Magnetoimpedance and Stressimpedance effect at FeSiB Wires

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Abstract

In this study, the magnetoimpedance (MI) and stress impedance (SI) effect properties of $Fe_{77.5}Si_{7.5}B_{15}$ wires have been investigated. Wires were annealed at 460 ºC for different times. The largest change in the MI was observed at 1MHz ac current frequency value. At this frequency value, the change in MI was about 40% in the wire that as-received, while the change in the wire heat treated at 460 ºC for 10 minutes was found to be 169%. It has been determined that low time annealed leads to increase in magnetic softness.

Keywords: Amorphous wire, magnetoimpedance, stressimpedance, coercivity.

FeSiB Tellerde Manyetoempedans ve Stresempedans Etki

Öz

Bu çalışmada $Fe_{77.5}Si_{7.5}B_{15}$ tellerin manyetoempedans (MI) ve stresempedans (SI) etki özellikleri incelenmiştir. Teller 460 ºC de farklı sürelerde ısıtılmıştır. MI değerinde en büyük değişim 1MHz ac akım frekans değerinde gözlenmiştir. Bu frekans değerinde, ısıl işlem görmemiş telde MI değişimi yaklaşık %40 iken 460 ºC de 10 dakika ısıl işlem görmüş teldeki değişim %169 olarak bulunmuştur. Tellere uygulanan düşük süreli ısıl işlemlerin manyetik yumuşaklıkta artışa yol açtığı belirlenmiştir.

Anahtar Kelimeler: Amorf tel, manyetoempedans, stresempedans, koersivite.

1. Introduction

The magnetoimpedance (MI) effect is defined as the total impedance ($Z = R + iX$) change resulting from the passage of ac current through a conductor under a dc magnetic field. The changes occurring in impedance with applied mechanical stresses are called stress-impedance (SI) effects. In addition, it is expressed as a large magneto-impedance (GMI) effect at very high change in the impedance of the materials based on the applied external magnetic field (Phan and Peng 2008). Changes in impedance are the result of changes in the interaction between the magnetization of the material and the variable magnetic field produced by the current. Studies on the MI effect first began with the reporting of a large magneto-impedance effect (GMI) on amorphous ferromagnetic FeCoSiB wires in the early

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90's (Panina and Mohri, 1994: Beach and Berkowitz, 1994). These initial studies were the beginning of studies on MI effect. Then, MI and SI effects were studied for samples of different forms such as wire, ribbon and film (Vazquez, 2001; Kolat et al., 2000; Xiao et al., 2000; Kim et al., 2001; Pal et al., 2006; Bayri and Atalay, 2004; Knobel et al., 1997; Mandal et al., 2000). MI effect in amorphous, crystalline and micro-wires has been studied by Chiarac et al (Chiriac and Ovari 2002). In this study, it was determined that the DC magnetic field applied along the wire axis changed the impedance value. Depending on the ac current frequency applied to the samples, it was stated that the contribution to magnetization is the domain wall movement at low frequencies and the magnetization orientation at high frequencies. MI effect depends on many factors such as magnetostriction, the conductor's domain structure, the anisotropy occurring in the conductor, the frequency and the magnitude of the current passing through the conductor (Phan and Peng 2008). The GMI effect was studied on $Fe_{4.5}Co_{67}.5Nb_{0.5}Mn_{0.5}Si_{12}B_{15}$ amorphous wires by Zhou et al. (Zhou et al., 2001). Samples were heated in the temperature range from 300 ^oC to 450 ^oC for 30 minutes. It was determined that GMI value reached a maximum with increasing heat treatment temperature and decreased after 350 ^oC. It was observed that high heat treatments caused the crystallization of the samples and accordingly, the GMI value decreased sharply (Zhou et al., 2001). The fact that amorphous ferromagnetic materials with wire or strip form change depending on external dc field and tensile stresses enables these materials to be used in the technological field as sensor applications.

Therefore, in this study, the effect of MI and SI for $Fe_{77.5}Si_{7.5}B_{15}$ wire samples was studied.

2.Material and Method

Wires used in experimental studies were supplied by Unitika company (Japan) and cut to 10 cm length. Samples were annealed in air in a non-inductive tube furnace at temperature of 460 $\circ$C for different times. The M–H curves were obtained using a dc digital system; the coercivity (H_c) was derived from the M–H curves. Sample impedance was measured using HP4294 impedance analyzer and HP4294A probe. The system also allows the measurement of resistance and inductance values, which are components of the impedance. MI data were obtained at 100 kHz, 1MHz, 5MHz and 10MHz frequencies with 5mA constant amplitude ac current. In MI measurements, a solenoid for the outer dc magnetic field and a pair of Helmholtz coils were used in SI measurements. The application of the DC current along the coil or solenoid was controlled by a computer. The data from the impedance analyzer were collected and averaged by the computer at each step of the magnetic field. The average of the impedance data leads to a large reduction in noise / signal ratio and thus clearer MI effect curves. As a function of the applied magnetic field, the MI ratio was determined by $\Delta Z/Z$ (%)=100[Z(H) − Z(Hmax)]/Z(Hmax).

3. Findings

Figure 1 shows the magnitude of MI with the applied external magnetic field of the as-received $Fe_{77.5}Si_{7.5}B_{15}$ wire for different frequency values.
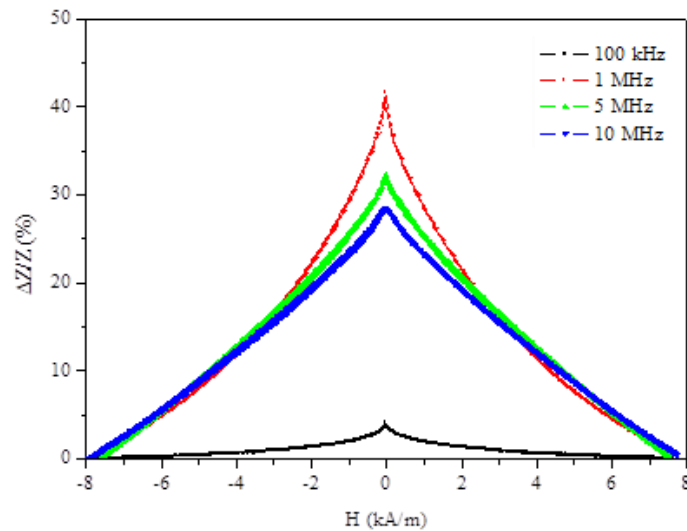
Figure 1. Magnetic field dependence of the impedance values for as-received $Fe_{77.5}Si_{7.5}B_{15}$ wires at various frequency values.

The maximum change in the as-received wire was found to be approximately 40% at 1MHz frequency value and it was determined that the change decreased with increasing frequency value. For the frequency value of 10MHz, MI change was calculated to be about 28%. As seen in Figure 1, single peak behaviors were observed in MI curves.

The value of the ac current frequency passed on the sample and the applied external dc magnetic field play an important role in determining the MI curves. Figure 2 shows the magnetoinductance change of the as-received $Fe_{77.5}Si_{7.5}B_{15}$ wire depending on the applied magnetic field. Impedance is expressed as the sum of resistance and inductance. As shown in Figure 2, a great contribution to the material impedance at low frequencies ($\leq$100kHz)) comes from the inductance value.
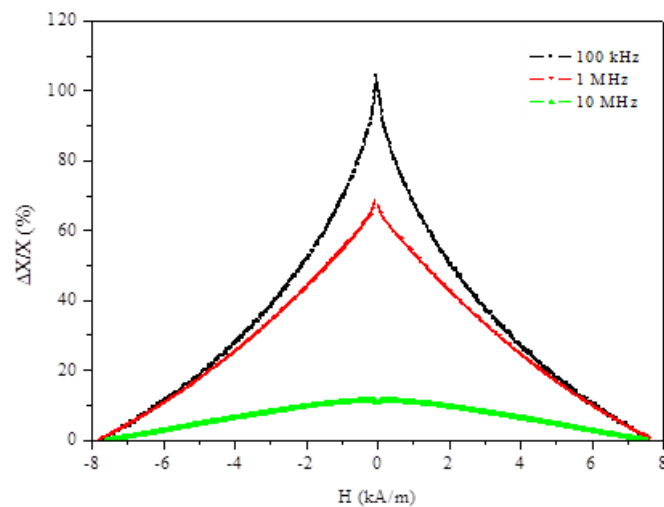

Figure 2. Magnetic field dependence of the inductance values for as-received $Fe_{77.5}Si_{7.5}B_{15}$ wires at various frequency values

The magneto-resistance change of the As-received $Fe_{77.5}Si_{7.5}B_{15}$ wire depending on the applied external magnetic field is given in Figure 3. It is seen that the contribution of the resistance component to the impedance value is greater with the increase of the frequency value.
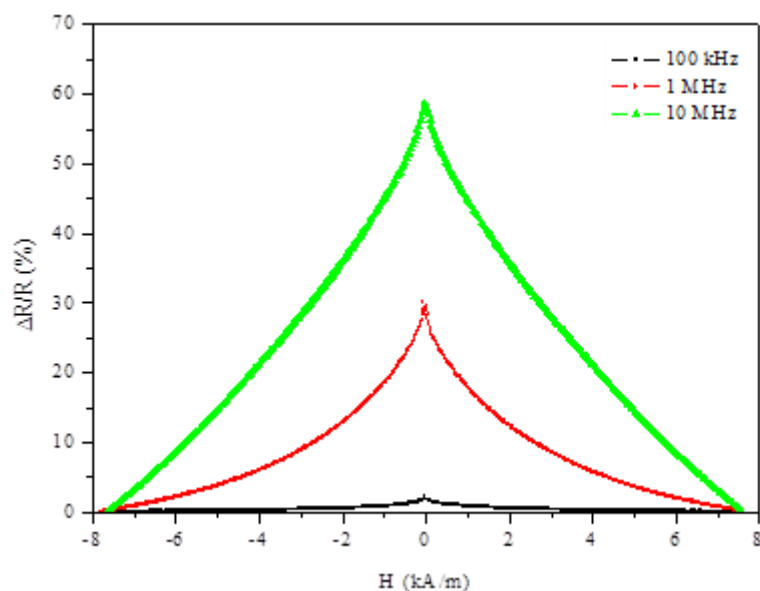

Figure 3. Magnetic field dependence of the resistance values for as-received $Fe_{77.5}Si_{7.5}B_{15}$ wires at various frequency values.

Figure 4-7 shows MI changes with dc magnetic field applied at 100kHz, 1MHz, 5MHz and 10MHz drive current frequency values for asreceived and annealed Fe77.5Si7.5B15 wires at 460□C for different times, respectively. For 100kHz and 1MHz drive current frequency values, it was observed that the maximum impedance changes observed in the asreceived and annealed Fe77.5Si7.5B15 wires at different times occur at values where the outer magnetic field is approximately zero. Curves at these frequency values show single peak behaviors (Figures 4 and 5). It was observed that single peak behaviors did not change with increasing annealed time at 100 kHz ac current frequency applied to the sample. For the 100kHz frequency value, the MI change was calculated as 54% after 10 minutes of annealed and decreased to about 5% after 180 minutes (Figure 4). Similarly, it is seen in Figures 6 and 7 that the maximum MI value after 10 minutes of annealed decreases with increasing annealed time.
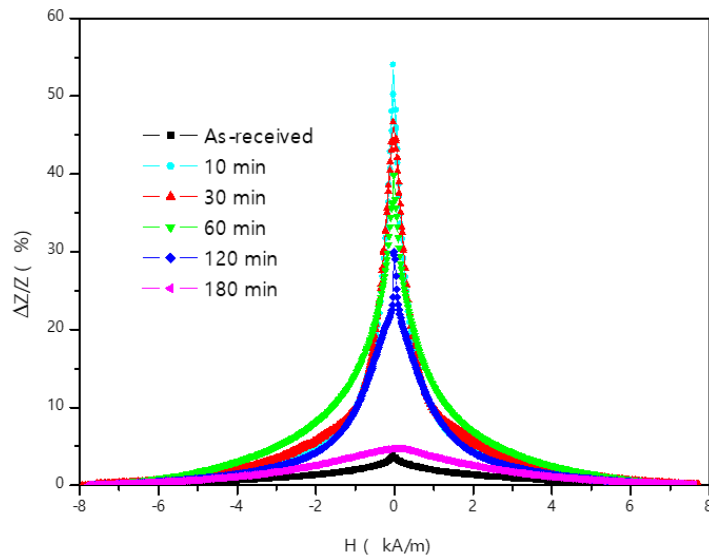
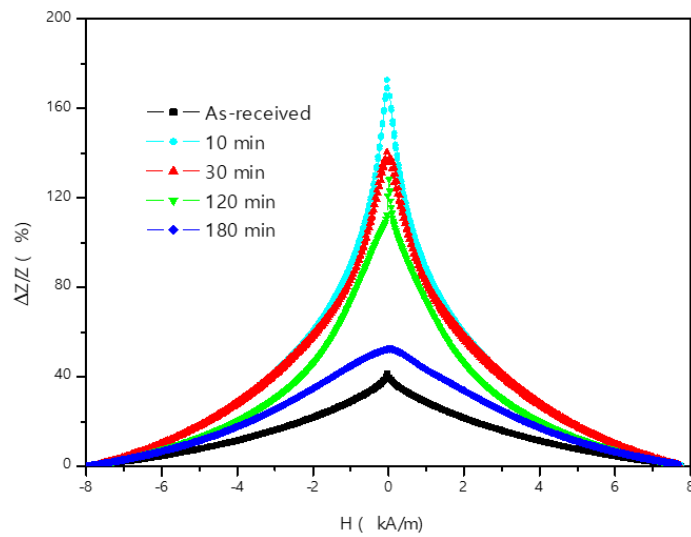**Figure 4.** MI curves for100 kHz frequency of $Fe_{77.5}Si_{7.5}B_{15}$ wires annealed at different times.

Figure 5. MI curves for 1MHz frequency of $Fe_{77.5}Si_{7.5}B_{15}$ wires annealed at different times.
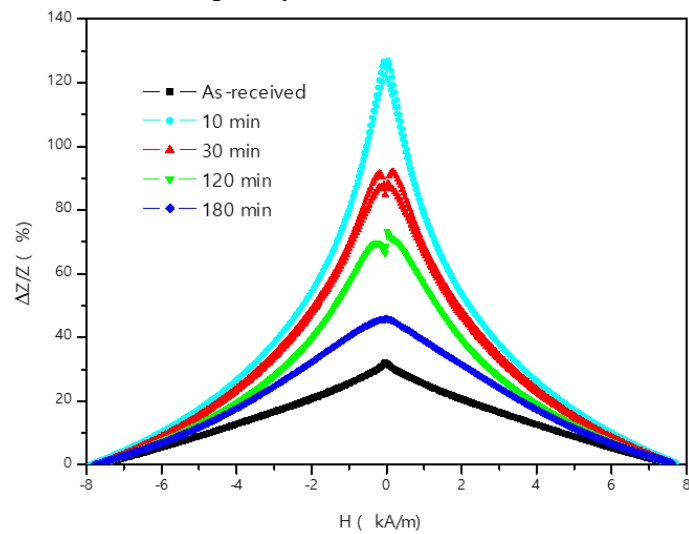

Figure 6. MI curves for 5 MHz frequency of $Fe_{77.5}Si_{7.5}B_{15}$ wires annealed at different times.
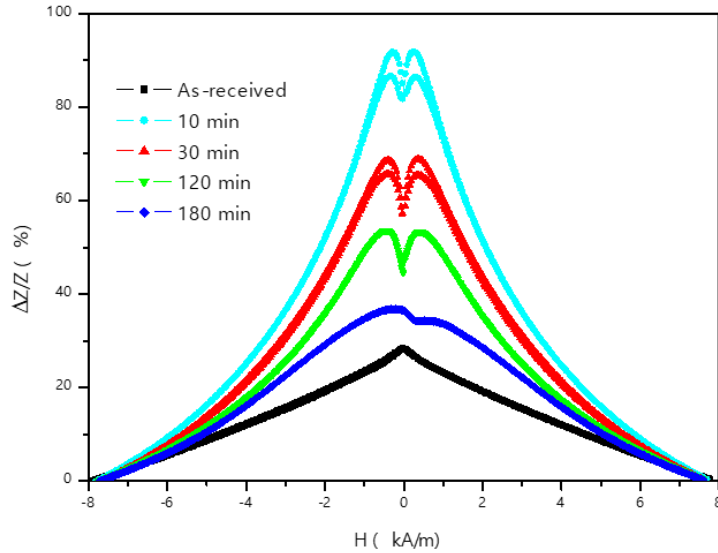
Figure 7. MI curves for 10 MHz frequency of $Fe_{77.5}Si_{7.5}B_{15}$ wires annealed at different times.

Figure 8 shows MI variations of $Fe_{77.5}Si_{7.5}B_{15}$ wires based on annealing time for different drive current frequency values. For wire sample annealed for 10 minutes, MI changes were determined as 54%, 169%, 127% and 92% at 100kHz, 1MHz, 5MHz and 10MHz drive current frequency values, respectively. The maximum change observed for all drive current frequency values occurred after 10 minutes of annealed and MI changes were observed to decrease with increasing annealed time. It was determined that the greatest MI value for the given frequency ranges occurred around the frequency of 1MHz (Figure 8). This is a result of both domain wall motion and magnetization orientation contributing to the impedance due to permeability for this frequency value.
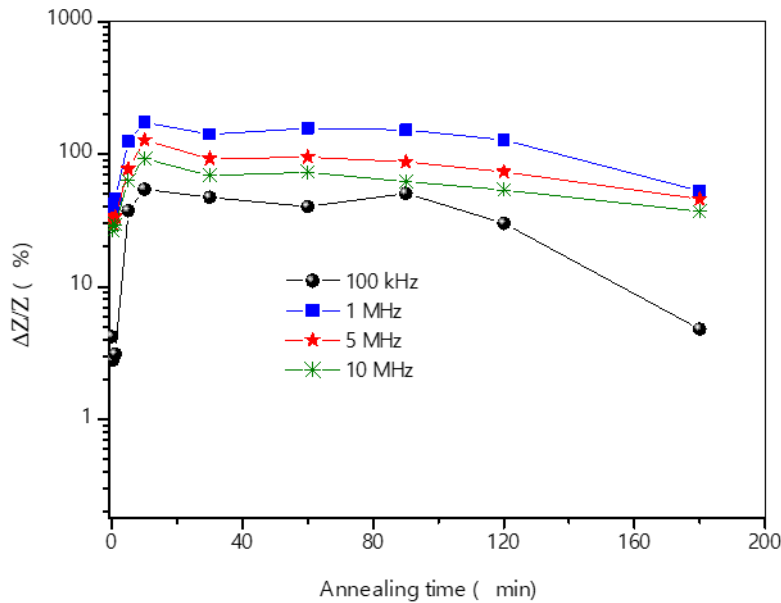

Figure 8. MI values depending on the annealing time of $Fe_{77.5}Si_{7.5}B_{15}$ wires for different frequency values.

Figure 9 shows the value of MI and coercivity values at 1MHz frequency value depending on the annealing time for $Fe_{77.5}Si_{7.5}B_{15}$ wires. For the as-received sample, the MI change was approximately 40% and the coercivity value was calculated as 6A/m. While the coercivity value was about 1.2 A/m in 10 minutes depending on the annealing time, it started to increase after this time and increased to about 500 A/m after 180 minutes.
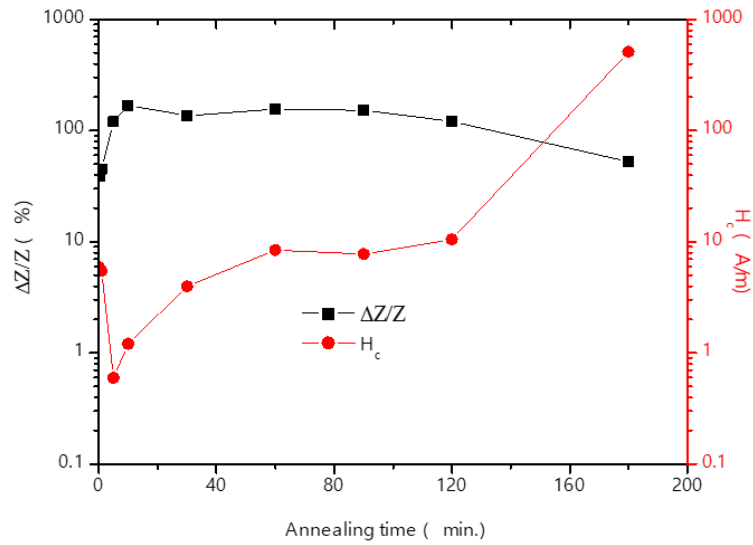

Figure 9. MI and coercivity change due to annealing time for $Fe_{77.5}Si_{7.5}B_{15}$ wires.

Tensile stress similar to the external magnetic field applied to the sample cause changes in MI values. The MI values of the as-received Fe77.5Si7.5B15 wire at 1MHz frequency value for different tensile stress values against the applied external magnetic field are given in Figure 10.
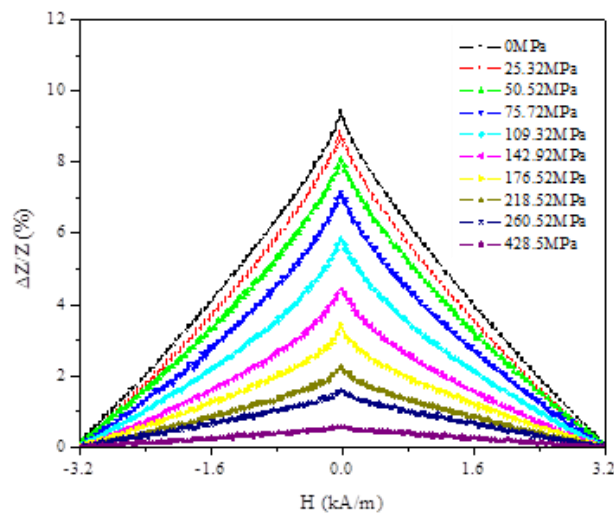

Figure 10. MI values of as-received $Fe_{77.5}Si_{7.5}B_{15}$ wire against magnetic field under different tensile stresses.

Figure 11 shows MI change with the magnetic field applied for different tensile stresses of the wire annealed under the furnace for 5 minutes. The peak values $\Delta Z/Z$ (%) of as-received and 5 min annealed wires reduced from 10% at $\sigma = 0$MPa to 0.6% at $\sigma = 428.5$MPa and 45.3% at $\sigma = 0$MPa to 1% at $\sigma = 428.5$MPa, respectively (Fig. 10 and Fig.11).
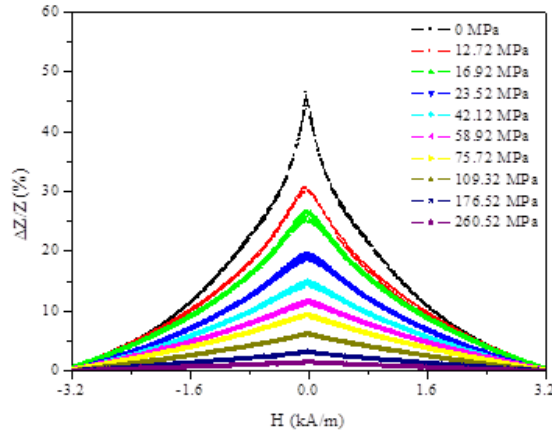

Figure 11. MI values of annealed for 5 minutes Fe$_{77.5}$Si$_{7.5}$B$_{15}$ wire against magnetic field under different tensile stresses.

Figure 12 shows the MI change for different tensile stress values of the sample annealed for 90 minutes. For this annealing time, asymmetric property was observed in MI curves. Asymmetric value of MI curve decreased gradually with increasing stress and asymmetric MI curves disappeared at 109MPa stress value and single peak behaviors were observed again. It was determined that the peak values of $\Delta Z / Z$ (%) for wires annealed in 90 minutes decreased from 31% at $\sigma = 0$MPa to 0.7% for $\sigma = 428.5$MPa.

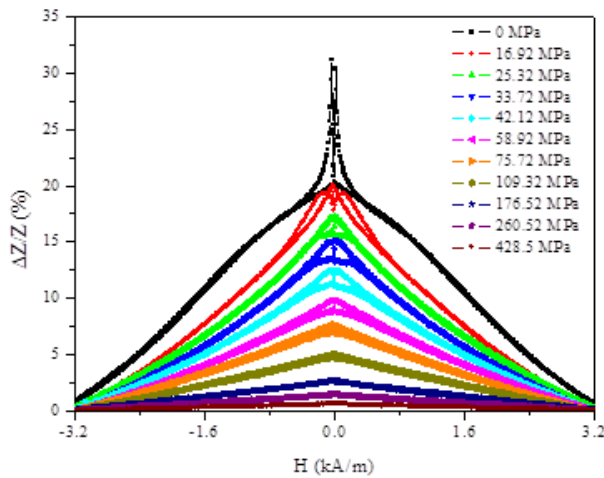**Figure 12.** MI values of annealed for 90 minutes Fe$_{77.5}$Si$_{7.5}$B$_{15}$ wire against magnetic field under different tensile stresses.

The variation of MI values with applied stress stresses of as-received and annealed wires is given in Figure 13. As seen in Figure 13, the magnitude of the MI effect decreases with the increase of stress applied in all measurements.
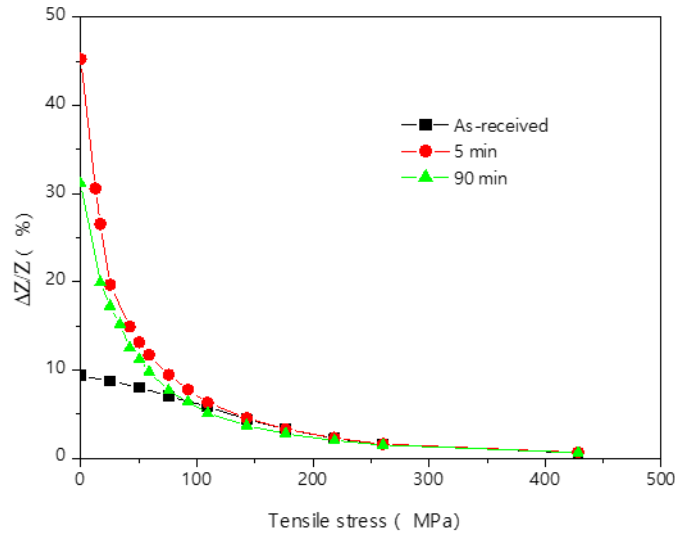

Figure 13. $\Delta Z/Z$ (%) ratios as a function of applied tensile stress for as-received and annealed $Fe_{77.5}Si_{7.5}B_{15}$ wires.

4. Results and discussion

Magnetic permeability plays an important role in the interpretation of MI data. The impedance is proportional to the square root of the circular magnetic permeability for wire samples ($Z \propto \sqrt{\mu_\phi}$) (Phan and Peng, 2008). Therefore, an increase or decrease in magnetic permeability will correspond to an increase or decrease in impedance value. Depending on the drive current frequency, MI values arise from their contribution from domain wall motion and magnetization orientation (Knobel, et al., 2003; Phan and Peng, 2008). At the frequency of 1MHz, the greatest value was observed as a result of both processes contributing to MI change. For high frequency values (5 and 10 MHz), the magnetization orientation is effective due to the suppression of the domain wall displacement in long term heat treatments, and accordingly, double peak behaviors arise in the curves. In addition, for these drive current frequency values, it was determined that the observed double peak behaviors showed asymmetric properties. Similar results were given by Knobel et al. (1996) on annealed wires. The variation of the coercivity and MI values of $Fe_{77.5}Si_{7.5}B_{15}$ wires by annealed can be interpreted by separating them as low, medium and long term (Figure 9). At low annealing times, there is a decrease in coercivity (Hc) and an increase in impedance change. The contribution of the crystalline anisotropy to the total anisotropy is zero, since the structure remains completely amorphous in this region. However, since annealed treatments in this region reduce the internal stresses of the sample, it reduces the magneto-elastic anisotropy and thus the total anisotropy energy (Atalay, 1992). The total anisotropy value of the sample is inversely proportional to the impedance value due to magnetic permeability. The impedance increases in this region due to

the decrease of anisotropy. In medium term heat treatments, there was not much change in coercivity and MI values. Nano-crystalline Fe_2B phase is formed in amorphous alloys in long term annealing. This crystal phase increases the total anisotropy energy value and accordingly the impedance value decreases. Fe_2B phase causes an increase in pinning points in amorphous structure. This leads to a sharp increase in coercivity values and a decrease in MI values (Atalay, 1992; Squire et al., 1994).

It was determined that MI values decreased in all tensile stresses applied on the wire. In samples with positive magnetostriction value, tensile stress will try to direct magnetic moments in line with the length of the wire depending on the domain structure of the material, which will cause the size of the MI effect to decrease (Bayri and Atalay, 2004).

As a result, it was observed in this study that external DC magnetic field and tensile stress caused changes in MI effect for $Fe_{77.5}Si_{7.5}B_{15}$ wire samples. Especially low-term annealed has been found to lead to an improvement in the magnetic softness, leading to an increase in MI effect. It was observed that the largest percent MI change for all samples occurred at a frequency of 1MHz. For this frequency value, while the change in MI was 40% in as-received wire, the change in the sample annealed at 460 °C for 10 minutes was determined as 169% and it was observed that the change decreased with increasing annealed time. Also, tensile stresses applied to the sample revealed changes in MI effect. According to the experimental measurements, $Fe_{77.5}Si_{7.5}B_{15}$ wire was determined to be sensitive to both the external magnetic field and the tensile stress applied. This sensitivity will allow these wires to be used in sensor applications.

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