FIRST IMPRESSIONS OF ADI CHAIN INSTALLED IN THE AMATIKULU DIFFUSER

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Abstract

Amatikulu Sugar Mill has installed Austempered Ductile Iron (ADI) block links and side plates on two diffuser chain strands. These links were cast in South Africa at a substantially lower cost than forged chain links. Some development emerged concerning the pattern, casting procedures and quality assurance required to ensure that high quality links were produced. Extensive tests were performed on the new links, including tensile and ultrasonic tests, and the cutting of cast links to inspect casting quality and procedure. Old links were also tensile-tested for comparisons.

The two chain strands have been in use for one season and have proven successful. Some links were disassembled for inspection after one season and the inspection results of these links and the rest of the chain are discussed.

Some other advantages of using ADI are also discussed. These advantages include lower cost, through-hardening of links, smaller chain order size and a shorter delivery time.

Keywords: Austempered Ductile Iron, ADI, diffuser, diffuser chain, factory process

Introduction

The diffuser chain at Amatikulu is reaching the end of its service, and will require replacement in the next few years. The chain flanges and bushes are worn and there is severe corrosion around the bores of both the inner and outer links. Thus far, refurbishment of chain strands has consisted only of bush and pin replacement (and replacing some severely worn links). This is a very costly exercise in itself, costing close to R1000 to refurbish per link, and it was decided in 2004 to replace two strands out of the sixteen installed with new chain links and bushes, re-using recently replaced pins. This would then free up a set of used links, which had been re-bushed.

Diffuser chains are available from manufacturers like GEKA and Tsubaki, at approximately R2500 per link[1]. What contributes even further to the cost of Amatikulu's chain is the strange pitch of 17.463" (443.56 mm). The reason for the strange pitch is not known; standard manufactured links now have 250 and 500 mm pitch. It was suggested by Bob Strachan to use locally cast ADI links with Tsubaki bushes and pins, which would cost ca. R1200 per link, and R1000 per link if the pins were excluded. While ADI is not a new material to the

[1] Quoted prices are based on a currency exchange rate of ca. R1.00 = 16.00 Japanese Yen.

automotive industry, its use in the sugar industry has been limited to slat carriers. What was also needed was to assess the remaining life of the old chain while the ADI was trialed.

Forging the chain was considered, but the cost of imported forgings was no better than imported castings. The only local forge (in Atlantis) capable of the work was not willing to consider it beyond initial investigation, even given the large order quantity. Casting at a local foundry was opted for, since the original foundry has been closed.

Current chain condition

The current Ausrex diffuser chain was cast in Australia by Fowler Rex in 1974 and again when the diffuser was extended from 13 stages to 16. The pitch was 17.463" with a pitch tolerance of ±0.005"; the material used was a manganese steel alloy, flame-hardened to a depth of 3 mm minimum (with 4.8 mm being the quoted depth achieved) with a Rockwell C hardness of 50. Surface hardening has the disadvantage – that, although the casting retains a tough core, the wear of the chain accelerates when the hardened layer is worn through. Some work hardening is expected from the manganese steel, but the wear is expected to be faster on the chain once the hardened layer is worn through. The chain flanges, originally a depth of 16 mm, have worn down by ±8 mm per flange.

The links have also suffered corrosion-erosion around the bush journals (see Figures 1 and 2). Shown in Figure 1 are typical examples of the corrosion-erosion that is present on most of the old Ausrex links. The corrosion is deepest close to the bush, and varies from 3-6 mm depth. The corrosion weakens the link by reducing the cross-sectional area, it also causes the bush-ends to crack (Figure 2). The inner link in Figure 2 shows initial stages of corrosion around the bush. Note that the bush is cracked on both ends; this introduces bending stress in the pins and the links.

Figure 1. Worn Ausrex chain outer links.

Figure 2. Worn Ausrex inner link.

The corrosion always occurs between mating faces of the inner and outer links, concentric around the bush. Galvanic corrosion is expected around the stainless steel bush caused by the galvanic cell formed by the stainless steel bush and the manganese steel links. Cane fibre also enters the gaps between the inner and outer links; this will wear the corrosion layer away. These two processes contribute to the corrosion-erosion seen between the mating surfaces on the links.

This corrosion highlights the need for diffuser liming or some other means of pH control. The juice pH in the diffuser should ideally be maintained at no lower than 6 and no higher than 7 for overall optimisation of the diffuser. The pH in the diffuser should be closer to 12 to prevent corrosion, which will be unacceptable for the extraction process. Therefore some corrosion will always be expected. As yet, no corrosion is evident on the new chain.

A fair degree of electrolytic corrosion was expected at the point of manufacture in 1974, and it has certainly emerged over many seasons at AK and Felixton (FX), although the manganese alloy was considered the best after stainless steel at the time.

There were initially severe problems with the Ausrex pins cracking, most of which have been replaced by Tsubaki stainless steel SUS403T pins and SUS420J2 bushes, which have proved to be successful. At this stage AK ultrasonically tests pins twice-annually to detect any cracking, which is expected due to the increased loading on the pins caused by the corrosion of the links. None of the original links have failed to-date under normal operation.

Manufacture of the ADI chain

The Ausrex chain links were designed for a safety factor of 9.4, with a designed breaking load of 3430 kN (770 000 lbs) under pure tension. Given the cross-section of the chain at the bores, this would require a tensile strength of 760 MPa. The design load was 365 kN, based on maximum input torque. It was decided that ADI grade 2 would be adequate to provide a similar strength (see Appendix II), while retaining ductility, even with through-hardening - especially given that modern diffuser chains are generally designed for safety factors of 4-5.

Joerg Foundry in Rustenburg cast the ADI links for Amatikulu. The old links and drawings were used as a base for the pattern design of the new ADI links, with some minor differences. The time saved by having locally cast links was invaluable in being able to solve difficulties while the bushes were on order ex-Japan. With the foundry not having handled such large section chain castings, several site visits and tests were conducted to ensure quality. Problems encountered were:

- Warping of the thinner outer link plates
- Shrinkage defects on the thicker inner link blocks.

Casting problems

The slight warping of the outer links was corrected by simply machining the links to size after allowing a substantial casting allowance. The pattern of the side-link has now been altered to introduce a rib parallel to the link flanges, which has eliminated the warp without adding excessive weight to the chain (see Figure 3).

Figure 3. Experimental side link with added centre stiffener.

The initial batch of chain was inspected at Joerg on February 17 2005, and it was immediately noticed that there were many outer links with cold-drawing depressions at the risers, and also lots of ‘breakout’ on the edges of the links. Crater-like defects were found on the flange surfaces of the outer links, but did not extend beyond what could be seen with the naked eye.

A tensile test was conducted on February 28 at CSIR, where two samples of the worst-condition links from the old chain were tested, along with a sample of the new chain. The old links can be seen in Figure 1; they were worn and had severe corrosion. The first set of old links broke at the bore of one of the side links with a tensile pull of 1559 kN, revealing casting (and possibly corrosion) defects, while the second set failed to grip in the machine jaws. Figures 4-6 show the first sample, failed at the bore of one of the outer links. The lowest recorded failing load of 1559 kN or 158 919 kg on the old chain was lower than the estimated breaking load of 237 386 kg, which was based on the measured hardness of BHN 217. The corrosion around the bushes contributed in reducing the chain’s breaking load, by increasing the stress concentration around the bushes as well as increasing the bending in the pins.

Figure 4 shows the first sample, failed at the bore of one of the outer links. Figures 5 and 6 show the mating fractured planes of the old links. Figure 5 is most interesting as it clearly shows inherent defects in the cast, which were not apparent on visual inspection before testing. The defects have possibly been developed further by corrosion. Note the pattern of the hollows running at 45º from the bottom of the corrosion crater close to the bush. The new cast links initially slipped in the machine jaws under tension, and were then rotated 90° so that the jaws could grip the flanks of the flanges, which had been machined to size. The new chain broke at a safety factor of 7.5, failing on an inner block link, revealing a shrinkage defect at an ingate point (Figures 7 and 8).

Figure 4. Failed test sample B1-B2-L1-L2.

Figure 5. Failed section B1-B2-L1-L2.

Figure 6. Mating failed section to Figure 5.

Figures 7 and 8 show the new link sample, failed at a short distance away from the bores with an obvious shrinkage defect, about 30 mm long. The strength was commendable even with the casting defect. No defect had been apparent before the test. Another tensile test was conducted on March 9 2005, where the old links which had failed to grip were re-tested, along with three new ADI links. The results of all the tensile tests can be seen in Table 1, and Figures 10 to 20 in Appendix III.

Figure 7. Failed ADI chain with defect.

Figure 8. Mating section to Figure 7.

Table 1. Tensile test results.

Test date	Sample	Maximum load (kN)	Safety factor	Remarks
28-02-2005	Old links B1-B2-L1-L2	1559	4.27	Failed at outer link defect
	New link 1	2750	7.53	Failed at inner link defect
09-03-2005	Old links B3-B4-L3-L4	1710	4.68	Failed on outer link (slight defect)
	New link 2	2446	6.70	Failed at outer link defect
	New link 3	2800*	7.67	Failed on outer link; no defect seen
	New link 4	2283	6.25	Pin pulled out

*The 2800 kN figure was extrapolated from the graph. The machine operator had incorrectly set the graph scale at 2500 kN instead of 3000 kN.

Some bending of the pins was also noticed during the tensile test of the new chain, which induced a bending moment in the chain. This reduces the breaking load of the chain links, which is now subjected to bending as well as tension and not only a tensile load. The breaking loads shown on new link samples 3-4 are not truly indicative of the strength of the link, but that of the assembled chain due to the combined loading of the links. The links of sample 4 did not break but were pulled off the pins.

Figure 9 is a typical stress-strain graph of the tested links. There is an initial elongation at low load which gives way to a linear stress-strain relationship, until the link assembly starts to yield plastically. The 'reduction' in strain after the breaking point is due to the 'spring' in the machine itself[2].

Closer scrutiny of the links at the foundry resulted in several being sawn through the ingate points. Further defects similar to those shown in Figures 7 and 8 were immediately found on sawn inner links, but not on the outer links. It was difficult to visually detect any such defects on the outside of the links, especially where the links had been fettled. The decision was then made to ultrasonically test 100% of the inner links and 10% of the outer links, and any outer link to fail an ultrasound would require that the remaining 90% be tested. No defects were

[2] Based on hardness and wear measurements and calculations of the AK diffuser chain in 2003.

detected on the outer links, but 54 of the 310 inner links were defective, and were remelted and recast. The defects were caused by the ingate pour cooling faster than the link, resulting in the ingate drawing back metal from the link. The number of ingates was increased from two to three, and were moved further away from the bores. Two feeders were also added 90º away from the ingates to assist with any further cold-drawing.

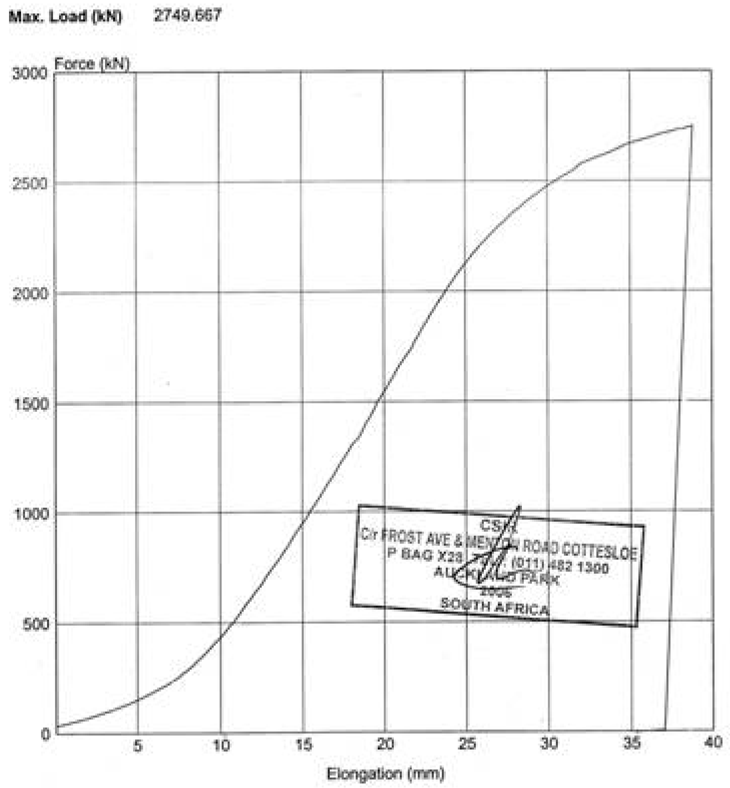

Figure 9. Typical stress-strain graph of the ‘new link 1’ sample shown in Figures 7 and 8.

Similar casting defects from shrinkage were reported in historic data with the Ausrex chain, and the patterns were altered to move the risers further away from the bores. Defects were located with ultrasonic tests and X-rays, and it was found that when the links were surface hardened, the hardening process revealed any significant defects due to the high heat input and rate of heating - any defects exploded or bubbled. The original hardness of the old links was quoted as 50 RHC; lower values are now expected because the hardened layer has been worn away.

Operational problems

During the 2005/6 season, several bushes could be seen emerging from the link bores. This occurred on both inner and outer links, and no external forces or pattern could be attributed as the cause. It was found during the off-crop that the problematic links had bushes on the lower end of the tolerance (Ø63.475 mm), while the bores in the links were found to be on the top end of the tolerance (Ø63.450 mm). The interference between bush and bore was increased from the original 25-120 microns to 150-200 microns, which should prevent subsequent movement. The Ausrex bushes expanded with heat treatment and were fitted with a tolerance of 0.004” (100 microns).

One unexpected problem was the large difference in length between the new chain and the old chain over 60 m; the tailshaft of the diffuser is currently adjusted to produce an acceptable tailshaft catenary in all the old chains (strands 3-16). The new chain (strands 1-2) hung at a low, ungainly level and tended to catch on the runner plates, but removing a link produced a catenary that was over-tight. Also, some sideways drift was evident in strands 3-8, and without the new chain hanging at the same level to counter the drift, strands 3-4 climbed over the new chain at the catenary before the tailshaft. Fortunately, the over-tension trip before the tailshaft prevented any damage and serious downtime. Vertical plates were welded on the runner-plate close to the tailshaft between chain strands 2 and 3 to prevent a recurrence.

A selection of ten links were randomly selected for inspection during the off-crop. The author found strange thumb-sized depressions close to the riser points on outer links. Ultrasonic testing revealed no problems on the outer links, but two of the 10 inner links tested showed an internal defect in the areas as found before during the tensile tests. One defect could be seen as roughly the size of a pea, while the other was similar to that seen in Figures 7 and 8. Links with defects were replaced by the supplier.

Overview of ADI

Austempered ductile iron, or ADI as it is commonly called, is a relatively new member of the ductile iron family. The properties of ADI are achieved through a special heat treating process called austempering. This sophisticated heat treatment requires a cycle of heating and salt bath quenching at precise times and temperatures. After heat treatment the ADI need to be shot blasted to ensure further improvement of the surface properties. The resulting material has a combination of exceptional strength and toughness, often exceeding that of alloy steels. The special processing for ADI provides a material that does not contain embrittling carbides, unlike steels, which must derive their strength from the presence of carbides. ADI's unique properties, in conjunction with ductile iron's superior castability, results in a material which can be used to cast complex shapes, with a greater certainty of consistent quality, superior cosmetics, and tolerance control when compared with steel (http://www.lethbridgeironworks. com).

The composition of austempered ductile iron is much the same as conventional ductile iron (also referred to as nodular iron or spheroidal graphite iron); that is, a carbon content of 3.0-4.0%, and silicon content of 1.8-2.8%. Sulphur and phosphorus levels are minimal (see Appendix I). Ductile iron has a tensile strength exceeding conventional grey cast iron, and also allows significantly more deformation. This is achieved by a microstructure of spherical nodules of graphite separated by ductile regions of a pearlite matrix (Smith, 1993), which can also be developed as an all-ferrite matrix given the correct alloying elements (Keough JR (1998). Ductile iron data for design engineers, Section IV, Austempered ductile iron http://www.ductile.org).

The advantages of ADI are considerable and can be summarised as follows:

- 10% lighter than plain carbon steel (density 7100 kg/m^3)
- ability to through-harden
- a wide range of mechanical properties can be achieved by the heat treatment
- cost is ca. 20% less per unit weight than steel and 50% of aluminium

- high fracture toughness, considering the high tensile strength. ADI fracture toughness is twice as high as conventional ductile iron, and equals or betters cast or forged steels
- high abrasion resistance. ADI with a hardness of 30-40 RC will compare with quenched and tempered steel at 60 RC. The surface hardening produced by the stabilised austenite content creates abrasion resistances higher than that predicted by the overall material hardness
- improved machinability over steels with equivalent strength. The predictable growth of ADI during heat treatment makes it possible to final machine before treatment in some cases - as was done in the case of the diffuser links.

The hardness of the ADI-2 chain averaged about 319 BHN (34 RC), while the Ausrex chain was quoted at 475 BHN (50 RC). The abrasion resistance described above will play an important role in the seasons to come. The other obvious difference is that the ADI is through-hardened, which should compare favourably with the surface-hardened Ausrex chain.

Applications of ADI have been numerous in the automotive industry, including engine brackets, cams, differential and annular gears, control arms, camshafts, crankshafts, sprockets and shafts, to name a few.

Conclusions

The wear seen on the chain after one season is negligible, and there is no sign of corrosion around the bushes yet. The remaining life of the old chain is difficult to ascertain.

The initial impression of ADI is that it is a viable alternative material for diffuser chain. However, quality control cannot simply be assumed and must be monitored closely. It should also be left to the chain supplier to specify chain strength and tolerances. The safety factor and tensile strength are satisfactory, although the breaking loads in the tensile tests were not as high as initially expected. The short manufacturing lead-time, low order amount and lower cost achieved are great advantages over alternative chains.

REFERENCES

Smith WS (1993). *Foundations of Materials Science and Engineering.* Second Edition, McGraw-Hill. pp 492-495.

APPENDIX I:
Comparison of chemical composition between ADI and Ausrex chains.

The table shows the chemical composition of the ADI chain as certified by Joerg, the recommended chemical composition and control ranges by ADI Treatments Limited, and what little is known of the Ausrex chain chemical composition.

Table 2. Chain chemical compositions.

Element	Ausrex	ADI (Joerg Foundry)	Suggested target*	Control range*
Carbon	**0.35-0.45%**	**3.4-3.9%**	3.60%	± 0.20%
Manganese	**1.2-1.7%**	**0.33-0.38%**	0.35% max	± 0.05%
Silicon	**0.60%**	**2.4-2.8%**	2.50%	± 0.20%
Sulphur		0.004-0.014%	0.02% max	
Phosphorus		0.025-0.030%	0.04% max	
Chromium		0.042-0.071%	0.10% max	
Molybdenum		0.014-0.023%	0.30% max	± 0.03%
Nickel		0.67-0.98%	2.00%	± 0.10%
Copper		0.70-0.84%	**0.80% max**	± 0.05%
Magnesium		0.043-0.054%	0.04%	± 0.005%
Tin		0.000%	0.02% max	± 0.003%
Vanadium		0.014-0.022%	0.10% max	
Titanium		0.030-0.036%	0.04% max	
Aluminium		0.014-0.020%	0.05% max	
Boron		0.000%	0.002% max	

*ADI Treatments Limited, Suggested foundry requirements for ductile iron that is to be austempered (ADI Datasheet 1.2).

APPENDIX II:
Austempered ductile iron properties.

ADI Treatments Limited, suggested foundry requirements for ductile iron that is to be austempered (ADI Datasheet 2).

Table 3. ADI properties.

ASTM897M 90	**850-550-10 GRADE 1**	**1050-700-07 GRADE 2**	**1200-850-04 GRADE 3**	**1400-1100-01 GRADE 4**	**1600-1300-00 GRADE 5**
STATIC PROPERTIES					
Tensile Strength (MPa)	966	1139	1311	1518	1656
Yield Strength (MPa)	759	897	1104	1242	1449
Elongation (%)	11	10	7	5	3
Hardness BHN (BID mm)	302 (3.5)	340 (3.3)	387 (3.1)	418 (3.0)	460 (2.85)
Young's Modulus **(GPa)**	163	160	158	156	155
Compressive Strength (MPa)	1380	1650	1935	2275	2520
Shear Strength (MPa)	870	1025	1180	1370	1490
Modulus Of Rigidity **(GPa)**	65.1	64	63.2	62.4	62.1
Poisson's Ratio	0.25	0.25	0.25	0.25	0.25
DYNAMIC PROPERTIES					
Fatigue Strength (@ 10 Million Cycles)					
- Rotating Bending (MPa)	450	485	415		
- Reverse Bending (MPa)		415	380		
- Axial Push - Pull (MPa)		385			
- Max Allowable Contact Stress (MPa)	980	1175	1365	1560	1750
- Single Tooth Bending (MPa)	700	770	615	560	455
Charpy Impact (@ 21ºC)					
- Un-Notched (Joules)	120	120	93	80	53
- Notched (Joules)	12	10.6	9.3	8.6	8
Dynamic Elastic Modulus (GPa)	170	168	167	165	164
Estimated Ductile/Brittle Transition Temp (°C)	-20	-20	-20	-20	-20
Fracture Toughness (MPa - $M^{½}$)	100	78	55	48	40
Strain Hardening Exponent (SI Units)	0.1192	0.1376	0.1465	0.16	
Fatigue Strength Coefficient (SI Units)	2000	2720	3100	5020	
Fatigue Strength Exponent (SI Units)	-0.12	-0.146	-0.16	-0.205	
Fatigue Ductility Coefficient (SI Units)	-0.566	-0.628	-0.752	-0.848	
Fatigue Ductility Exponent (SI Units)	290	260	240	200	
PHYSICAL PROPERTIES					
Density (g/cm^3)	7.0965	7.0872	7.0779	7.0686	7.0593
Thermal Expansion Coefficient (mm/mm/C) X 10^{-6}	14.6	14.3	14	13.8	13.5
Wear Resistance (AMAX Pin Test, Vol. loss mm^3)	10.9	10.8	10.6	10.3	9.8
Linear Expansion **Inches/Inch (Ferritic/Pearlitic)**	.0012/.0002	.0018/.0008	0.0025/.0013	.0027/.0016	.0028/.0017
Thermal Conductivity **(BTU-in/h-sq.ft-F/W/Mk)**	153/22.1	151/21.8	149/21.5	147/21.2	145/20.9
Internal Damping (log decr.) X 0.0001	5.26	5.41	5.69	12.7	19.2

APPENDIX III:
Tensile test results.

Figure 10. Failed test sample B1-B2-L1-L2.

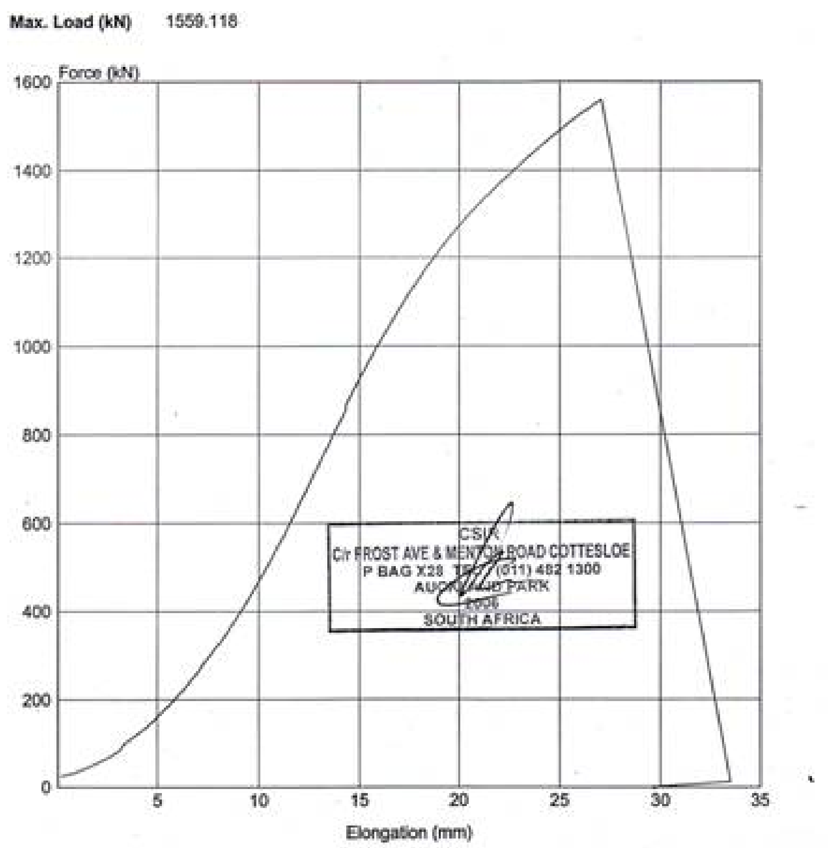

Figure 11. Stress-strain graph for old links (B1-B2-L1-L2) in Figure 10.

Figure 12. Failed new link 1 sample.

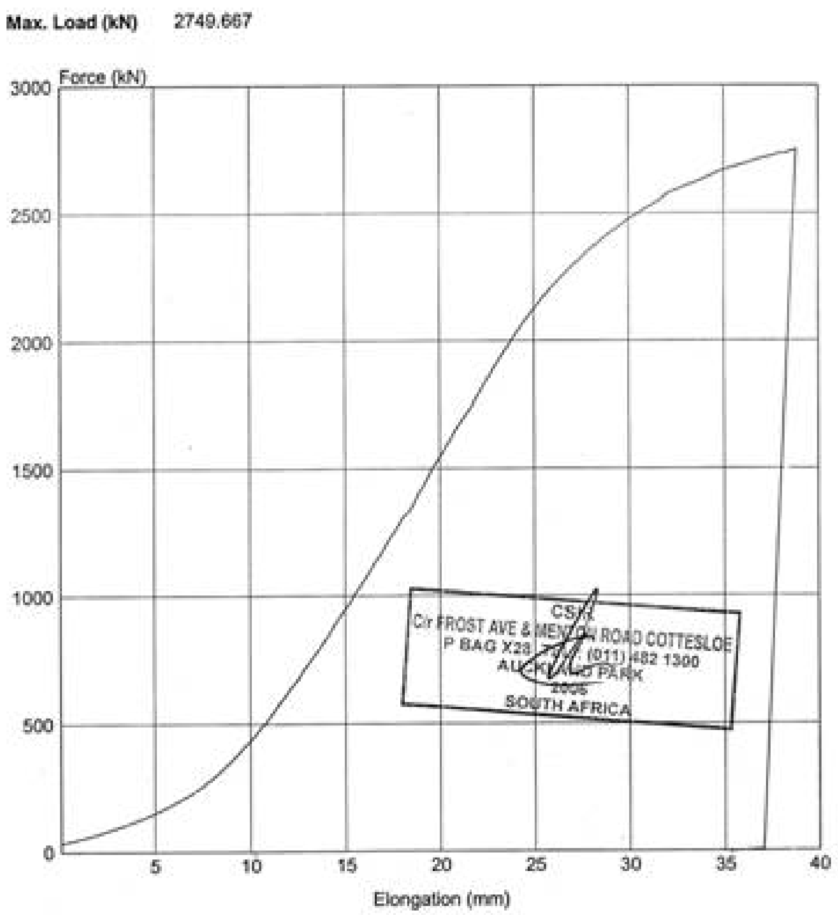

Figure 13. Stress-strain graph for link in Figure 12.

Figure 14. Failed test sample B3-B4-L3-L4.

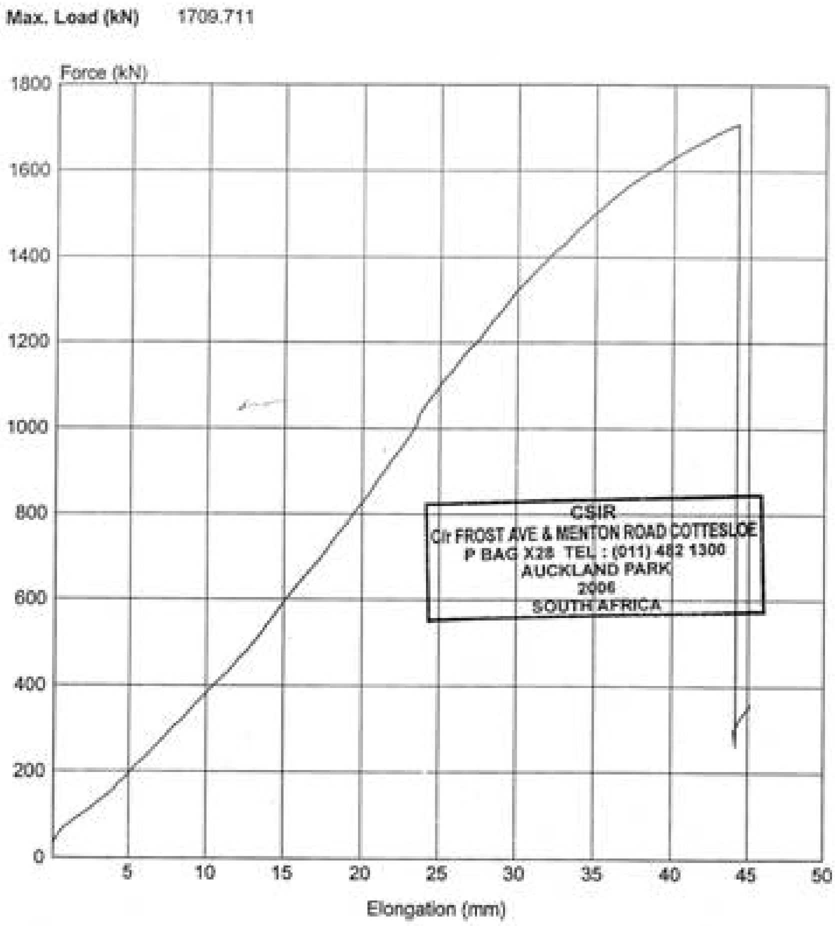

Figure 15. The stress-strain graph of links B3-B4-L3-L4 in Figure 14.

Figure 16. Failed defective new link 2 sample.

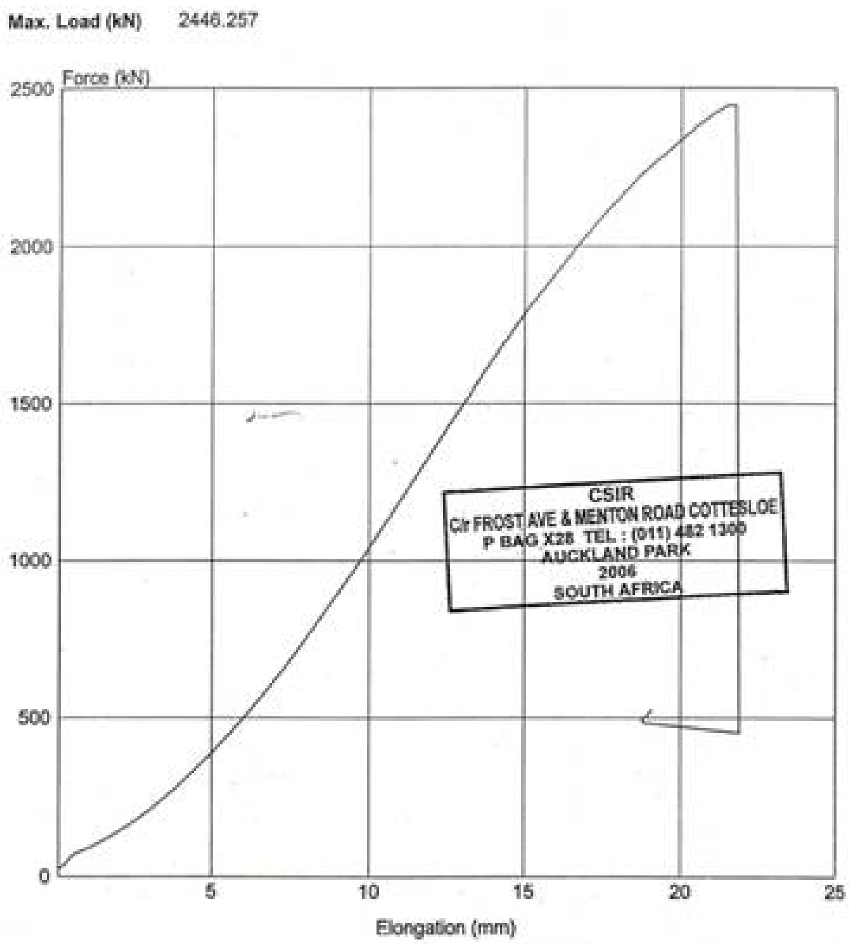

Figure 17. The stress-strain graph for links in Figure 16.

Figure 18. Failed new link 3 sample.

The breaking load in figure 19 was estimated from the graph as 2800 kN.

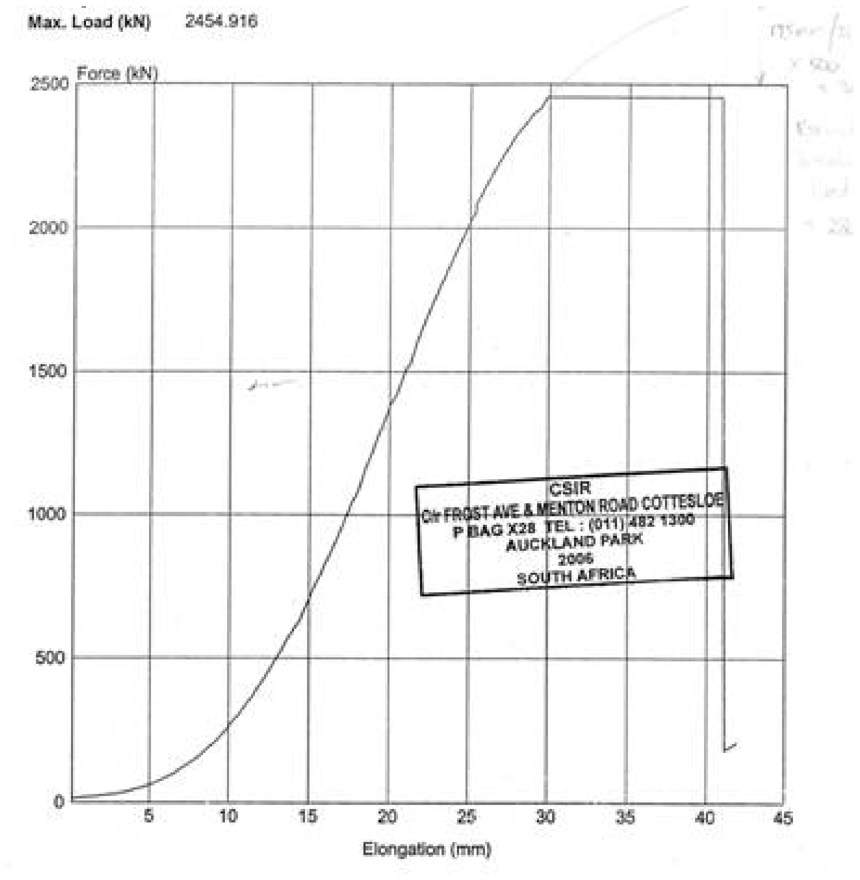

Figure 19. The stress-strain graph of the new link 3 sample, with the incorrectly scaled graph.

The pins in the links tested as shown in figure 20 pulled out of the links before fracture could occur.

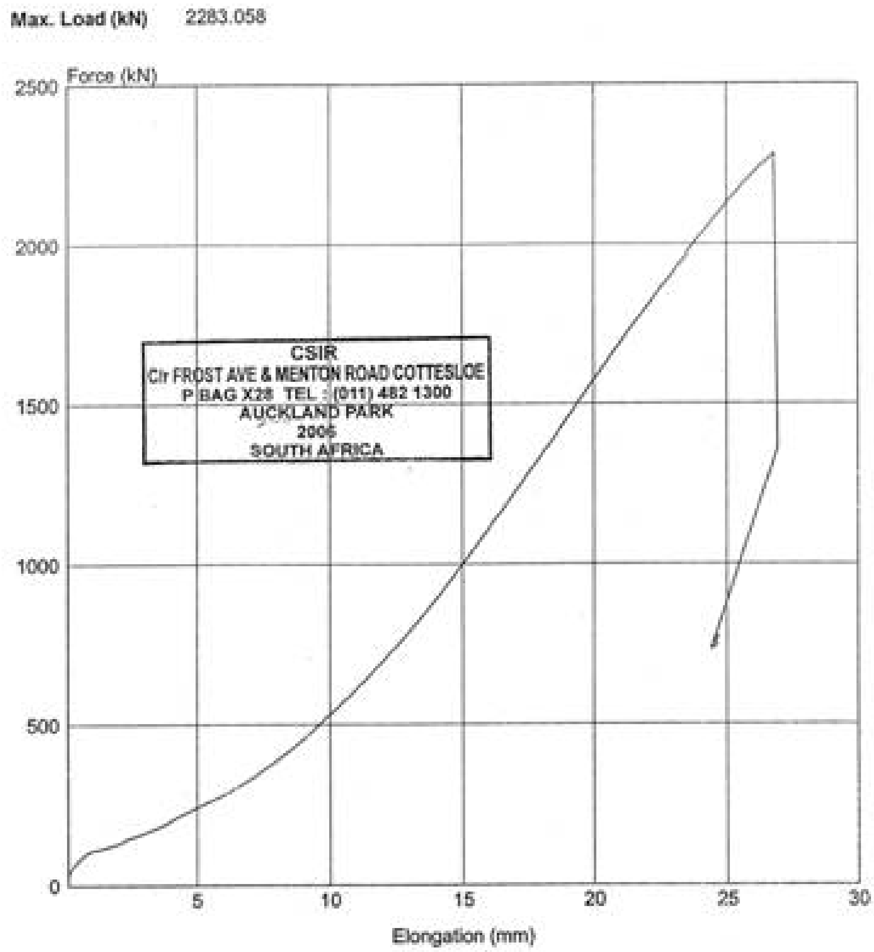

Figure 20. The stress-strain graph of the new link 4 sample.