SMART MATERIALS TECHNOLOGY FOR ROOFBOLTING APPLICATION IN THE MINING INDUSTRY

J.S. Moema,[1*] M.J. Papo[1] and R Paton[1]

[1] Mintek, Private Bag X3015, Randburg. 2125. South Africa

ABSTRACT

The large number of rock falls, the danger associated with such events and the frequency of their occurrence, especially in the deep mining activities in South Africa, has led to the development of a smart material (Smartbolt™). Some 50% of underground fatalities are a result of rock-related accidents and 40% of these fatalities are due to rockbursts. A rockburst is an unpredictable, violent event. The smartbolt would be able to anticipate the potential collapse of rock, for example in supported tunnels. This will alert miners that a change in loading conditions has occurred, and warns that a rockfall may occur. Mintek, the Safety in Mines Research Advisory Committee (SIMRAC) and the Department of Science and Technology (DST) have been involved in a research project focusing on the development of a smartbolt for underground monitoring operations.

A smartbolt is a metastable austenitic stainless steel alloy that, when stressed, undergoes a microstructural transformation. Its properties change from non-magnetic to magnetic, depending on the degree of plastic deformation, thus leading to a change in longitudinal ultrasonic sound velocity. The smartbolt is installed along with the conventional carbon steel rock bolts for added protection and safety underground. Stainless steel was selected as its chemical composition will allow the roof bolts to remain functional even in mines containing highly corrosive mine water. The smartbolt will enable rock engineers to anticipate and record rock movement. The two rockbolt systems are expected to complement one another. A portable ultrasonic monitoring device is used to measure sound velocity along the length of the bolt. Its probe is applied to the smartbolt head, and in so doing, the change in the microstructure that results from the stresses exerted on the smartbolt by the changing mining roof conditions can be monitored. The smartbolt is more correctly described as being able to produce a measurement of unstable rock.

Alternative interrogating equipment has been sourced from USA. This VX Velocity Gauge is portable and can measure the sound velocity of a 0.5m long bolt. The alloy has a good combination of high strength and ductility; this makes it a suitable sensor candidate for extreme conditions of high tensile and shear stresses, similar to conventional roof bolts. A Smartbolt prototype entered the 2005 SABS Prototype Award Competition and won an award. This shows that there is an opportunity for the Smartbolt prototype to be recognised by both civil and mining industries. The Smartbolt prototype is presently in the commercialisation phase. To illustrate the effectiveness of the technology, prototype roofbolts (20mm in diameter by 2m long) were manufactured and installed in a South African gold mine. Data from the underground field trials have been collected and more data are currently being gathered, especially in the areas that show high stresses or a potential rockfall.

1 INTRODUCTION

The regular collapse of mine roofs, and the consequent impact on injuries and fatalities, is a recurring problem in South Africa. This appears to be worsening due to the increasing depths of mining. A solution to ameliorate this problem is the development of a smart material which can determine *in situ* the potential for overloading of support in individual areas of the mine. The so-called Smartbolt, when stressed, undergoes a microstructural phase transformation if the bolt is plastically deformed: its properties change from non-magnetic to magnetic. The microstructural change also has an influence on the sound velocity characteristics of the material.

Such a smart material could be used in mine roof bolts. It would be highly advantageous to assess the condition of a mine roof support system by monitoring the stress levels experienced by the roof bolts. The Smartbolt can then act as a sensor in determining the stresses in mine workings.

The phase transformation within the smart material can be monitored using a portable magnetic or ultrasonic non-destructive technique to determine any change in loading conditions, and to warn of a possible overload condition. An important aspect of this kind of smart material is that the incubation strain on yielding of the bolt is reduced as much as possible, and that the rate of the microstructural phase transformation is high, thus enabling effective monitoring.

The present paper reports on a laboratory evaluation of the stress/strain characteristics of such mine roof bolts developed out of a metastable austenitic stainless steel [1]. Results of initial field testing of the Smartbolt prototype in a South African gold mine are given. A subsequent paper on the modelling responses of this alloy will be reported elsewhere [2]. The Smartbolt is installed along with conventional carbon steel rock bolts for added protection and safety underground. Stainless steel was selected, as its chemical composition will allow the roof bolts to remain functional even in mines containing highly corrosive mine water. The conventional steel rock bolt would provide support in the mine, while the Smartbolt will enable rock engineers to anticipate and record rock movement. The two systems are expected to complement one another.

For the field work, a portable ultrasonic (USM 25 DAC) monitoring device was used to measure sound velocity along the length of the bolt. Its probe is applied to the Smartbolt head, and in so doing one can monitor the change in the microstructure that results from the stresses exerted by the changing mining roof conditions. A portable magnetic instrument (ferritescope) was used for the laboratory testing. Both test methods are complementary, however the ultrasonic technique is more suited to underground conditions as it can detect bent and broken roofbolts *in situ*.

2 EXPERIMENTAL

2.1 Microstructural Studies

A Smartbolt™ is a metastable austenitic stainless steel alloy with a smooth metallic surface finish. Its length varies according to different mine roof requirements. Its shape and form are different from the conventional carbon steel bolts because its outer surface is not ribbed (see Figure 1). When stressed underground, it undergoes a microstructural transformation where its properties change from non magnetic to magnetic, depending on the degree of plastic deformation. This change in microstructure also leads to a change in the ultrasonic sound velocity through the Smartbolt.

To study the microstructural changes, laboratory and industrial annealed specimens were mechanically polished to a 1μm finish using diamond paste, and finally electropolished in 20 percent perchloric acid at 18 volts for 30 seconds (20ml perchloric acid plus 80ml alcohol). This was followed by electrolytic etching in 10% oxalic reagent. Electrochemical polishing was necessary to remove any deformation-induced martensite that may have formed during the mechanical polishing.

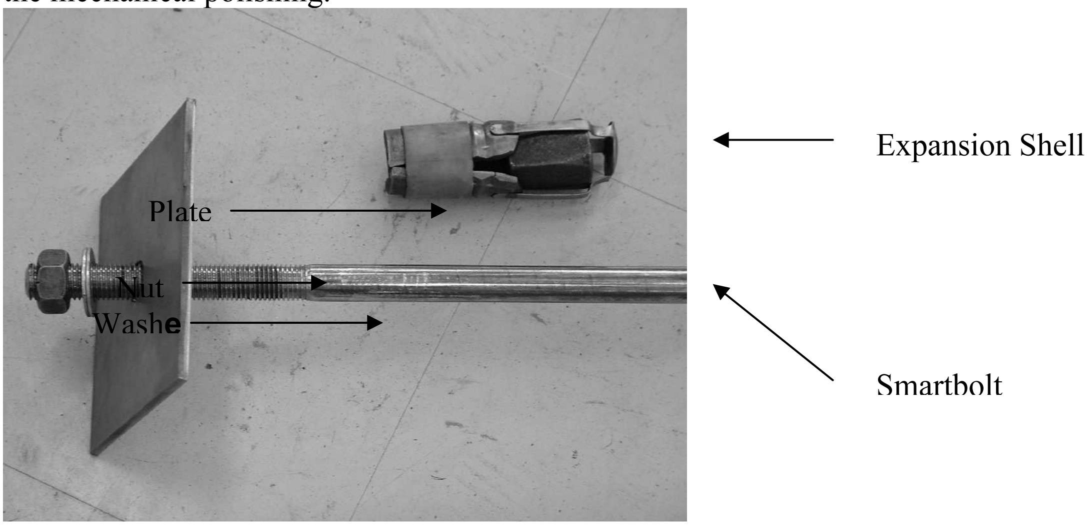

Figure 1. A photograph showing a close-up view of a 1.5m long smartbolt, washer, nut, expansion shell and plate.

2.2 Mechanical Properties

To study the transformation characteristics of the alloy, a computer interfaced Instron 1175 tensile testing machine was used to conduct interrupted tensile tests according to ASTM E8 [3]. These tests were carried out on laboratory annealed smartbolt alloy and standard Type 304 stainless steel. These samples were round tensile specimens of 6.25mm diameter and a 25mm gauge length. They were carried out at a constant crosshead speed of 1 mm/min which corresponds to an initial strain rate of $1.3 \times 10^{-4} s^{-1}$. This strain rate was considered to be sufficiently low to prevent excessive local heating in the specimen. The samples were tested to failure at room temperature.

For the determination of mechanical properties on industrial hot rolled smartbolt material, round tensile specimens of 12.5 mm diameter and 50 mm gauge length were machined. Duplicate tensile tests using a Tinius Olsen Super L system 600kN frame tensile testing machine were carried out. The frame was also used for tension testing of mini bolts.

2.3 Smart Material Monitoring

Ultrasonic sound velocity is a physical property influenced by microstructural features. A change in microstructure by the use of applied stress may be potentially monitored by accurately measuring the longitudinal ultrasonic velocity. For the laboratory evaluation, a ferritescope was used to measure changes in the magnetic response with stress/strain.

2.4 Field Testing

A gold mine was chosen for field tests since gold mines are generally deeper than other mines such as platinum. The rock morphology (reef ore) is unstable due to its weak tensile properties. In addition, rockfalls commonly occur in gold mines. It was found that the proposed test site used 20mm diameter by 2400mm long roofbolts. The installation and tensioning or tightening process of a roofbolt to an appropriate load using a torque wrench is illustrated in Figure 2a and 2b. All sets of the installed Smartbolts were cement grouted and mechanically anchored so that during blasting. It is considered that the Smartbolt technology is more appropriate using anchoring rather than frictional forces.

A **B**

Figure 2. A photograph showing the installation and tensioning or tightening process of a roofbolt.

3 RESULTS AND DISCUSSION

3.1 Microstructure

The laboratory and industrial annealed microstructures of the smartbolt alloy are both fully austenitic with no presence of carbides. Figure 3 shows an electrolytically polished and etched smartbolt alloy that consists of austenite grains with twinning. The black spots seen in this micrograph are non-metallic oxide inclusions. Martensite, which is ferromagnetic, was not detected in the alloy in the annealed state because of the low M_s temperature (i.e. the temperature at which martensite starts to form). Martensite can often be induced above the M_s by cold work and this occurs at a temperature that is designated as M_d (i.e. the highest temperature where plastic deformation can induce martensite nucleation) where $M_d > M_s$. A micrograph of a strained smartbolt alloy is shown in Figure 4 and consists of bands of finer twinned strain-induced martensite in an austenite matrix. The formation of martensite plates is assisted by a elastic tensile and shear stress, also normal strains. It is clear that the smartbolt alloy undergoes transformation during the early stages of straining.

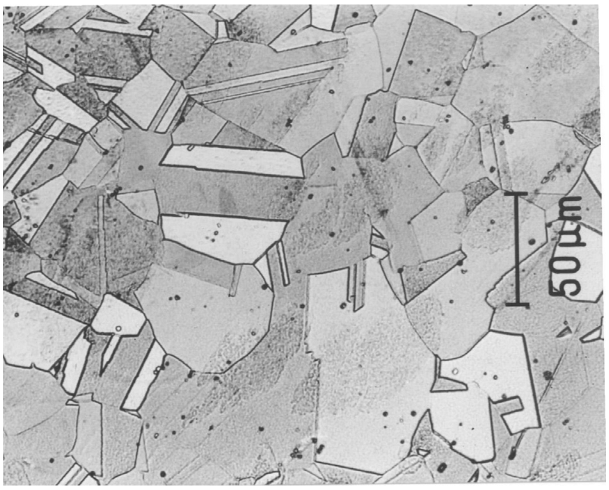

Figure 3. Microstructure of smartbolt alloy in the annealed condition showing austenite.

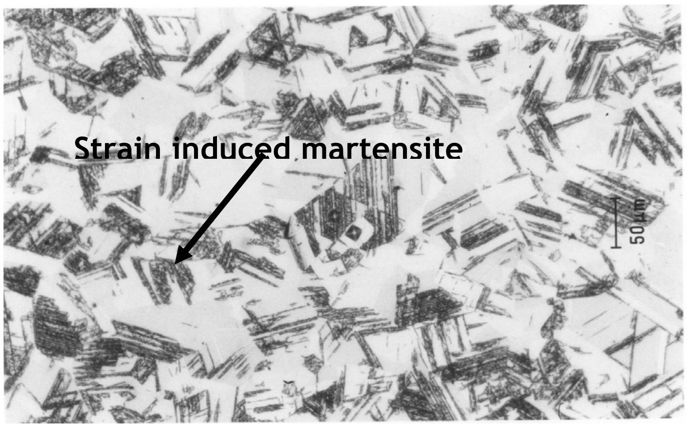

Figure 4. Microstructure of smartbolt alloy in the strained condition showing strain induced martensite (black plates) in an austenite matrix (white phase.)

3.2 Mechanical Properties

Transformation characteristics under uniaxial tensile testing were studied. Figures 5 and 6 show the amount of martensite (measured as % magnetism) formed during tensile testing as a function of % elongation. This study was carried out to determine if this material could be used as a strain-monitoring device. The martensite (α') obtained from plastically deformed austenite (γ) is ferromagnetic and is readily detected by magnetic measurements. The magnetic permeability of a sample was measured with a ferritescope. This is a two-point probe which, when placed on a sample, is energised by the low frequency magnetic field and induces a voltage. This induced voltage is a direct measure of magnetic permeability.

The tensile properties of the alloy tested at room temperature are summarised in Table 1 and also graphically presented in Figure 6. It can be seen that the smartbolt alloy is substantially harder than Type 304 stainless steel partly due to its much higher carbon and nitrogen contents. The annealed proof strength values are fairly similar to the current carbon steel grade [5] used for roofbolts (made according to ASTM F 432 of 1989, grade 55 or 75). The proof stress of the alloy in the hot rolled and annealed (HRA) condition ranges from 438 to 451MPa, which is somewhat higher than that for Type 304 at 319MPa.

The Ultimate Tensile Strength (UTS) values, relative to the proof stress values, are an indication of the instability of the alloy. It is clear that the smartbolt alloy is the most unstable alloy, as it has a relatively high ratio of UTS/Proof Stress. Typical values for the tensile strength of industrial Type 304 are 560 to 635MPa.

The minimum elongation specified for Type 304 is 40% compared to that of the smartbolt alloy, which is 25 to 30%. Bressanelli [6] proposed that because of the limited ductility of the martensite phase, premature fracture might occur that results in decreased uniaxial ductility. In the smartbolt material, alpha prime (α') martensite is nucleated very quickly and hence this will reduce the % elongation and produce a characteristic flat-face fracture.

Table 1. Tensile tests results (6.25mm diameter specimens)

Alloy	**UTS (MPa)**	**0.2%Proof Strength (MPa)**	**Elongation (%)**	**Condition**
Type 304	733 ±1.0	319 ±63	83	Lab annealed
Smartbolt™	1063 ±24	438 ±2.0	30	Lab annealed

It is clear that the smartbolt alloy undergoes transformation during the early stages of plastic behaviour with low incubation period, $e_{sm} \approx 2$. This is unlike the commercial Type 304 which has a higher incubation period ($e_{304} > 15$) and requires at least 16% plastic strain to give a measurable response. It can be seen that the incubation strain of the smartbolt alloy is reduced (≈2%) and that the microstructural transformation rate is high, thus enabling effective monitoring.

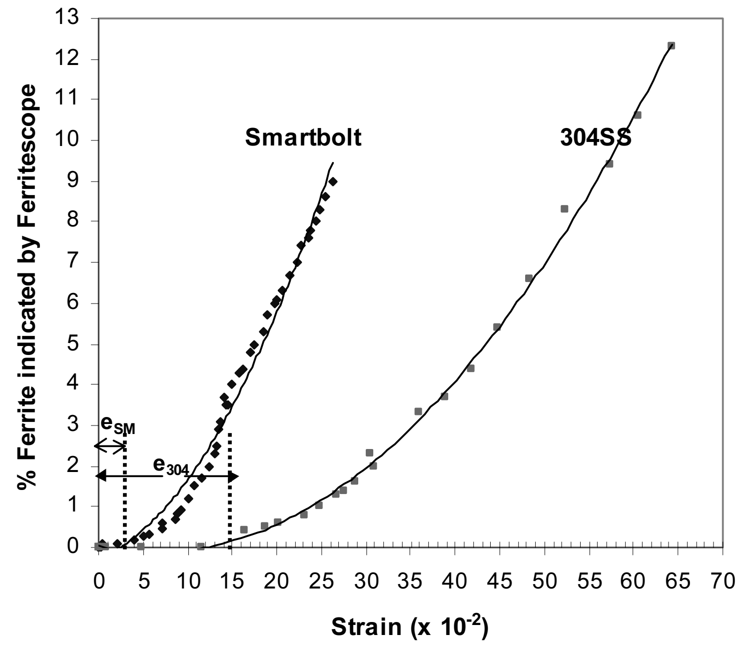

Figure 5. Percentage ferromagnetic phase versus strain for the smartbolt alloy and Type 304 stainless steel as determined by a ferritescope.

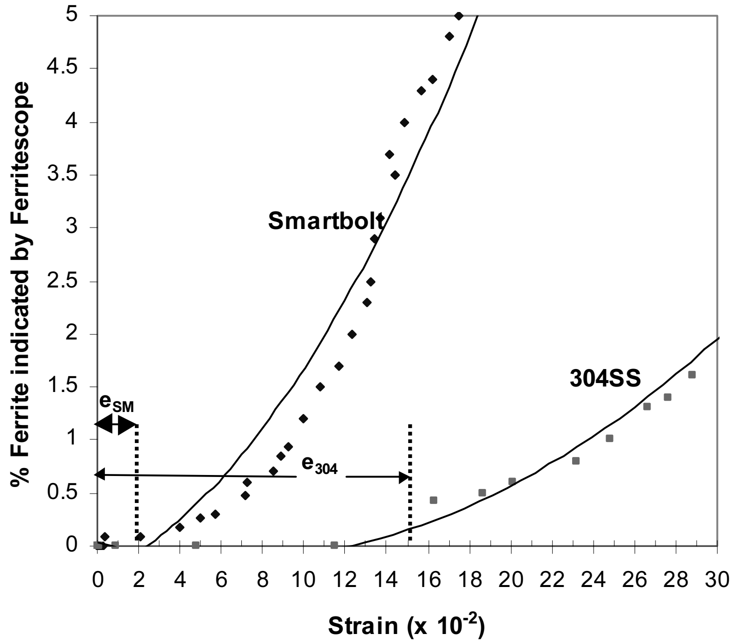

Figure 6. Percentage ferromagnetic phase versus strain for smartbolt alloy and Type 304 stainless steel showing the incubation period more clearly.

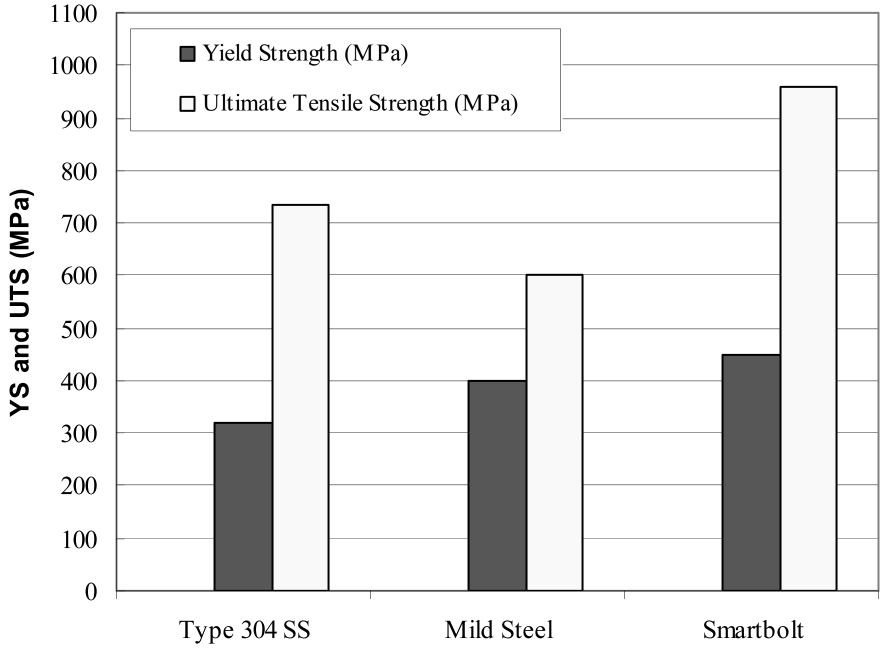

Figure 7. Comparison of mechanical properties between Type 304 stainless steel, mild steel and smartbolt alloy.

3.3 Testing in the Mine

To test and illustrate the effectiveness of the smartbolt technology, a test site was identified and prototype roofbolts were installed in three different sections of a South African gold mine. Loosening of rockbolt anchors after the blast appears to be a major problem in most of the mines where conventional mining is taking place. This is due to the current tensioning method which is generally done manually with a simple tool such as a spanner. It was therefore agreed with the mine personnel to install the smartbolts using both grout and expansion shells, and to use a torque wrench for pre-tensioning of the bolts to a value of ±35Nm.

In many situations underground, the bolt is not in pure tension, but usually in a combination of tension and shear. Allowance, therefore, must be made for multiaxial loading conditions, as the transformation characteristics of the smartbolt alloy are different in this case. Uniaxial tension produces less martensite compared to a multiaxial state under the same experimental condition. This is due to multiple slip systems being activated in a multiaxial loading condition. The warning guidelines that are shown in Table 2 were constructed based on the multiaxial modelling work that was carried out on the bolts, and these were used to interpret the readings from underground monitoring [1].

Table 2. Potential smartbolt warning guidelines

Ultrasonic sound velocity (m/s)		**Comments**
Uniaxial	**Multiaxial**	
5640 to 5652	5640 to 5676	Stresses in elastic range
5652 to 5672	5676 to 5715	Bolt is yielding
>5672	>5715	Bolt is showing substantial plastic deformation

Fourteen Smartbolts were installed in a haulage tunnel to monitor the stresses that are experienced in that area. These Smartbolts were monitored by interrogation with an ultrasonic device over a period of ten months to see if there was any microstructural change [7].

The results obtained during the fieldwork are graphically presented in Figure 8. Almost 50% of the installed smartbolts experienced significant increases in stress. Also, some of the bolts developed a monotonic pattern of increasing load with time. With continued mining in the vicinity of this area, it is anticipated that further increases in load/stress will be measured. At present, mining is taking place at level 93, which is just above this section.

4 CONCLUSIONS

A metastable austenitic stainless steel alloy has been identified as being suitable for acting as a smartbolt. When stressed underground, the alloy undergoes a microstructural transformation, with its properties changing from non-magnetic to magnetic, thus leading to a change in longitudinal ultrasonic sound velocity.

It was observed that the smartbolt alloy could be used as a strain-sensitive sensor in rock bolting applications. It was demonstrated that acoustic measurements have a complex dependence on the multiaxial strain state, and therefore more knowledge of this strain state is required. It is envisaged for use in South African gold mines. Installed prototype Smartbolts, interrogated with an ultrasonic device over a period of ten months, showed a monotonic pattern of increasing load with time.

It can be concluded that there is an opportunity for this Smartbolt™ prototype to be recognised by both civil and mining industries. The smartbolt prototype is now in the commercialisation phase.

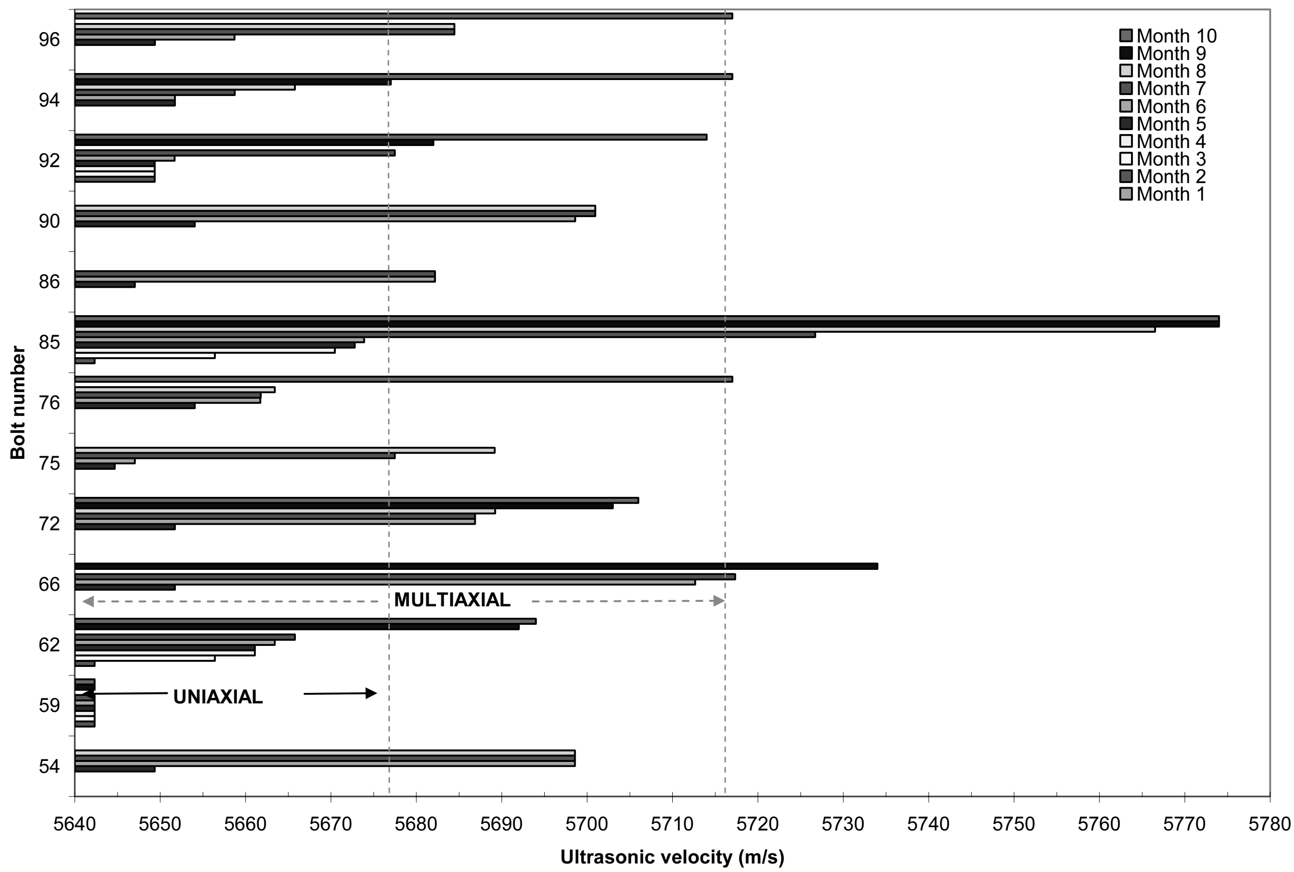

Figure 8. The results obtained from a South African gold mine

5 ACKNOWLEDGEMENTS

The permission from MINTEK (South Africa) to publish this work is acknowledged. The author wishes to thank the DST-Innovation Fund administered by the National Research Fund (NRF) for sponsoring this project. The technical contributions of Mr R Paton, Mr J Kerr and Mr S Roberts are also acknowledged. The Special Alloy & Metallurgical Services (SAMS) and Mittal Steel SA are thanked for the production and processing of industrial Smartbolt™ bars. We also thank Mr S Petho for granting permission to use the South Deep gold mine as a testing site.

6 REFERENCES

[1] J.S. Moema, *A Study of Smart Materials for roof bolts application in the Mining Industry*, M. Tech Dissertation, University of Johannesburg 2006.

[2] J.S. Moema, R. Paton, M.J. Papo, and A.F. Mulaba-Bafubiandi, *Modelling of the plastic behaviour of a Metastable Austenitic Smart Materials for Roof Bolt Application in the Mining Industry*, (*not yet published*)

[3] ASTM E8-99., *Test Method for Testing Testing of Metallic Materials*, American Society for Testing and Materials, West Conshohocken, USA, 2000.

[4] Bressanell, J.B., Trans. ASM, 54, (1966), 223

[5] ASTM E432-89 *Standard Specification for Roof and Rock Bolts and Accessories*, American Society for Testing and Materials, West Conshohocken, USA, 2000.

[6] S. Petho, private and e-mail communication to Joseph Moema, 4 April 2006.

[7] USM 25, Technical Reference and Operating Manual, Krautkramer, EN 12668-1