device applications, the most commonly employed are austenitic stainless steels, commercially pure titanium and titanium alloys, and cobalt-base alloys. In general, these materials are paramagnetic. Magnetic properties of the stainless steels may be affected by their alloying elements, atomic grain structure and amount of the cold-working during fabrication. In their basic forms the stainless steels have a ferrite grain structure, similar to carbon steel, and they are ferromagnetic, Table.1. The addition of nickel in the 300-series stainless steels modifies the crystal grain structure to austenitic structure, which is paramagnetic. The austenitic grades are mostly non-magnetic in the unworked state due to their nickel content.
When 300-series stainless steels are cold-worked, straining of the atomic lattice structure in the areas of cold-working forms the ferromagnetic grain martensitic structure. Generally speaking, the higher the nickel content in the steel the more stable the austenitic structure and less magnetic response from cold-working. Consequently 316 stainless steel containing higher amounts of nickel, exhibits virtually no magnetism after cold-working in most cases, while 304, with lower nickel content, may become partially ferromagnetic. Austenitic (300-series) stainless steels that have become magnetic due to work hardening can be returned to a paramagnetic state through annealing or stress-relieving. Brief heating at elevated temperatures revert the affected grain structure from the martensitic state to the austenitic one. Since 400-series stainless steels are entirely ferrite or martensitic, their magnetic properties cannot be reduced through annealing. There is no plating or finishing processes, such as passivation, that can reduce or eliminate work hardening induced magnetism. They are merely superficial and do not change the affected grain structure.

3. Experimental set-up

Experimental material specimens – austenitic stainless steel having a quasi-cylindrical shape, Fig.1, is inspected in this study.

Three different biomaterial grades are inspected, respectively: chrome-nickel stainless steel AISI 304, chrome-nickel-molybdenum stainless steel AISI 316L and chrome-nickel-molybdenum-titan stainless steel AISI 316Ti. Initially, all the inspected specimens are prepared from one piece of material, by the cutting at the defined dimensions. Thus, all the specimens have the cylindrical shape, with an initial height (measured from the base to the top) of $h = 14$ mm and with a radius of $r = 6$ mm. It is very important to be all the specimens dissolution-annealed after the mechanical cutting. The samples underwent the recrystallization annealing process at the...
temperature of $T = 850 \, ^\circ\text{C}$ for time of $t = 15 \, \text{min}$, followed by air cooling to reduce the strength applied during cold-working. Thus, the residual magnetic field caused by the cutting is eliminated. This regime is defined as the reference state. Then the process of the controlled plastic deformation may be applied. The deformation is performed by mechanical pressing of the opposite sides of the cylindrical specimens, using the ripper system. Seven different values of the applied plastic deformation are realized: $\text{PD}_1 = 1\%$, $\text{PD}_2 = 2\%$, $\text{PD}_3 = 5\%$, $\text{PD}_4 = 10\%$, $\text{PD}_5 = 20\%$, $\text{PD}_6 = 30\%$ and $\text{PD}_7 = 40\%$. These percentage values represent shortening of the specimen after the applied deformation, in comparison with the reference (non-deformed) specimen, which has the length of $P_{\text{REF}} = 100\%$. The fluxgate magnetometer, shown in Fig. 2, is used as the sensing element for measuring of the intrinsic magnetic field. This sensor picks-up the response signal in the sensitive axis. Its its voltage output signal is converted to the magnetic field strength value, using the appropriate calibration curve of the sensor. The commercial type is used (Canon Inc.). The sensor allows to measure magnetic field in the frequency range of $f \in (0; 3.4 \, \text{kHz})$. Individual magnetic field component is sensed, respectively. Thus, three-dimensional scanning is achieved for each specimen. Each specimen is inspected as follows: a classical raster 2D scan is performed above the specimen. Thus, the inspected area has a square shape, with dimensions of $\text{dims} = 50 \, \text{mm} \times 50 \, \text{mm}$, while the resolution between individual scanning lines is set to $\text{res} = 0.25 \, \text{mm}$. It gives in results of $n = 100$ scanning lines per each specimen. Further, the sensor is positioned in constant distance from the top side of each specimen, at lift-off distance of $l_0 = 2 \, \text{mm}$. This distance between the surface of the specimen to be inspected and the center of the sensing element is keep at constant value. Thus, all the specimens are inspected under the same conditions. The gained signals are acquired with the resolution of $\text{r}_{\text{DAQ}} = 16 \, \text{bits/channel}$ and with sampling frequency of $f_s = 2 \, \text{kS/sec}$. User interface for data manipulation, controlling the stage and processing the data are created and designed using the LabVIEW (Virtual Instrumentation).

4. Experimental results and discussion

The obtained results of the experimental measurements are introduced in this section. Figures 2 - 5 display visualization of the intrinsic magnetic field in terms of the individual sensed components. Images present the all parts of individual specimens: the base, the top and the shell, respectively. The dotted line in the graphs represents the profile of the specimens. Obtained signals for the rotation of the specimens were obtained as follows: the fluxgate sensor was kept at the constant lift-off position and the specimens were rotated with step of ten degrees. Each picture represents magnetic field distribution above the specimen. Only the selected results are presents in this section. As can be seen, when plastic deformation of 10% was applied, the strongest response arise AISI 304 biomaterial. Further, the AISI 316 Ti magnetic field is also detectable, although with lower intensity. Finally, the AISI 316 L magnetic fields was too weak to be detected via fluxgate sensor. Almost the same conclusion can be stated for the highest plastic deformation level of $\text{PD}_7 = 40\%$. The gained results present stronger field intensity in comparison with all the previous states. Moreover, these specimens were successfully inspected from higher lift-off distance of $l_0 = 10 \, \text{mm}$. (This fact is needed mainly in biomedical practice: contactless detection ability from distances of several centimeters.)
All of the obtained results and discussed facts are in direct correlation with the theoretical background, from the material engineering point of view. It means that structure of this experimental material has strong influence on its magnetic properties after previous plastic deformation.

Figure 2. Experimental results: Z-component differential responses, lift-off = 2 mm, AISI 304, (dotted line = profile of the specimen)
Figure 3. Experimental results: Z-component, lift-off = 2 mm, differential responses, AISI 316Ti, (dotted line = profile of the specimen).

Figure 4 displays the 3D magnetic field reconstruction obtained for the inspected specimens. This comparison is introduced to be visible the differences among individual steel grades. The dependence of the individual components of $\Delta H$ over individual axes is shown. The full-line represents profile of the sample. As can be seen from these results, the most-uniform shape of the field occurs for AISI 304 specimens. Towards to weaker magnetic properties of the material, magnetic field becomes more non-uniform. This information is useful for the inspection process: directional properties of these cylindrical specimens may vary when different grade of material is used.

Figure 4. Experimental results: $PD_T = 40\%$, 3D visualization of the intrinsic magnetic field, AISI 316L (left), AISI 316Ti (center) and AISI 304 (right).
5. Conclusion

The article dealt with investigation of the austenitic stainless steels after various level of plastic deformation. All inspected materials are intensively used in biomedicine as for implant or replacement purposes. The presented experimental work showed that these materials become partially ferromagnetic due to the austenitic to martensitic phase transition, which can be sensed by use of sensitive magnetic field sensor. Intrinsic magnetic field sensing at individual three-components brought new information about characterizing of these materials. Plastic deformation is non-homogeneous and non-linear process. Thus, by measuring of electromagnetic properties the deformation level can be indirectly investigated.

The presented results showed that the plastic deformation level is in direct correlation with magnetic field strength, measured by the fluxgate sensor. The strongest response were sensed for the AISI 304 specimens and on the other hand very weak signal was detected for the AISI 316L one. This biomaterial grade is limited in evaluation for this kind of inspection. Further, the AISI 316Ti material reveals stronger magnetic field than of the same grade of 316L. This is caused by the addition of titanium into the composition. Differences in the microstructure of the inspected biomaterials after the previous heat treatment observed by light microscope was experimentally confirmed by
means of performed measurement. This means that magnetic properties of the materials are to way to determine its mechanical properties. This fact is very important to be these materials evaluated nondestructively. This finds many applications on the field of biomedicine as well as other technical applications.

It can be concluded that proposed procedure offers relevant results for these biomaterials investigation. Further work will focus on quantification of the deformation martensitic component presented in these biomaterials. Main challenge is to show low deformation levels at higher lift-off distances with commercial sensors.

References