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The present work was submitted to the Faculty of Engineering

Elongation of transfer chute service life on material perception

Bachelor Thesis

by

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15 - August - 2018

Statatutory Declaration

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I hereby affirm in lieu of an oath that I provided the submitted bachelor thesis

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Place, Date

Signature

Acknowledgement

A successful accomplishment of this study was made feasible with help from people that surround me. Even from overseas, a generous pack of help was constantly deployed to me for my study. Their never-ending help and efforts are highly apprecieted and gratefully acknowledged. I am much indepted and thanked particularly to

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Abstract

This study has looked into wearing mechanism on liners in transfer chute used at Oyu Tolgoi mine. And it searched for ways to reduce wearing rate so that the mining operation could benefit in numerous ways. Wearing takes place dominantly in form of abrasive wear whose base is on micro-cutting mechanism. Worn liner samples made of Hardox 500 mark and a bag of coarse ore were provided for study purpose by the company. For referential purpose, the same intended steel marked as 110Г10Л was requisted and supplied from Erdenet Mine. After analytic analyses, it has been still believed that wearing rate advances as thickness of liners reduce. The conducted hardness test shows hardness gradient, emphasizing wear rate deviation. But microscopic analysis does not show much of evidence that wearing rate could be different over thickness. And heterogeneous wearing rate over liners was noted. The employed steel - (as producers state that martensite - bainitic structured) Hardox 500 for making liners, is known as the best selection for operation under high abrasive conditions. No material enhancement effort was made, therefore. Instead, combination in usage of hardox 500 and 550 was suggested for more homogeneous wearing rate distribution over the liners. At the most optimistic scenario, the combination could increase chute service time by 100% and reduce liner inefficient use by 28.9%. Taken assumptions for the estimations may be superior. Sections dedicated for studying hardox steels' usage, mechanical properties, suppliers statement are present in the study.

There were so many case studies on the internet explaining and praising use of a sophisticated modern computational softwares based on **Discrete Element Method** on chute design. Not only chute that is its reach but also all heavy machines that work with bulk materials: comminutors, mills, chutes, mixers, silos and so on. But almost no work has been found on matter of wear mechanism from material scientists perception, at least among studies that are costless. A custom method determining wear rate was attempted to be developed analytically. But it has been omitted in the report due to required data was not possible to obtain. On-site measurements were vital for the method to become mature.

The company

With a start Investment Agreement in October 2009, the project named Oyu-Tolgoi was commensed its infrastructure construction in Southern Gobi of Mongolia. The deposit was first discovered all the way back in 1980 by Mongolian & Russian Geochemical Survey Team. Abnormally high amount of molybdenum was its first recognition. The Investment Agreement was made between Ivanhoe Mines, OT LLC and Rio Tinto PLC with Government of Mongolia. Within the scope of the Agreement the fiscal and regulatory environment were defined in which the project will operate. Government of Mongolia owns 34% equity of OT LLC with an option to increase it by a further 16% After 30 years of providing terms can be reached with Ivanhoe Mines at that time.

Oyu-tolgoi project contains a series of deposits containing copper, gold, silver, and molybdenum under over 12km stretched land. The minerals lie in 5 distinct ore bodies that are divided into 3 deposits: Southwest and Central bodies comprise the Southern Oyu deposit, Hugo North and Hugo South bodies comprise the Hugo Dummet deposit, and Herugo deposit. Currently, surface mining operation has been taking place at open pit mine located at Southern Oyu deposit. In parallel with this, underground construction development is under progress approaching Huge Dummet deposit which is ranked as the highest in coarse ore concentration. The project developed two mining plans, one for short term based on proven reserve, the other is for long term based on proven reserve and inferred resources. For long term, open pit or block caving mining method for Hugo South, and two block caving scenarios for Heruga. According to 2010 technical report by Turqouise Hill, the deposits are ranked as follows, from highest in value to lowest. In figure 1, the ore bodies are shown.

Hugo North > Southwest > Central > Hugo South > Heruga

Figure 1: Oyu Tolgoi deposits

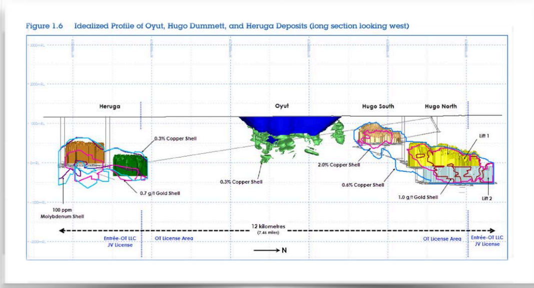


Table 1 summarizes estimated reserves of each deposits and contained metals in it. The estimation was made successivly in years of 2010, 2016 by Turquoise Hill.

The initial construction work, which was first phase of open pit planning that encompases 10 phases, built water borefields, water treatment, housing, airstrip, support facilities, railroads, and power station. With that, the initial production rate is designed to be 100 kt of coarse ore processing per day for open pit excavation. Depletion of the open pit deposit will gradually be displaced with excavation from Hugo North once the underground development for the deposit is completed.

Both long and short term Plans created mine plans which guides the whole operation. Figure 2,3,4,5 briefly concludes the excavation plans and Contained metal amounts. For the mine to be capable of handling required amount of coarse ore, a constant expansion and upgrade has been being made.

Figure 2: Mine plan for short term

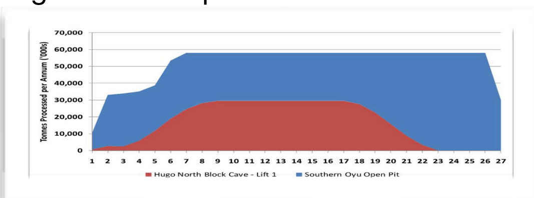


Figure 3: Metal amount for short term

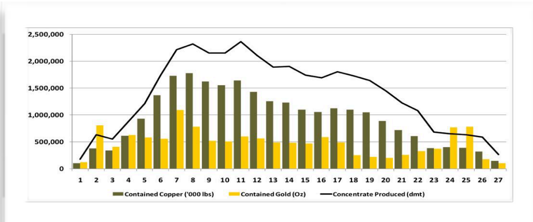


Figure 4: Excavation plan for long term

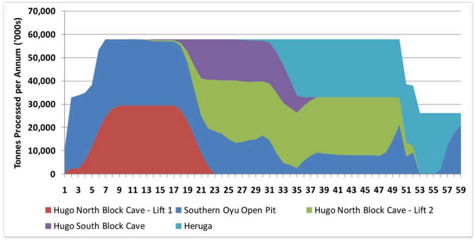
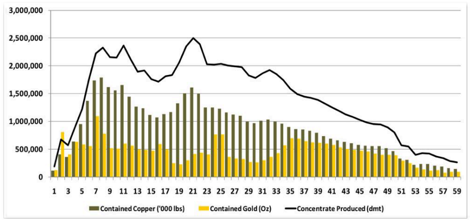


Figure 5: Metal amount for long term



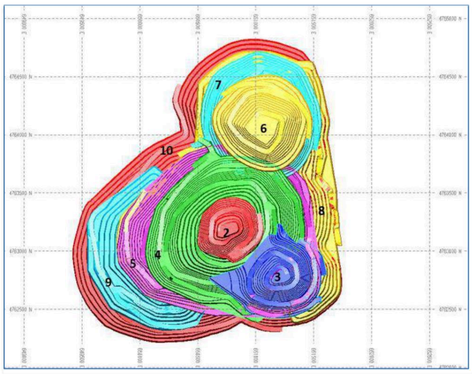
From the figures, it is seen that mine's annual production will stabilize at around 60 Mt, and ore concentration will gradually fade. For the longest run, deposits are planned to be mined in 60 years, but further exploration might extand the duration.

The mine's ore processing facility commenced its operation in 2012, produced first concentrate in 2013. Over 5 years of accumulated experience and improved practices made it possible for the facility to process 110kt of coarse ore per Day. According to technical report 2016 by Turqouise Hill, the increased capcaity is reduced to 102kt due to mining of harder rocks from phase 4, open pit. Figure 6 explains the 10 phases of open pit mine.

Some collected Information at the time of this study was summarized below

It is expected that Hugo North underground mining will first draw bell in mid-2020 and sustainable production in 2021, peak production in 2027.

Figure 6: Color coded 10 phases



At of end of first quarter, 2018, Oyu-Tolgoi had a total workforce, including underground construction, of more than 14000, of which 95% were Mongolian.

It has been said that Oyu-Tolgoi mine is expected to be world's third largest copper producing mine at its peak production rate in 2025.

The project pays multiple taxes in accordance with the Invest agreement:

Corporate income tax	**25**%
Mineral royalties	**5**%
Value added tax	**10**%
Custom Duties	**5**%
With drawing tax	**20**%

5 shafts were dedicated to support underground mining operation, of which shaft #1, #2, #3 are complete by first quarter, 2018.

Table 1: Deposits and their contents

	Tonnage, Mt		**Cu, %, t**	**Au, g/t, t**	**Ag, g/t, t**	**Mo, ppm, t**	**CuEq, %, t**	Gangue, t
Oyut-open pit 0.22% cut-off CuEq	grade		0.52	0.35	1.35	53.9	0.72	372315193
	measured	377	1966321.3	114.5	448	20411.6	2697511.6	
	grade		0.38	0.23	1.11	56.4	0.51	708540912.7
	indicated	715	2739242.1	144.1	700.3	40369.7	3678631.1	
	grade		0.29	0.16	0.86	44.2	0.38	386393766.18
	inferred	389	1116289.9	53.52	294.3	16782.9	1472813.2	
Oyut-underground 0.37% cut-off Cu Eq	grade		0.4	0.78	1.15	38.8	0.83	13831149
	measured	14	54884.6	9.7	14.4	544.3	113398	
	grade		0.35	0.59	1.19	34.3	0.67	92044538.9
	indicated	93	323411.1	50	101	3220.5	628678.5	
	grade		0.39	0.32	0.85	25.4	0.56	157481248.7
	inferred	159	614163.6	46.4	124.2	4037	900380.1	
Hugo Dummet 0.37% cut-off CuEq	grade		1.96	0.46	4.46	30.4	2.25	94837579
	measured, north	99	1935477.1	41.1	401.1	2993.7	2223508	
	grade		1.57	0.37	3.46	34.2	1.81	847304799.5
	indicated, north	877	13789196.8	298.8	2769.4	29937.1	15872998.4	
	grade		0.81	0.28	2.4	33.1	0.99	972149641
	inferred, north	990	8026310.4	255.7	2165.4	32658.6	9788968.9	
	grade		0.77	0.07	1.78	66.4	0.83	831445246
	inferred, south	845	6519024.2	52.8	1372.3	56245.4	6978059.3	
Heruga Deposit 0.37% cut-off CuEq	grade		0.39	0.37	1.4	113	0.64	1797070492.2
	inferred	1816	7097354	609.7	2318.3	205477.2	11623748.6	

Introduction

General

Currently the mining is excavating coarse ore from its open pit deposit “Oyut” which accounts nearly 20% of the total proven resource. The rest over 80% resource is distributed over 2 deposits that lie deep in underground. The company is expanding its capability of processing ore assuming that underground mining will commence in 2020. Its construction development is ongoing.

The excavated coarse ore from the open pit goes through multiple mechanical, physical, and chemical processes to become enriched concentrate. At the open pit site, earth material is blasted, then transported to crusher (primary crusher), by means of excavator and dump trucks. At the primary crusher, massive rocks get reduced in size, the biggest lump size becomes 330 mm. Crushed rocks include lump fraction of 10% by mass [R6]. Figure 7 shows dump trucks charging the primary crusher.

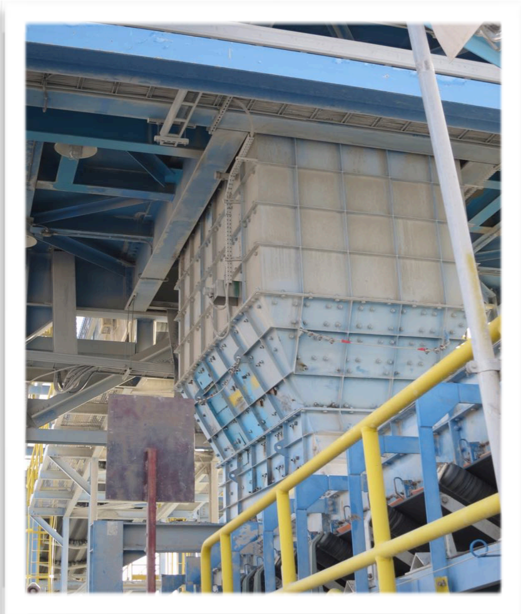
Figure 7: Primary crusher charging

After primary crushing, the crushed material is transported by combination of conveyor belts and transfer chutes to stock piling where the material is collected. Average amount of transported ore is, currently around 110000 ton per day. Over 3 km distance, 3 conveyor belts, 2 transfer chutes, 1 hopper under the primary crusher do the transportation work. Belt runs at speed of 3.78 m/s to catch up the requirement [R6].

Figure 8 shows the conveyor system that is responsible for delivering primarily crushed rocks to stockpiling. Along its length, the conveyor system is almost completely covered by circular roof that is protecting the coarse ores from environment: raining, snowing to some degree, and preventing spillage and dust to form. Openings are at only transition points. Figure 9 shows on-site application of transfer chute in material conveying system.

Figure 8: Encapsulated conveyor belt

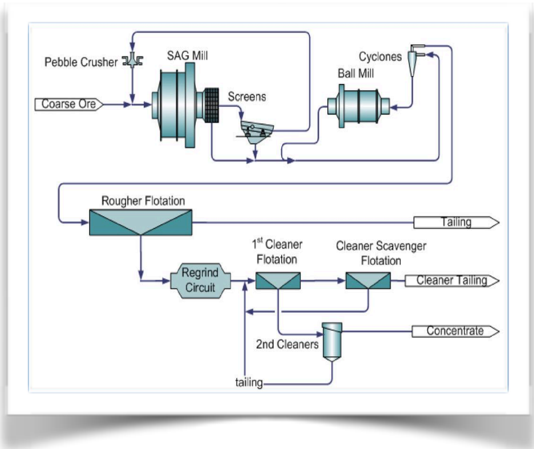
Figure 9: Transfer chute between belts



Under a huge housing, the delivered rocks build a giant pile that, when it is full, is capable of feeding the processing plant around 10 days at normal processing rate without being fed. Again, by means of conveyor belt, the coarse ore is transported to its next step machines. Its next stop is secondary crusher (Pebble crusher). Then, the company employs SAG (semi-autogenous grinding) mill and AG (autogenous). This gravitational method involves particle-particle interaction as well as particle-steel ball interaction.

For assurance of technically appropriate size of particles, the grinding circuit hired cyclone classifiers. It essentially judges what sized particles go for next processes and what sized particles to re-enter to the grinding cycle. Figure 10 views the facility layout showing main steps involved in mineral processing.

Figure 10: The facility layout



The classifiers separate small sized particles that suit in froth flotation process to run. The flotation cells are installed in a series so that flotated fraction gets collected and purified successively though cells. The flotation process is hybrid operation between physics and chemistry.

The next operation is drying. For the operation, larox filter is employed that is capable of drying planes of enriched oreat a time. The last stop along the chain process is bagging. Again, conveyor belt transports the material.

After this chain of operations, the coarse ore having copper concentration of around 0.22% is enriched to 25~30%. The concentrated ore is poured to bags of two ton and shipped to Mongolian southern border where the buyers receive it.

Temperature

According to the literature [R7], temperautres range from an extreme Maximum of about 50ºC to an extreme minimum of about -34ºC. The typical air temperature fluctuates between 6ºC and minus 21ºC. In the coldest month, January, the average temperature is minus 13ºC. Table 2 shows air temperature measuremend in Bayan-Ovoo. From surrounding habitats around Oyu-Tolgoi: Khanbogd, Dalanzadgad, Hailiutu and Bayan-Ovoo, climate study at Bayan-Ovoo is best representing temperature at Oyu-Tolgoi.

Table 2: Monthly temp. at Bayan Ovoo

Months	Minimum, C	Average, C	Maximum, C
1	-34	-13	9
2	-33	-8	16
3	-25	-0.4	24
4	-22	9	31
5	-13	18	38
6	0.4	23	50
7	4	25	40
8	3	23	39
9	-5	17	39
10	-20	7	30
11	-27	-3	25
12	-33	-10	14

The values are from measurement in 2016.

Humidity

The average relative humidity ranges from 18.7% in May to 53.3% in Januray. Daily relative humidity is dependent on current temperatures and varies considerably. Monthly relative humidity is summarized in table 3. The data is from year of 2002 and 2003.

Table 3: Monthly relative humidity

Months	Minimum, %	Average, %	Maximum, %
1	19	53	81
2	13	38	67
3	3	24	88
4	2	24	90
5	1	19	100
6	1	31	97
7	5	37	100
8	8	36	100
9	1	34	100
10	1	30	81
11	5	41	85
12	11	44	81

Percipitation

Average annual precipitation is 57 mm/a, 90% of which falls as rain and the rest as snow. Snowfall accumulations rarely exceeds 50mm. In an average year, rainfalls occur on only 19 days, and snow falls on 10-15 days. Precipitation data from 1957 to 2002 has been studied and tabulated in table 3.

Table 4: Rainfall summary

Months	Maximum daily, (mm)	Monthly, Avg. (mm)	Avg. Rain days per month, (days)
1	2.1	0.4	0.6
2	3.8	0.4	0.6
3	4.4	0.8	1
4	10.4	1.4	0.8
5	19	3.1	1.5
6	16.2	8.1	3
7	29.5	18.1	4.5
8	102	17.8	3.9
9	19.2	5	1.4
10	4	0.9	0.6
11	4.3	0.6	0.7
12	1.5	0.2	0.4
Total	-	56.8	19.0

The south gobi region has a continetntal, semi-desert climate. The spring and autumn seasons are cool, summers are hot, and winters are cold - typical in desert climate. The project site has low average humidity and significant variations in daily temperature.

Processing operation involves activities both in- and out-doors. Indoors facilities are heated during winter time. So threat lies outside especially when temperature gets its extremums.

The Oyu-Tolgoi project is aware of climate at targeted land, and planned continuous mining operation. Minor disruptions due to climate are expected.

The coarse ore

The main Oyu Tolgoi deposits are of “porphyry copper-gold” and “high sulfidation copper gold”. The high grade ore core is characterized by 1 to 50 cm wide contorted milky white quartz veins in sericite, albite, minor tourmaline - altered quartz monzodiorite and biotite-magnetite-a;tered augite basalt, overprinted by chlorite and sericite. Chalcopyrite with subordinate pyrite, bornite, and molybdenite occurs as late veinlets fillings fractures in quartz veins and disseminated through wall rocks. Less frequently, gold occurs on grain boundaries with bornite or as inclusions in bornite, quartz, or carbonate [R9].

Problem Statement

Introduction

At each stop in ore processing operation, specifically designed heavy duty machines run. There happens planned and unplanned stops of machine due to repairing reason, maintenance, inspection, and a sudden break.

The blasted, then primarily crushed coarse ores are handled by combinations of transport chutes and conveyor belts. The transportation system handles 110000 ton of coarse ore per day. The number translates into around 6000 ton per hour.

The conveyor belts are responsible for transporting the coarse ore, whereas transfer chutes are for conveying it from one conveyor to another. The installed transfer chute is of type of rock box having three main body parts: hood, body, discharge and 1 feature element - rock box. The chute is 8.371m tall, and lined inside with Hardox 500. Coarse ore particles fly into the chute, through hood at speed of the belt (3.78m/s), at angle of the belt's inclination (around 7 degree). A contour that is built up by particles as shown in figure 11, collapses as belt transits from troughed zone to flattened, and from flattened to free space. In the air particles draw three dimensionally trajectories. In the table 5, current configurations of conveyor system is summarized.

Figure 11: Rock contour at troughed belt

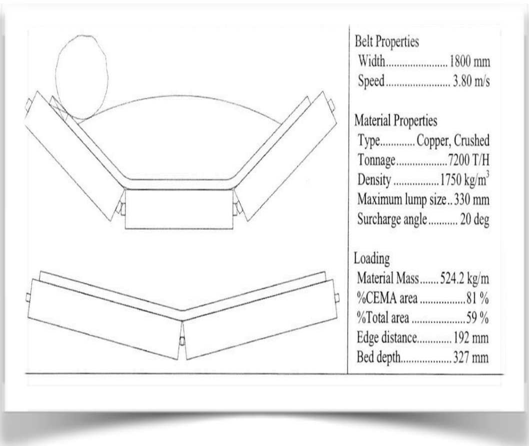


Table 5: Conveyor system configurations

Conveyor speed, m/s	3.78 (3.8 designed)	Through put, tph	4589.3 (designed 7200)
Belth width, mm	1800	Maximum lump size, mm	330
Belt edge distance, mm	192	Lump fraction, %	10
Ore depth, mm	327	Angle of repose, degree	55-60
Trough angle, degree	35	Surcharge angle, degree	20
Belt thickness, mm	39	Liner hardness, HBW	470-530
Idler length, mm	666	Temperature span, Celcius	-27 +40
Head pulley diameter, mm	1200	Ore uni-axial compressive stress, Mpa	45
		Bulk density, kg/m3	1750-1800

Through the transfer chute, shown schematically in figure 12, the particles essentially impact two times at subsequent rock boxes. In addition, to prevent liners from wearing, small rock boxes are installed inside the chutes, shown in figure 13. Defining trajectories of particle is an essential key for designing a transfer chute [S10]. Defining trajectory is often hindered by non-constant behavior of nature, and redirection caused by rock boxes.

To remedy this difficulty of defining trajectories, in practice, nowadays, an analysis called DEM has been dominating over traditional practices [S#, S#, S#]. In classic way, the problem is usually addressed to application of "continuum method", which in comparison to DEM method is rather simple, less time consuming, and easy to conduct.

Figure 12: Technical drawing of transfer chute

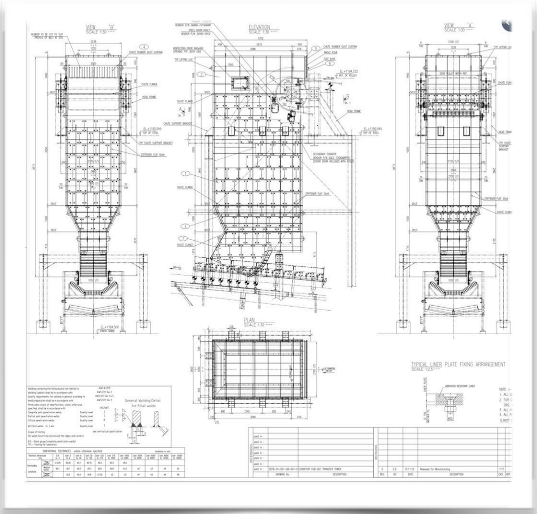


Figure 13: Rock box resembling ledges

At the rock boxes, wearing can be presumed negligible as accumulation of rocks form a protective layer made of the handling haterial itself. According to statement given by maintenance Team, Oyu-Tolgoi, the wearing occurs substantially at side walls at rock boxes shown in figure 14 [R11], and at skirting liners.

Figure 14: Thickness of liners

Liner

Transfer chutes protect their interior by liners. The liners experience wearing by mechanical interactions with coarse ores, shown in figure 15. The wearing rate was observed so high that, once, the wearing took beyond liners. Consequently, the transfer chute is pierced, then rocks spilled.

Liners are of type of HARDOX 500 mark. According the geometry of the transfer chute, the liners are casted with specific alloy contents that allow it to be highly resistant against intesive wear. The casting process takes into account dimensions and locations of the holes of the bolting, so that the liners arrive ready to be installed directly. Liner being replaced during maintenance work on 5th, May is shown in figure 16.

Figure 15: Inside chute

Figure 16: Replaced liner

In the picture, a worn liner is seen. Its original shape was rectangular, from which the resulted shape is derived.

Statement

Liners are mostly of size of 450x402x25. Provided worn liners, left from coarse transportation process are seen in figure 17.

Figure 17: Worn liners

Description: the liners are provided by Oyu-Tolgoi mine for study purpose. Left piece is from Side wall, right piece is from skirt.

For these liners' cases, they lost approximately 40.3% (wall liner), 68.16% (skirt liner) of its weight. The loss occurred between dates of 24/Feb/2018 and 24/May/2018. So a rough wearing rate is: 372.41 gram for side wall liner and 263.23 gram per day for skirt liners. Between the mentioned dates, approximately 6.600.000 ton amount coarse ore was transported. This brings another dimensioning of quantifying the wearing rate. Wearing rate: 0.002393 gram for side wall liner and 0.00339 gram for skirt liner per ton ore transported.

The problem, the company is facing is that liner materials wear out at rate of 0.002393gram, 0.00339gram per ton coarse ore transported at side wall liner and skirt liner, respectively. The company inspects the transfer operation situation once in 4 weeks [as was said]. The wearing rates are considered to be high. For that it reason it should be reduced as far as possible so that the transportation operation benefits in many ways.

Purpose of study

While many researches have been dedicated on matter of chute design, no study was found on chute lining. In practice, chute owners follow experience, and compare then select from available products on the market. In bulk material handling cases, chute are often well protected by chute design element - rock box which is perpendicularly extended ledge from inner surface forming an open box. The box gets filled by handling material which then acts as a protective layer, made of rocks, for chute inner from furiously flying rocks. The pile is regenerative and collapsible.

Oyu-Tolgoi mine currently lines its transfer chutes with Hardox 500 HBW and Q345D abrasive resistant steels [T3]. On the market, there are Hardox marks differentiated by their hardness: 400, 450, 500, 550 and 600 each specifically designed for uses where high abrasion wear threats the machine life.

The purpose of this study is to define current configuration of conveyor system, calculate wear rate analytically, finally compare Hardox family marks as substitution to Hardox 500.

Significance of the study

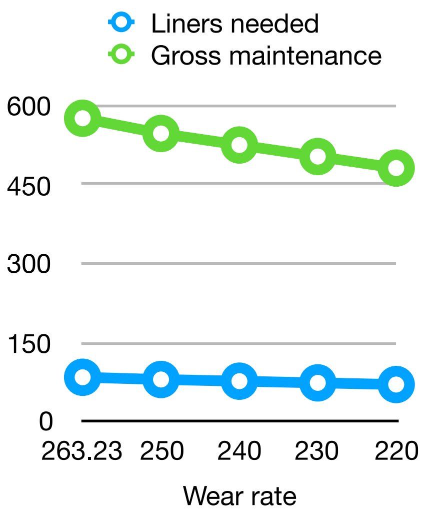
Introduction

In the wearing process, there are number of influential parameters. Some of them are easily manipulatable and governed by demand, and some not. The current wear rate, at average, is 263.23 gram per day on liners. Having this number reduced, there will be number of improvements and saves:

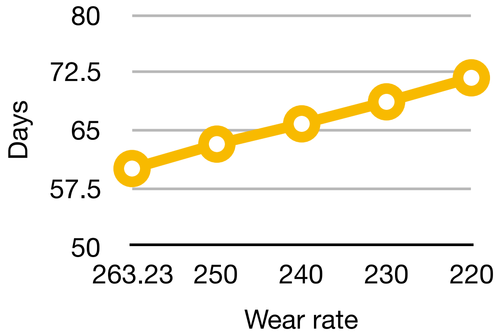
- Chute productivity: the chute would be standing passive less frequent for maintenance.
- Reduced cost: elongated service life of the chute means less number of liners needed in an unit period of time, e.g. quarter, year; so by saving liners, cost is reduced.
- Productive workers: having chute liners last longer, workers would be less distracted by chute shutdowns.
- More safety: having the chute stopped and repaired less frequent, duration of time replacing liners will be reduced in an year, for example. This means less time under dangerous conditions. Replacing liners inside chute is considered as work in a confined space. Risk of injuries increases inside it.

Change in number of worn liners, maintenance duration, chute service time, and system restart frequency are shown in graph 1,2,3 respectively as function of wear rate on yearly basis.

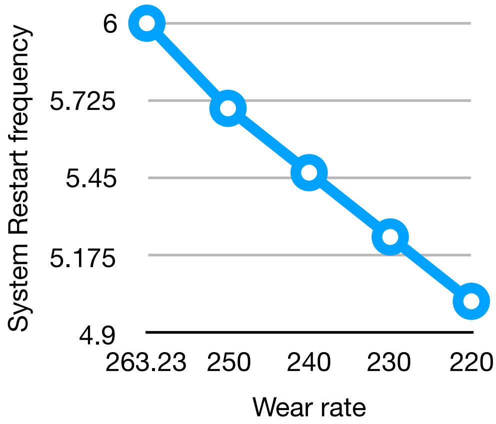
Graph 1: Liners in year and gross maintenance in an year



Graph 2: Chute service time



Graph 3: System Restart frequency in an year



Conclusion

Accurately defined wear is of much importance. It will provide a reasonabley reliable prediction on a next chute shutdown. Wearing is Function of number of parameters: rock flow, hardness, temperature, chemicals, dust, geometry of chute and so on. And as it is a confined space, chute shutdowns arise risks for incidents. Workers need to detach worn liners and attach liners of Maximum 39.19kg.

Direct and indirect costs follow a chute shutdown. Frequency of chute shutdown is dependent upon wear rate. Thus, to save costs and increase efficiency, wearing rate must by kept at minimum while chute's performance fulfills the company's demand. Not only cost that is reduced, more importantly working under dnagerous conditions is decreased. Decreasing wear rate of 263gr/d to, for example, 240gr/d, the transportaion saves 85 liners, cuts 50 hours for chute shutdown in an year.

Literature review

Transfer chute

Success of heavy duty industries substantially relies on performance of their machines [S7]. When machines require less maintenance, less cost and high productivity result. Mining sector is the major representative of this.

Quite number of machines are lined in a sequence, each is contributing to the final product. Concentration is produced through a chain operations of machines. A machine shutdown breaks the whole chain making continuity of manufacturing dependent on every single machine in the sequence. Figure 18 shows a typical ore processing scheme. The chain process starts from open pit blasting and excavation, then transportation to enrichment process, finally bagging and shipping.

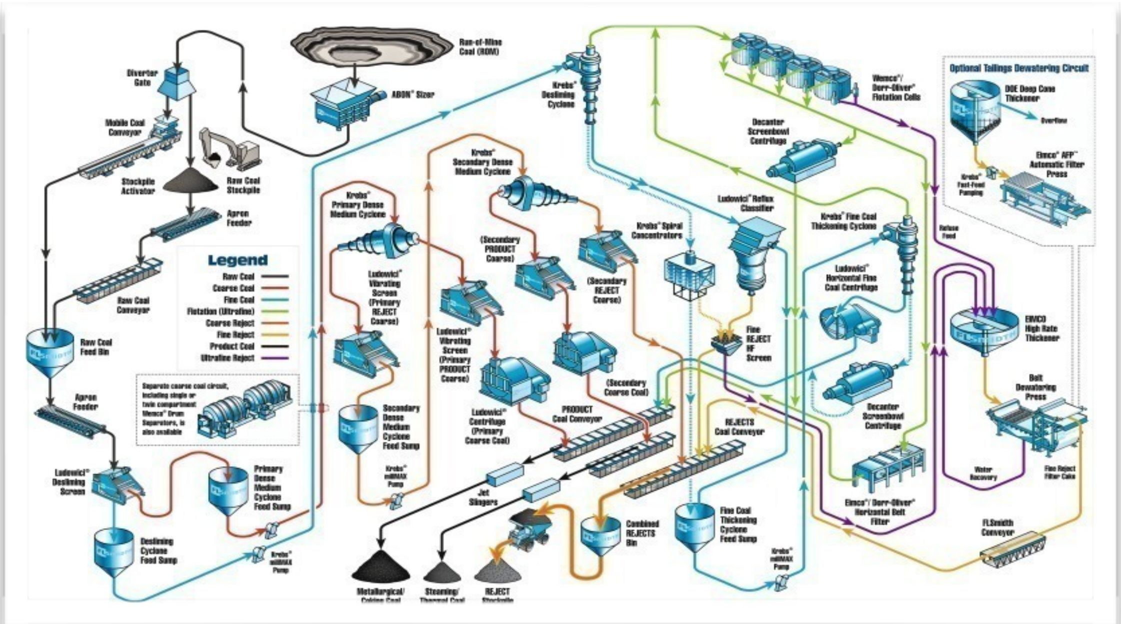
Such mass production manufacturing companies are strongly tied with its raw material conveying system [S11]. The system plays a big role defining capacity of the factory. In the past, in mining operation, materials used to be transported by means heavy duty dump trucks. This convention is changed into conveyor belt system that is more beneficial in every way: no dust, no noise, no CO2 emission, higher producitivity due to continuous operation. However, initial installation, complexity, flexibility, and belt related problems are issues that attract much attention and efforts.

Wherever high rate of material handling rate is needed, conveyor belt is employed with transfer chutes. Transfer chute is a link between two in-[1] or out-line[2] conveyor belts. Due to feasibility limitations, and complexity, inflexibility of a single long conveyor belt, separate autonomous conveyors are preferable. A transfer chute connecting two in-line conveyor belt is shown in figure 19.

Transfer chute has main two function in the transportation operation: diverting the flow, and passing the flow to another conveyor belt or a subsequent machine in the chain sequence that is beneath the chute, i.g, hopper, silo, mill, and so on.

Conveyor systems with its assistant - transfer chutes have found its application in many types of mass production, such as: continuous manufacturing of (liquid/dry/frozen/any) foods, goods, pharmacies, agriculture, and mining.

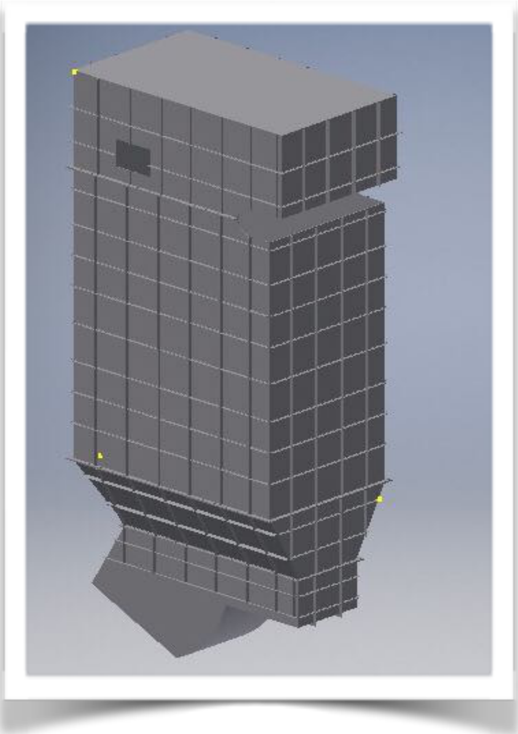
Figure 18: Ore processing scheme



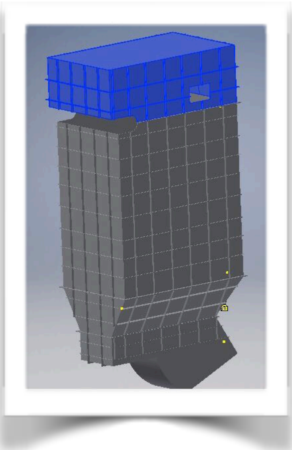
1 material flow with no change in direction

2 material flow with a change in direction

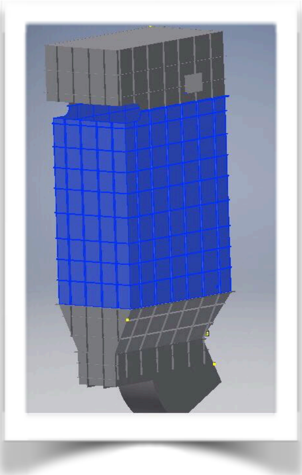
Figure 19: In-line transfer chute



Design and size of transfer chute vary among applications. Influential factors are namely: size and nature of handling material (fines or rocks, chemically active or not, dry or suspended etc), and required capcity. Commonly, there 3 fundamental parts: hood, body, discharge in any type of transfer chute.



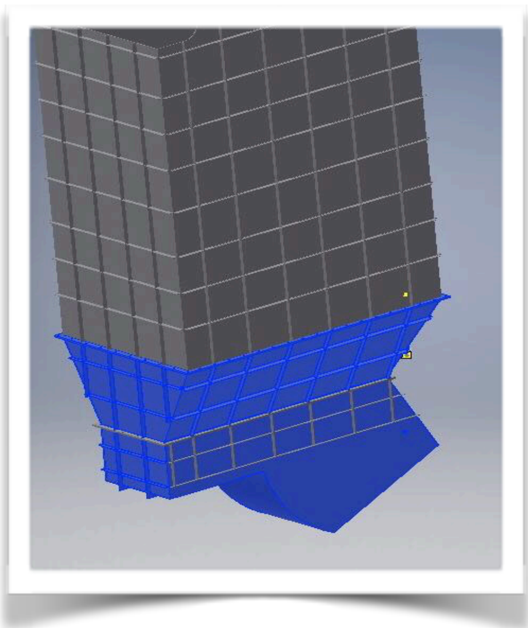
Hood, figure 20: this part of the chute meets the incoming flow from conveyor belt. Hood is responsible for completely devouring the material without any loss. To reliably receive the material flow, its opening at least partially contains the head pulley of the conveyor belt. Due to a sudden impact of material flow at hood, flow speed gets reduced substantially. The reduction could raise an issue of plugging, however correct design would never hand a chance for that. In most cases, reduction in material flow speed is preferable as slower particles are less harmful to inner of the chute, meaning less damage.



Body, figure 21: as its name suggests, the part is placed in middle of chute. This zone is responsible for connecting upper part of chute - hood with lower part of chute. Height of body part is set in a way that required particle acceleration comes. In this part of chute, material often performs a free fall, suspended in air until desired speed is achieved. Air flow in form of vortex - air swirling, arises against the flow. As a consequence, fine particles are subjected to formation of dusts.

Discharge, figure 22: at the end of journey of material flow through a transfer chute, materials pass by discharge, and get diverted and loaded onto next conveyor belt or a machine that performs the subsequent operation. The illustrations are drawn in Inventor and showing the chute that is being studied.

Figure 22: Chute discharge



For a continuous flow to have no blockage, a chute needs to encompass enough volume while it is still fulfilling a requirement to be compact and feasibly manufacturable.

Every chute, disregarding type, has hood, body and discharge in common. In addition to them, depending on application, chute can have more elements. Popular elements are listed and explained in the following section.

Dust curtain, figure 23: transfer chute is almost wholly closed environment except at two ends of it. The fact implies that there are two possible exits for dust to escape. Airborne dust is hazardous to human, environment, and machines parts, especially mobile parts such as, in example of mining, idlers, pulleys, motor. Practical solution for prisoning dust is to cover the two openings by pieces of curtain. Columnar curtains are need to be spaced such that it does not retard the material entering and exiting.

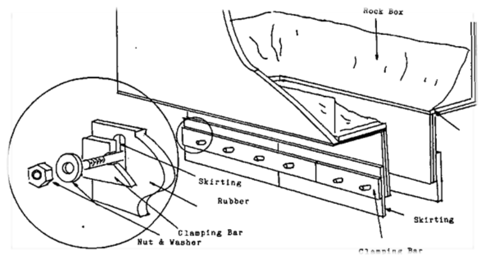
Figure 23: Chute curtain

Liners, figure 24: mechanical and chemical nature of such handling material exposes danger to the inner skin of chute. If liners are not installed as protection for chute, material flow will eventually fierce through the chute, creating spillage - unintended loss of material. Especially engineered liners based on over centuries collected metallurgical experience are on our side against wearing of chute components. In mining, where hard, high amount of material is conveyed, abrasive resistant liner is the remedy and long lasting so that conveyor system operates without stop for a reasonable period of time. Conveyor belt stop is so costly that it should be kept at minimum.

Figure 24: Liners inside a chute

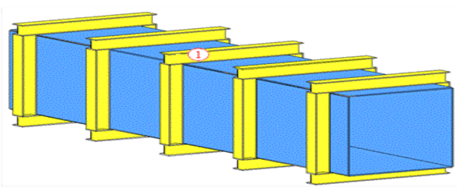
Skirt, figure 25: accelerated material has a chance to jump off or miss the receiving conveyor belt. Skirt line with is skirting liners is essentially intended to prevent the scenario from happening. Skirt line is assembled after discharge part, and takes up a certain length. When material is loaded centrally while having in-line velocity, skirt line takes the least damage, and is to raise safety and performance. A desperate need of it arises when conveyor system stops and starts.

Figure 25: Skirt line



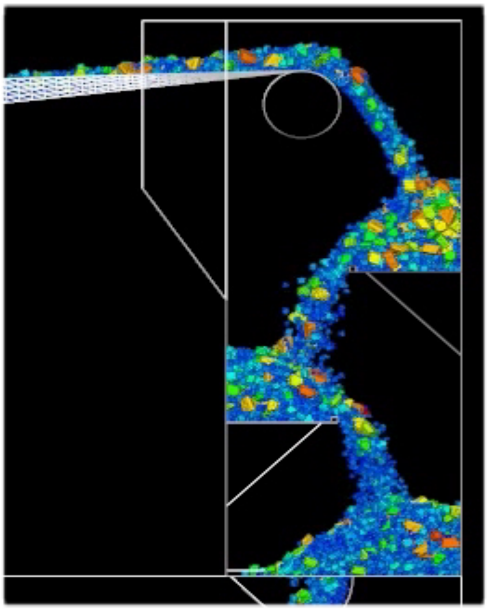
Stiffener, figure 26: particularly in mine sites, when conveying material from primary crusher, large lumps can put a chute under danger. Thickening chute wall is costly. Instead stiffener, like a belt, is invented to firm the chute.

Figure 26: Stiffened tube



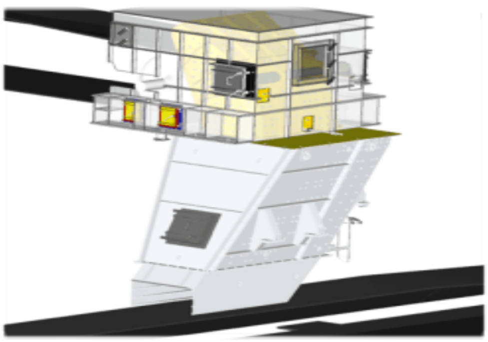
Rock box, figure 27: minimal structure and ease in design accentuates its attraction into bulk handling operations. It is nothing but a top open box, in which material accumulates. The accumulation will essentially becomes a protective layer. This is the most efficient protection of inner of chute against wear. Liners under the material accumulation can be almost forgotten as infinitesimal impact and wear reach there.

Figure 27: Rock box



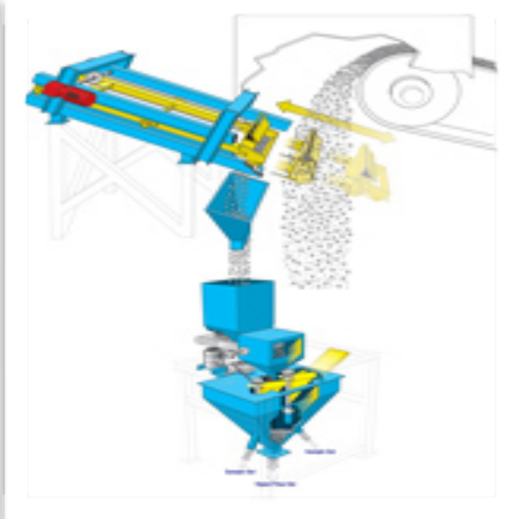
Monitor window, figure 28: it is an openable hole placed at hood. Its intention is provide insight of chute from above. On-run visual investigations can be made through the window. Furthermore, the elements offers chances to observe dynamic of flow in the chute so that possible improvement suggestions can be made.

Figure 28: Monitor window



Sampler, figure 29: occasionally, this element is needed in some cases where flowing material needs to be sampled and studied. An example of such need could be to measure: viscosity, cohesiveness, size and so on of material.

Figure 29: Sampler



Not limited with aforementioned elements of chute, there are more.

Chute and chute parts can be casted and are connected by means of welding, bolting. In a literature it has been stated that current applications of chute capacities span from 2000 to 150000 ton per hour. Due to feasibility, complexity, and economic limitations, performance of such chute is top bounded.

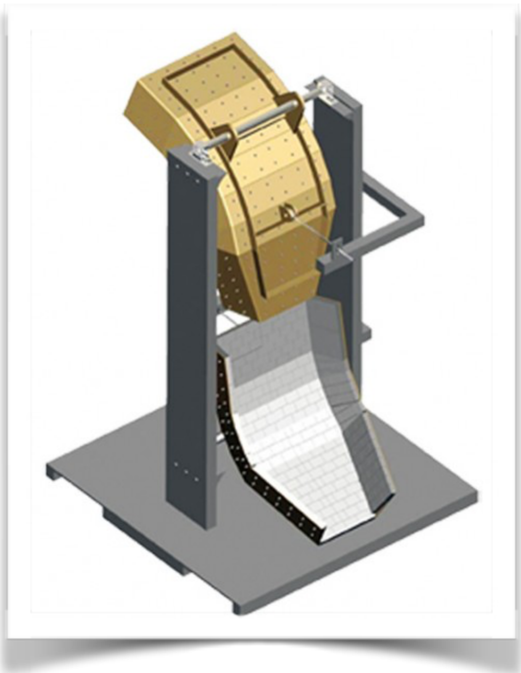
Chute types

Within the scope of the literature, 4 types of chutes are studied: rock box chute, hood and spoon chute, spiral chute, and deflector plate chute. Facility layout and demanded capacity determine chute's shape and geometry.

Rock box chute: rock box is an element to transfer chute; not only element, but a chute itself can form rock boxes - big boxes. This specially suits in applications in mining or quarrying. The types of applications are characterized by conveying high lump fraction with high throughput[3]. Material flow builds a pile on rock boxes. The piled material gets crushed by incoming flow, and ultimately becomes a solid protective pile. Within the given length of its ledge, pile is built agreeing the materials internal angle of repose. Every addition exceeding that angle will fall down. Rock Boxes should be designed such that required discharge speed, and enough room for non-plugging are fulfilled. Combination of rock boxes and liners protect the chute and promise long lasting operation.

Hood and spoon chute, figure 30: the type of chute is substitutable for rock box chute, but there is no possibility for sacrificial material pile to form inside it. The design is mainly tubular, having hood and discharge curved such that their curvature agrees material dynamic with minimum but optimum altering. As it is one continuous curved tube, and as material flies in contour of triangular, shape of the chute is much of consideration. It follows difficulties in manufacturing the type of chute.

Figure 30: Hood and Spoon chute



Spiral chute, figure 31: chute is said to fulfill two main functions: diverting and passing. An extra duty comes here. Additional function is to classify materials on account of their density. Indeed, the classification works on principle of centrifugal force, separating denser particles from lighter. Heavier particles, due to centrifugal force, are pushed outside. Ligher particles remain inside. The type is popular in handling materials that are relatively small and mild in size in comparison to that of in mining.

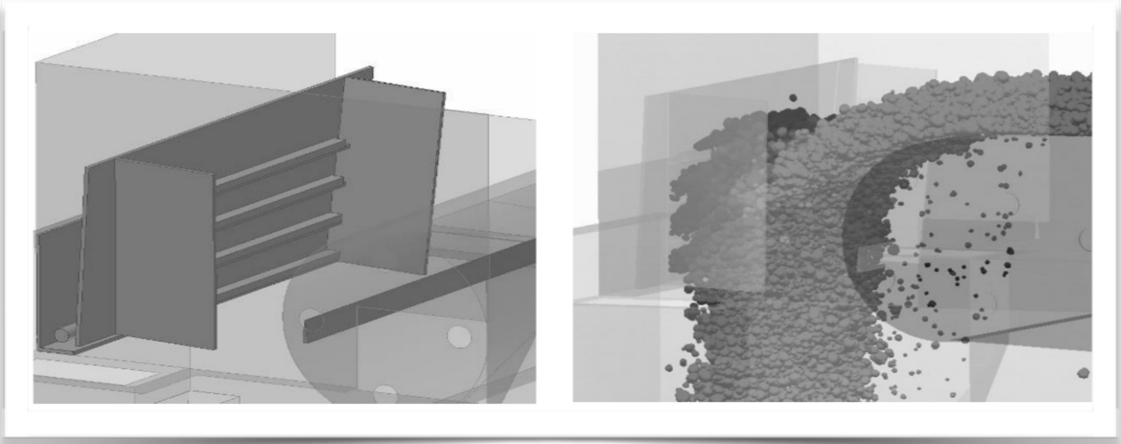
Figure 31: Spiral chute

The classification can be further enhanced by addition of water as it will exist as medium for particles displacement.

Deflector plate chute, figure 32: the type is what is first designed, meaning the crudest and oldest in its nation. Its working principal is quite simple. Material will hit a plate that essentially stops the flow and let it fall to next conveyor. Simplicity of its design is causing it to be still under application with low capacity. Although, maintenance, slippage, belt mis-tracking and so on conveyor related problems occur more frequently.

[3] size of material that pass through

Figure 32: Deflector plate chute



There is no standardized chute in mining sector as each mine is unique.

Chute design requirenents and problem

It does not a proof that nature is quite random, chaotic. The character impels mining operations to be unique. Even in same mineral mining, production line, installed equipments could be the whole different, the same is also true for chute.

Designing a chute means designing chute elements, and locating them at proper positions. Centuries long experience yielded some solid criteria for optimum chute design. Quite number of case studies were done by various engineers, and developers on account of improving the given chute in terms of productivity, safety. And it is hoped that researches seeking improvement will never end.

Chute design requirement:

Central loading: a chute design should allow handling material through the chute, by the discharge to be loaded centrally onto the receiving conveyor belt. Not complying of the requirement would receiving belt to mistrack[4]. Mistracking could cause the whole system to fail.

Horizontal discharge speed matching: receiving belt runs at a certain speed. To that speed, material speed should match so that minimum effort is made for

accelerating or decelerating of material. In a literature [S16], it has been stated that the speed should match in 10% proximity of belt speed. Intruding speed could lead to belt damage and spillage. Belt is the most expensive component of conveyor system.

Minimizing vertical discharge speed: intention is to protect the conveyor belt form material impact. Chute geometry should compromise the closest material speed for horizontal to belt speed and zero (ideally) for vertical.

No blockage or spillage: when chute is blocked by a material built-up, the whole system needs to shutdown abruptly. The shock delivers much damage to construction of the chute and conveyor, and takes days to be cleared. Therefore, according to literature [S10], chute cross section must encapsulate 60% more space than material flow volume. Spillage is often realized by wearing of skirting liners. Skirts should rather be hovering over the conveyor belt with minimum clearance. The open space should not allow material to pass and roll in-between them.

Chute related problems occur when chute design was given less attention. Simply, the chute must be designed so well that it complies all the requirements.

[4] an event when belt center-line deviates from conveying-line

Belt mistracking, spillage, dust, noise, plugging, belt damage are examples.
Before computation power finds its current advancement, chute designers used to model a chute by trial-and-error method. This is time, budget, manpower consuming and dangerous when creating such huge chute. Their previous fails and practices guided them toward better chute design.

Leaving those days behind, today engineers are taking full advantages of computers. Just by knowing material's mechanical parameters and chute geometry and operation conditions, an engineer can simulate the reality in a virtual environment where no danger, like an object falling is present. This method is friendly to time and budget, and once a reliably good model is achieved, every operation scenario can be experimentally and visually tested.

Operation of conveyor system faces mainly 3 distinct modes: start-up mode, nominal operation mode, shut down mode, occasionally sudden shut down mode.

Before an engineer gets to point of modeling a chute, he needs to possess a comprehensive knowledge of mechanical parameters of handling material and micro-mechanics that are taking place within the flow. That is done by on-site and laboratory tests. Tests determining the needed parameter are conducted for many times so that they got standardized.

Chute modelling

Introduction

Nowadays, engineers are asked to develop machines with highest possible performance with lowest possible maintenance and operation costs. The logic applies for transfer chute, too. Ever increasing resource demand on the Globe requiring transfer chutes to be more and more productive while being the most durable.

A careful modelling of chute is the key toward higher performance, therefore success. On the one hand, according to some literatures, chutes fail because detailed attention was not paid to the design. Consequently time, budget, and product losses follow. On the other hand, extant chutes fail, which were initially designed for certain maximum capacities are increased. This sets additional limitations to engineers that, they have to improve performance with minimum change in the existing chute design.

All credits to modern advancement in computation and software developers who made it possible to analyze a bulk flow particle by particle, accounting their speed, position, interactions etc. Current capability is so advanced that it can simultaneously take care of up to 100.000 particles continuously flowing, bouncing, impacting, and building a pile.

So computer power got engineers a new possibility to visually understand the flowing pattern. It is especially beneficial because lesser time, money, material, and effort is spent than actually building the model which was old inevitable way.

DEM & callibration

The most appreciated software is DEM (Discrete Element Method). The software is developed in many directions, each is specialized differently so that some specific features are greater than others among themselves. For example: there are softwares that are specialized for studying: stress, motion, heat, fluid, adhesion etc and some for damage, wear; all are applying knowledge of discrete element method.

A disastrous accident happens when a material flow blocks a chute tunnel. A consequent sudden shutdown of all chain operation of machines takes place. It can take days to clean the blockage and prepare the conveyor system for restart. Therefore, engineers endeavor to prevent a blockage from happening.

Blockage, or plugging occurs through gradual build-up of material at a stagnation point inside a chute. Thanks to power of DEM analysis that it is able to visually show the material flow inside a chute. However resulting video lasts about maximum one minute, a trend of material built can be noticed.

As was mentioned, DEM studies particles individually whether they are on air or in flow. When the handling material contains 5-50% liquid by weight, it is on tendency to build-up a pile and block the chute [S16]. Fine particles play an important role here as they pile building agents. Blocking can occur by different mechanisms. When a chute design does not allow material to leave as much as they enter, it plugs; or when material impact does not collapse an adhesively built pile, it plugs. In either mechanism, material trajectory is determining factor if material is piling up or not. DEM analysis can evaluate material flow and find particles trajectories.

For a DEM simulation to run, a designer need be ready to insert the following data:

- Chute geometry, pre-modelled chute in a compatible CAD program.
- Bulk material properties: grain size, density, material-material as well as material-chute liner friction coefficients, shear modulus, Poisson's ratio, cohesion, restitution coefficient of material etc.,
- And system configuration: belt width, thickness and speed, belt charge, pulley diamter and so on

On-run and in laboratories tests are required for the input parameters to be determined.

Once the parameters are inserted and a model is created, a calibration run takes place to make sure that the simulation is a reasonable representation of the actual operation. It has been said in one of the literatures that one minute of simulation takes around a day of computation time. Needed time is substantially influenced by number of particles and fraction of fines among them.

The calibration works comparing the actual facts with simulation results. Simulation undergoes the same operation conditions, and on-run facts are collected. So the two cases are compared. Little or no difference between the two means that the model is representing actual reality true.

To conclude, DEM analysis studies particles in a flow in terms of their interactions with each other, and interactions with the chute. All the studies come to a conclusion that material flow trajectory is crucial to be determined for designing a transfer chute.

A Case study

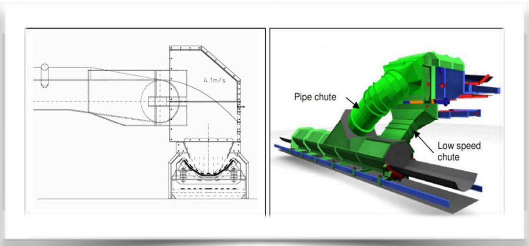
Among the studied literature, there were numerous researches and reports for improvement of chute desing, all applying DEM. A DEM practice was briefed in this section.

DEM based software helped a German underground coal company „Auguste Victoria“. The company produces black coal with an annual production of 3.1 Million tonnes. Its extracted coals come from its undergound deposit travelling underground route system of 103km which implicates use of several belt conveyors and transfer chutes. The continuous increasing demand on the coal market made the company to boost its production. Belts were designed to operate at speed of 3.2 m/s which is wanted to be increased to 4.1 m/s to realise higher mass flow rate. This caused suffered the old chute much. Simply, the chute design could not handle the increased amount of material flow. Consequent problems were chute blockage, belt wearing and mis-tracking that caused substantial down time. The chute design needed to be redisgned so that it can transfer required amount of coal. IBH GbR and FAR GmbH were assigned to develop a new design with possible minimum change in the chute to meet the demand.

The new principal design was called Segment chute and is shown in figure 33. Before the installation it should be proved, if the transfer chute is able to realise the different operating modes:

- Start-up and shut-down process,
- Delayed shut-down process of the feeding conveyor followed by a standard start-up process,
- Behavior of foreign objects like bore rods in the mass flow of the chute.

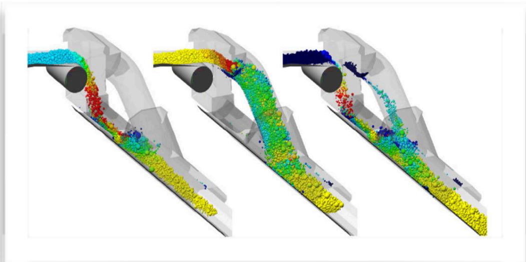
Figure 33: Segment chute design



When the system parameters are known, the new chute design was tested against the old design. The operation paratemers are: transfer angle - 90^0, belt width - 1.4m, mass flow rate - 4250 t/h bulk density - 1200kg/m^3, angle of repoes - 31, wall friction - 0.5, maximum conveyor speed - 4.1m/s, start-up time - 10s, time in stationary operation - 2s, shut-down time - 3s, delay between shut-down of feeding and receiving conveyor - 5s.

Well functioning transfer chute during the simulation of start-up, stationary and shut-down operation is shown in figure 34.

Figure 34: Modified chute operation



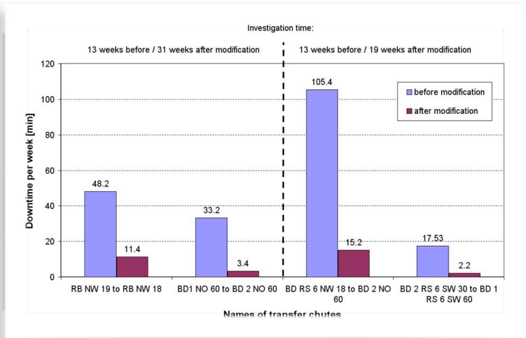
The new design consists of two passages for material: low speed, and high speed. At a belt speed of 2.33 m/s the material velocity simply down the first passage. With a speed of 3.7m/s almost all material is fed into the high speed passage. The flow inside passages can be described as smooth, and shows no turbulence or overturning particles. Passing materials get accelerated to 2.45m/s in the conveying direction. Hence, a comparably small belt wear can be expected. The observed problems were all eliminated. No material built-up was formed, belt-mistracking was reduced greatly by excellent material flow guide, dust and noise generation were reduced due to smooth flows.

Foreign objects such as a bore rods can be found quite often in the material stream. In many underground mines, the conveyor system is used as an easy way to transport damaged equipment parts. Due to bended design of the pipe chute, the transport behavior of long thin objects through the new design was especially interesting.

A DEM simulation was set up which included an idealised rod with 1m length on the top of the material stream. The simulation with the included bore rod shows no turning or blockage of the chute due to the rod in the material stream. The flow of rods longer than 1.4m seems also uncritical if the rod lies along conveyor direction. It is so because rod orients itself along the stream after some time. Therefore, the unlikely case of a rod which lies transversal to the transport direction was not simulated.

New and old desings were compared in terms of downtime duration in figure 35.

Figure 35: New & old comparison



The graph shows an excellent improvement.

Tribology

Introduction

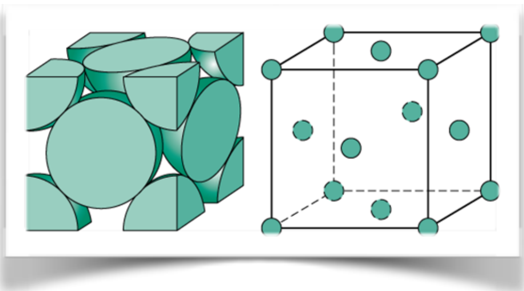
Tribology, this word is derived from Greek meaning the science of rubbing. Science and technology of interacting Surfaces in relative motion and of related subjects and practices are target of the topic. Tribological system, in general, are so complex that one needs to be fluent in various sciences, including physics, chemistry, applied mechanics, solid and fluid mechanis, thermodynamics, heat transfer, material science, rheology, lubrication, machine design, performance and reliability.

Microstructure of solids

Material scientists understood and discovered that there are 3 fundamental types of unit cell. Unit cell is the basic structural unit or building block of especially metals. For most metals, unit cells are often parallelepipeds or prisms having three sets of parallel faces. An unit cell is chosen to represent the highest symmetry of the crystal structure[5]. Crystal may be generated by translation of the unit cell integral distances along each of its edge. The unit cells are explained individually. The cells are:

Face centered cubic (FCC), shown in figure 36, unit cell is what builds Copper, Aluminum, Silver, and Gold etc. The cell is cubic in shape, atoms sitting at the corners of the cube and the center of faces. The type of cell has coordination number[6] of 12 and atomic packing factor[7] of 0.74 which is highest possible value.

Figure 36: Face centered cubic unit cell



Body centered cubic (BCC), shown in figure 37, forms Ferrium (alpha), Chromium, Molybdenum, Tantalum, Tungsten and others. The cell has an atom at cubic center, and atoms at corners of the cube. Corresponding coordination number is 8, and atomic packing factor is 0.68.

Not all metals have unit cells with cubic or at least parallelepiped symmetry; the final common metallic crystal structure is hexagonal - hexagonal close packed unit cell (HCP). Cadmium, Magnesium, Titanium and Zinc are typical representatives of HCP structured metals. Its atomic arrangement is that 7 atoms at top and bottom planes, 6 forming hexagon, 1 at its center, and more 3 atoms at mid plane forming a rectangular relation, shown in figure 38. In ideal case, ratio between height and lateral length yields 1.633 from which non-ideal cases deviate. The type of unit cell has coordination number 12, atomic packing factor 0.74 - as same as FCC.

Figure 37: Body centered cubic unit cell

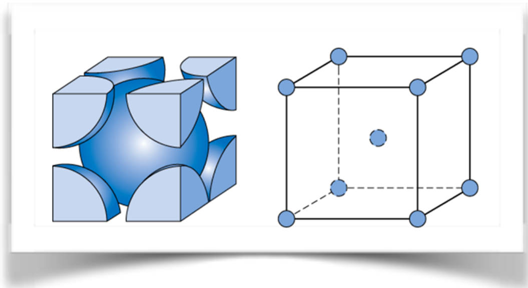
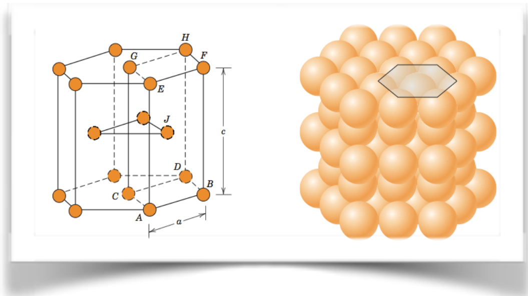


Figure 38: Hexagonal close packed unit cell



Different unit cells, different behavior of material.

Some metals, as well as nonmetals, may have more than 1 crystal structure, a phenomena known as polymorphism. The polymorphism concept is translated into allotropy when it is found in elemental solids.

So the unit cells build a metal. It should be noted that, the whole metal is form of clustering of orderly arranged unit cells -

[5] a description of arrangements of atoms in metal

[6] number of neighboring atoms that are closest to an atom

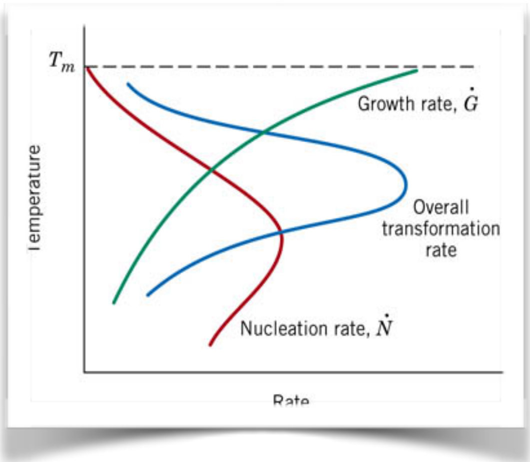
[7] volume fraction between particles inside an unit cell and the unit cell

called grains. Grains orient randomly in a metal. The understanding of crystal structure lies in the concept of grain. To discuss more about grain sizes and number, how metal solidifies from its liquid state should be, first, explained.

At elevated temperature more than melting, metal becomes a viscous fluid. When temperature goes down and reaches the melting temperature, the molten metal starts to solidify. Solidification starts from outer surface, then invades toward the center of its container.

As temperature drops, the freely swimming metal atoms initiate forming nucleations. Nucleation is simply clustering of atoms. Then, they grow and form grains. Nucleation and their growth happen in an unorganized way which causes grains to be randomly oriented inside metal. Solidification at different temperature implies different rate of nucleation and their growth. Figure 39 shows nucleation rate & grain growth rate as functions of solidifying temperature.

Figure 39: nucleation rate vs grain growth rate



Depending on their relative rate, grain size and number are determined. If nucleation rate is high and growth is slow, then there will be high grain numbers but small grains. The opposite case is valid.
In metallurgy, pure (or pollution free) and perfect grain structure is hardly achievable as there will always be contaminants, and empty or unoccupied lattice points[8] in grains.

Imperfections & dislocations

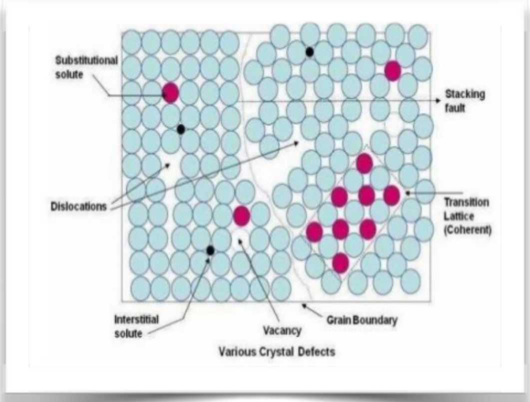
Metallurgist manipulate the solidification process varying operation conditions, such as temperature and/or chemical composition, and study the resulting materials. From there, relations between material properties and microstructure can be best pictured.

Formed nucleus wander in the solidifying liquid arbitrarily picking up atoms or digest another small grain - grain growing. As a result, imperfections and dislocations in zero, one, two, three dimensional are observed in a grain. Figure 40 shows dislocations in various dimensions. A crystal structure is built by combination of various atoms different in size and properties - imperfection, or some lattice points left unoccupied by any atoms - dislocation. Furthermore, two atoms may occur at space of one atom, or comparably small atoms may find itself in interstitial voids between bigger atoms, like carbon in steel. This in-homogeneity, if constituent elements are smartly manipulated, may benefit the material enhancing its mechanical properties.

Modern market demands require high strength alloys with certain specific properties such as high heat, thermal, and/or electric conductivity, wear and/or corrosion resistant etc. All of those material properties are direct reflection of their microstructures. Microstructure is what actually builds the materials' properties.

[8] Point in unit cells where atoms are allowed to sit

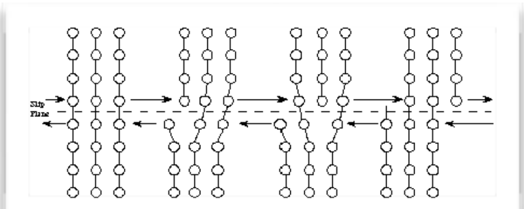
Figure 40: Dislocations in various dimensions



Hardness

Hardness is material's ability to resist deformation. Figure 41 explains how deformation takes place. The harder, the more durable. A surge in hardness could cause material go brittle[9]. Why some materials are harder than others? Answer is difference in microstructures. Microstructures of harder material do not allow its atoms to conquer its neighboring atoms easily in a direction a force is applied - deformation. This is the motivation to engineer a material. Atomic movement in a material must be prohibited as much as possible for a material to be hard.

Figure 41: Deformation mechanism



Description: dislocation movement goes in the opposite direction deformation movement, allowing atoms to shift continuously.

Hardening, thus prohibition of atomic movement or dislocation is achieved by several ways. Imperfections, dislocations, interstitials can be manipulated such that they hinder atomic migration in a metal. Atomic migration occurs by movement of plane(s) of atoms, each atom is taking position of its adjacent atom. For example: a big atom in a line of small atoms could hinder atomic shifting as the it will require much higher energy to move than small ones. Grain boundaries are great in stopping atomic migration. Its a random three dimensional spaces between grains that is empty, usually in planar shape. For migration to pass from one grain to another, it needs to find conducting medium which at grain boundaries is absent. Therefore, it finds hard time for the deformation to develop.

Many efforts are dedicated to disorder the material's crystal structure as far as possible to achieve higher hardness. And from the aforementioned example of hardening, it could be concluded that finer the grains, stronger the material.

Heat treatments

Grains of metallic material will always be one of the three fundamental unit cells: BCC, FCC, HCP, or their combinations. Advanced material properties, and misperfection in atomic arrangement in crystal structure are connected by concept called heat treatment.

Even in a solid state of metal, atoms, without any mechanical influence, are able to migrate throughout the metal, a phenomena known as diffusion. Diffusion rate - mobility of atoms is dependent upon temperature. High temperature means high mobility of atoms. Dislocations, misperfection are again helping agent in diffusion.

Heat treatment can be understood as act of encouraging or discouraging the diffusion effect. By performing heat treatment, atoms can be placed at proximity of desired location. Or, it can be understood as building of material at atomic level by knowing mobility of atoms with respect to temperature.

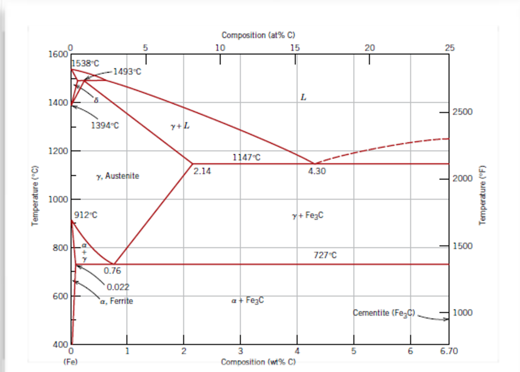
Metals exhibit different microstructures at varying temperature and composition. In figure 42, steel phase diagram is shown. At 727 C at eutectoid composition, steel suddenly changes its atomic structure

[9] a material characteristic that is hard but easily breakable

from BCC (alpha ferrite) and cementite Fe_3C into FCC (austenite ferrite), and vice versa. In phase diagram, time Perception is not included. Depending on temperature it takes some time to obtain specified microstructure.

To have steel austinite structured at ambient temperature, a technique called quenching is applied. It is a rapid cooling of material. The cooling rate must be so high that it does not give much time for atoms to relocate them according to its specified microstructure at cooled temperature.

Figure 42: Steel phase diagram



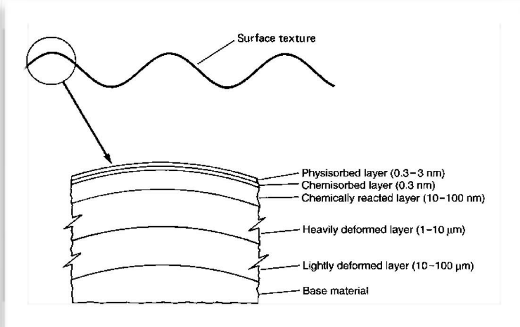
Higher cooling rate or strong quenching refers to faster nucleation and slow nucleus growth as figure # tells. Further increasing the cooling rate, the material would go forming bainite structure; martensitic at ultimate cooling rate.

Techniques of alloying, heating, holding at certain temperature, and sudden cooling are under metallurgists disposal to compose material properties, such as hardness.

Surface

Irrespective of the Method of formation, solid surfaces contain irregularities or deviations from the prescribed geometrical form. On top of solid having irregular surfaces, the solid surface itself consists of several layers having parameters varied across them. For more convenient comprehension, figure 43 is present. Layers and surface find their properties different with various thickness as a result of such forming and/or environmental effects. Friction, hardness, ductility, microstructures, conductivity and so on can be called as varying parameters in this context.

Figure 43: Layers under surface



The metallurgical properties (grain structure) of layers can be studied by sectioning the surface and examining the cross section by a high-magnification optical microscope or a Scanning Electron Microscope (SEM).

Microcrystalline structure, and dislocation density and type can be studied by preparing thin samples of the cross section and examining them with a transmission Electron microscope (TEM).

Surface roughness

A surface which seems smooth may be very unsmooth having hills and valleys - termed as asperities, at the surface. On microscopic sight, a surface is ground of extruded and intruded tiny needles, illustrated in figure 44.

Properties of These rough Terrain are origin of Friction, wear, cohesion and other material Surface related Parameters. When two surfaces meet and mat, these rough textures meet. It now becomes understandable that the actual contact is made through much smaller area than surface area. This is explained in figure 45.

The needle shaped textures retain the material behaviors acting anologously according to classical understanding of mechanic. They break once plastic limit is surpassed. They bend, stretch, deform and chemically react.

Wear mechanism

Wear can be perceived as mass removal or damage from one or both solid surfaces that are interacting with each other mechanically. Such mechanical interactions could be simply rolling, sliding, impacting etc,. Asperities and nature of their size and shape, and number, properties are determining factors for wear intensity. If there is no surface interaction, for example by means of lubrication oil, no wearing results.

Figure 44: True surface appearance

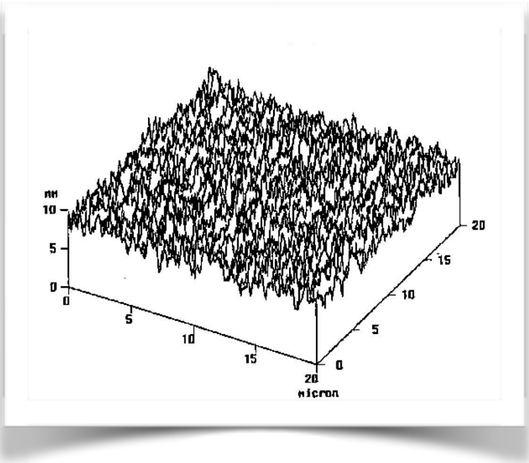
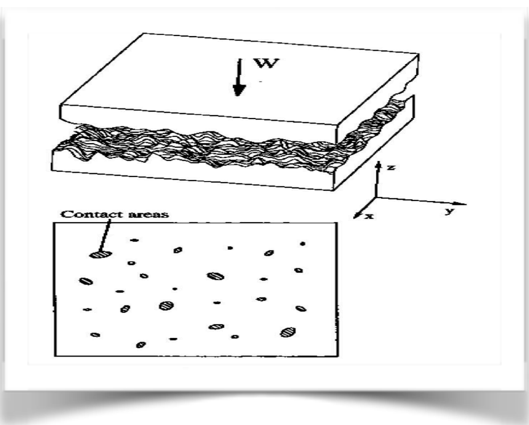


Figure 45: Actual contact area



Wearing is said to be perceived as damage to a Surface because the worn asperities could fill the surface irregularities having zero net mass removal. In this scenario, the interacting surfaces are kind of polishing themselves.

In the current knowledge, wearing occurs in 6 distinct forms, listed below, usually by means of mechanical and/or chemical interactions. The wearing rate can be accelerated by frictional or thermal heating.

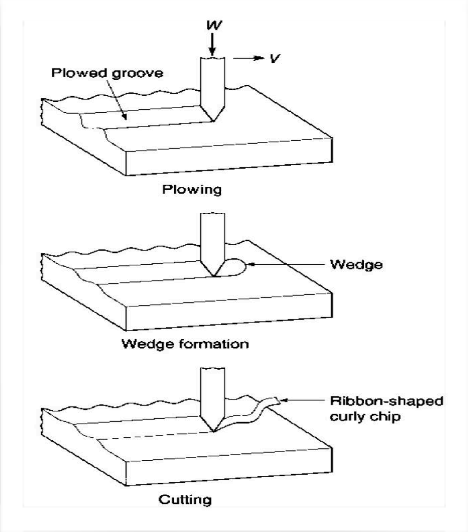
- Adhesive
- Abrasive
- Fatigue
- Impact
- Chemical
- Electrical arc induced

In a given case, wearing could happen through any creative combination of these 6 fundamental types. Remedies, preventions against wear are developed, however they never win it. Each type of wear is explained a briefly so that impressions how they take place can be given.

1. Adhessive type: it is material transference from one surface to another by act of adhering force. At sudden or cyclic load, either softer material or harder but linked with its mother body by soft material can detach from one body and attach to another. Adhesion force may be realised by microwelding due to abrupt impacts between asperities, or chemical interaction. The type of wear is enchanced by grain boundary effect. Garin boundaries are meeting boundaries of grains where irregularities, empty states are present. The effect has influences to friction, adhesion, surface fracture and wear all explained by the nature of empty or disordered states of atoms at the grain margins.
2. Abrassive type: this type of wear involves sliding two surfaces, and can involve participation of third body. Fracture and deformations are results of harder asperities sliding on softer ones. In this context, hardness is the major judge factor that decides which body to wear out. Abrassion, as observed, happens through two possible ways: 2 body interaction, and 3 body interaction, shown in figure 47. Consequence is that harder body damages softer Bbdy causing it to lose material from its Surface. Abrasive wear is recognized by their stratching Signature - series of parrallel grooves on abradded

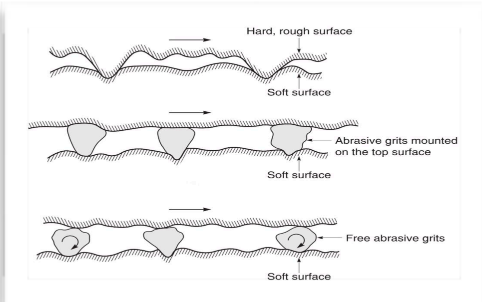
surface. The stratch scars may come as result of 3 possible actions: plowing - gradual fatigue material removal, wedge formation - developed material built-up at the end of stratching which is put at risk of detachment, and cutting. Pictoral explanation of the 3 actions is given in figure 46.

Figure 46: 3 stratching type



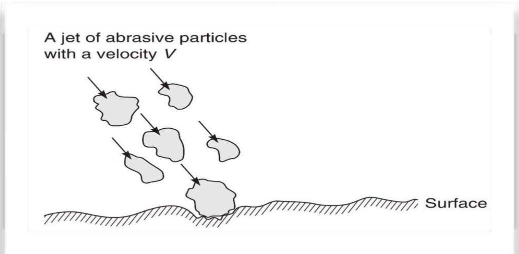
3. Fatigue type: by repeated loading and unloading without essentaiily wearing surface adhessively neither abrasively, a crack develops at and/or under surface. The crack becomes matured after designated cyclic force is applied. The matured crack will develop failure by any further force appliance. Rolling, sliding, impacting any mechanical action can be source of the type of wear.
4. Impact type: tiny particles impact a surface causes wear in either abrasive or fatigue manner. The difference is that the impacting particles do not conduct force as it was the case in previous types. Their kinetic induces impaction force. Figure 48 explains the wear pictorally. Depending on their flying speed, heat may be developed at interfacial region which encourages wear.
5. Chemical wear: the type of wear happens with mechanical aid that is creating new surfaces, such as: sliding, in corrosive environment. In air, the most dominant corrosive medium is oxygen. So chemical wear in air is generally named oxidative wear. Chemical wear will not advance if no new surface gets generated. It means, without mechanical influence, chemical wear will saturate with given material surface. High temperature, dense corrosive environment are favoring factors for chemical wear.
6. Electric arc induced type: through a electricity conductive medium, such as thin layer of air, liquid, the type of wearing could occur between two moving surfaces with arc strikes due to high potential difference. The arcing, as it happens on tiny area, smelts local surface. The smelted surface can solidify in contact with a foreign body and lead to adhesive wear. Developed heat may alter regional material properties such as: microstructure, thus hardness, ductility and so on. Arcing causes large craters, and sliding or oscillation after an arc either shears or fractures the lips, leading to three body abrasion wear resulting in catasptropic failures in electrical machinery.

Figure 47: 2 Body and 3 Body abrasion



Mechanical (hardness, force), physical (heat, arc), chemical (oxidation, surface) activities can develop a tribological system, for conclusion. Wearing is indeed everywhere from negligibly infinitisemal to instant rate.

Figure 48: Impact wear



In mechanical context, wearing can occur or enchanced due to several reasons.

- Machine overload
- Parts misalignment
- High friction between rubbing surfaces
- Insufficient and/or improper lubrication
- Bad maintenance
- Rough Surface Finish
- Environmental effects: temp., moisture etc

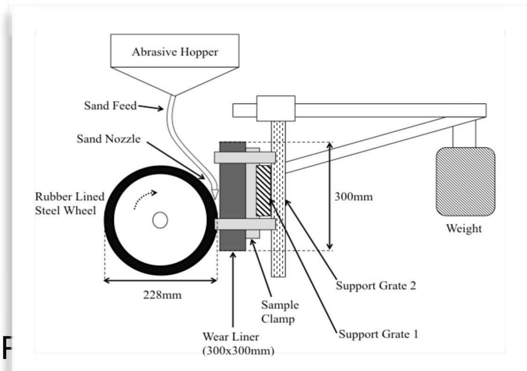
Wear measurement

A western Australian compony, BHP Biliton Iron Ore (BHPBIO) runs a coal mine with high capacity. The company's operation is reliant on its conveyor belt systems having transfer chutes at conjuctions. They defined chute liner to be sacrificial layer of material installed on inside transfer chutes, to protect the chute from damage. The chutes that are used at the mine also experienced high abrasive wearing. To access the abrassion, an updated version of dry sand rubber wheel (DSRW) test was designed and approved by the BHPBIO. And to test impact resistance, a drop-weight test was designed. The two wear rigs are explained here. Principal is simple; it replicates the actual operation in small scale with high level of control so that worn liners can be weighed.

DSRW test rig design

The DSRW test is often used for ranking abrasive resisntace of metals and ceramics. The test consists of a plane specimen loaded from one side, positioned against a rubber-lined rotating wheel, with an abrasive grit allowed to roll between. The schematic for the design is shown in figure 49.

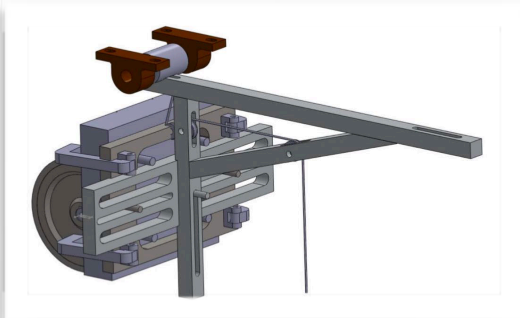
Figure 49: Dry sand rubber wheel rig



The design simulates three body abrasion wear, as abrasive grit is fed through a nozzle and allowed to freely roll over the speciman surface.

The gripped Sample can be shifted horizontally and vertically by grates on the sample holder. This, however does not allow full access to the sample, significantly increase the accessible points. The two Grates are shown in figure 50.

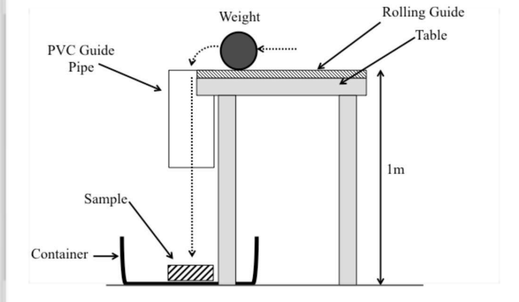
Figure 50: Sample holding grates



Wheel spinning speed, grit feeding rate, and relative locations are set by an examiner. Time to time, the operation is ceased for liner weight measurement to be conducted. From the worn sample scars, and produced worn material are studied to characterize the wearing process.

Drop-Weight test rig design

Dropping a weight from a defined height on the study object is how this test works. Schematic is shown in figure 51. 7.26kg Weight drops from 1m height. First half meter is directed by a PVC pipe so that weight can land on same point repeatedly
.
Figure 51: Drop-weight rig



The remained scars are studied with depth of intendation to access the impact. Final conclusion accessing a plate steel is made after several identical tests were performed.

Wear reduction Method

Wearing can be reduced to infinitisemal, but never be elimitaned. For wear reduction, efforts are put on preventing surfaces to meet with each other, for example, by means of lubrication. The methods mentioned in [S20] are essentially to eliminate conditions for high wear.

Liners

SSAB AB is a Swedish-Finnish company founded in 1978. The company process raw materials producing steels for multi sectors of economics. Its headquarter is in central Stockholm.

The company created technologies which, currently, produce many types of final goods made of high strength steels that found versatile applications in practice. The products are categorized into 4 groups whose names are shortened: Hardox, Weldox, Armox and Toolox. All the 4 products exhibit exceptionally good mechanical properties which highlighted them in market and in practice over other commercial steel products.

In addition to their high hardness, there are other distinct factors that make products from SSAB ranked higher than other steel commercials, i.g: high toughness, machinability by typical forming machines (bending, cutting, machining), high weldability in parallel to having higher hardness with lower carbon content, wear resistance, high surface precision, low dimension deviation, uniform thickness, releaved internal stress, uniformness in composition thus homogenous properties over volume and so on.

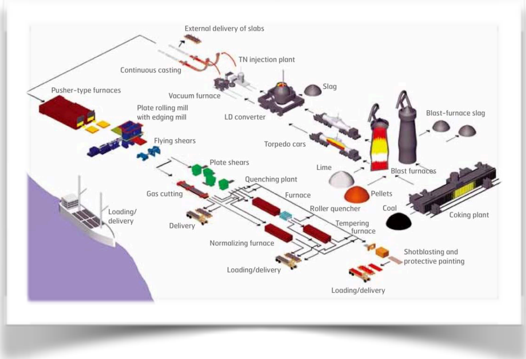
Hardness is what gives Hardox steel its unique wear resistance and structural strength. Sharp edges, asperities of particles find it harder to cut into harder material. High hardness also implies an excellent yield and tensile strength.

Hardness is one brick, and the other main brick that is making it strong against wears is toughness. When hardness makes it wear resistant and strong, toughness is what makes it possible to bend, form and weld the material without cracking. Even a crack forms, the nature of the material prohibit it to propagate.

The steel producing process are optimized to suit most complicated nitched products, which also benefits Hardox steels. A common feature that ensures good weldability is the accurate chemical composition, including very low carbon equivalent, closelt controlled contents of residual elements.

Hardox steels are produced by more or less the same procedure as other steels production. Figure 52 shows production procedure. The principal raw material are ore in the form of pellets. The raw material are converted into raw iron in blast furnace. Then it is transported in ‘torpeda cars’ to our own steel shop, where the LD converter refines the raw iron into steel by oxygen blowing, which blowers the carbon content of the iron. It is the carbon ceontent that is the main distinguishing feature between raw iron and steel.

Figure 52: Hardox steel production



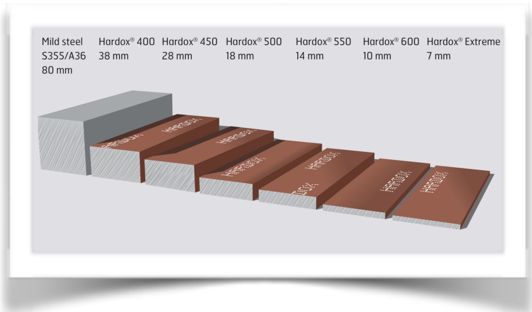
The steel is then processed to achieve exactly the right composition and temperature. The steel is cast into Slabs in the continuous casting plant.

The slabs are then transported to the rolling mill, where they are rolled into plate. To achieve the required properties, the plates may then be heat treated including quinching. Various post-treatment processes are then carried out, such as levelling, shotblasting anti-corrosion painting, cutting to length and width, and marking. The plate us then ready for delivery to the costumer.

As a positive consequence of swapping such as mild steel with Hardox steel, for example in mining or quarrying operations, a company wins less weight, as illustrated in figure 53. Therefore, the company can save costs by moving lighter machines with more load which sounds environmentally friendly due to lesser fuel or energy consumption.

Low deviation in hardness in order of 30 HBW makes its usage more favorable as it makes more reliable prediction of service life of equipment made of Hardox.

Figure 53: Fighting wear and weight



For purpose of immediate recognition of type of material, and anti corrosion, the products are differentiated and protected through colored painting. Depending on the products' final applications the protective layer of paint, which serves as a coating, can last as long as 6 months. The minimum protection is said to be 3 months [R25]. The lifetime can be reduced by means of mechanical processing on the products, for example: machining, grinding, cutting. The coating has no influence on welding, thus the welding can take place anywhere without preparation. Generally, a low-zinc silicate primer is the most dominant candidate for coating.

Color-code:
Hardox - red
Weldox - grey
Armox - grey

Product is labeled specifying its type and hardness on the color painting.

The products' mechanical properties are checked by
Tensile testing in accordance with EN 10 002-1,
Impact testing in accordance with EN 10 045-1,
Hardness testing in accordance with EN ISO 6506-1, 6508-1
Tensile test in thickness direction in accordance with EN 10 164

And

Surface is tested by ultrasonic testing in accordance with EN 10 160:1999

Unless otherwise agreed, delivery and inspection are subject to the technical provisions of EN 10 021.

Quality management system in accordance with EN 9001:2008. The system is doubly certified in accordance with AQAP 2110:3

For more convenience, the company produces parts accordance with geometry the costumers provide. Moreover, with the same mechanical properties, the company manufactures also solid bars and tubes.

Weldox

Through careful controlling of chemical compositions and process, the company is capable of producing highly wear resistant material with extra good weldability. Weldox steels promise flat surface, and uniform properties over its whole surface due to infinitesimal amount of residual (pollutant) elements. For whatever application, the material also holds properties of remarkably good bendability and machinability. An applied example is shown in figure 54. A mobile crane has made its parts out of Weldox steels.

Weldox high strength steel is manufactured in thickness ranging from 4 to 130 mm. Corresponding yield strength to the thickness extremes are 700 MPa and 1300 MPa, respectively and are guaranteed.

Figure 54: A mobile crane having parts out of Weldox steels

Weldox high strength steels conform to EN 10025-6.

Armox

Originally, the type of product was used in military applications due to their good ballistic properties with excellent toughness. For applications that are involving risks of explosion, such as various types of vehicles and storage premises, the steels are suitable as protecting surface. As of other types of steel products, Armox steels also show a property of easy machinability while retaining other mechanical properties at over moderate level. As armox 500T has excellent ballistic properties combined with high hardness (480 - 540 HBW) and strength, it found it typical applications in bank counters, security vehicles, VIP vehicles, burglarproof storage premises, security doors, and so on, figure 55. Even higher security can be offered by steels marked Armox 560T (530 - 59-HBW) and Armox 600T (570 - 640 HBW) which are the latest products of SSAB.

Figure 55: A vehicle armored with Armox steel

Toolox

Steel products which are intended for uses of light and medium duty applications, such as hand tools, machine parts, and so on. Their products are delivered preheated which makes them ready for instant use with hardness starting from 330 HBW. This fact eliminates further process that are risky, such as hardening (no further hardening is intended). Since the plates come preheated, there is no residual stress within them, meaning high toughness.

Especially tool manufacturers are prone to choosing Toolox products due to shorter production time, and more uniform and stable material properties. An example is shown in figure 56. Due to its pure metallurgy and hardening, Toolox has unique toughness and fatigue properties, which greatly increases the lifespan of the tool or machine component.

Figure 56: A tool part out of Toolox steel

Toolox plates are friendly to processes of machining, etching, polishing, and coating. Therefore, not only manufacturing of tools and machine parts are its production span; typical applications include: plastic moulds, edge-pressing tools, wear strips, plate pressing tools, etc.

Its ability to hold covering material on its surface allows itself to be more harder around 65 HRC by coating at surface. This also refers to long service life of its usage.

Hardox

Through a vast experience of processing steel, Hardox steels are produced and globally appreciated by sectors where high abrasive resistance, strength, impact roughness of steel are demanded. It application span ranges so wide that almost every heavy sector uses the steel. For example: in mining, quarrying, agriculture, waste recycling, and so on. Illustrated in figure 57 is a dump Truck armored with Hardox steel.

Hardox steels are on the market with thickness from 3 to 130 mm and hardness of 400, 450, 500, 550 and 600 HBW. Due to advanced metallurgical engineering of its alloy composition that brings higher hardness; products made of the steel are lighter and simpler. The mechanical properties are kept even at low temperature as low as - 60 degree. This unlocks its applications in cold environment - winter, still with specified properties. Its good weldability and machinability properties simplify production and repair work.

Hardox 550 offers solid benefits for applications like hammers, shredders, cutters, bolt on cutting edges, shrouds, dum truck discharge ends, and various linings in the mining and quarry industry. its mechanical properties are summarized in figure 58.

In one of Hardox commercial brochures, it has been stated that most of the commercial steels do not preserve their properties at elevated temperature, and have inhomogeneous distribution of property over surface. In contrast to that, Hardox steel plates do the opposite. Their hardness value deviate in a maximum order of 30 HBW meaning that 500 HBW hardness marked steel will have hardness from 470 to 530.

Figure 57: Hardox steel application Hardox 550

For a case of Hardox 550, the deviation magnitude is lesser - 25 HBW for plates of 40mm thick as illustrated in figure 59. This small deviation makes estimation of lifetime of a machine part made by Hardox steel closer to prediction.

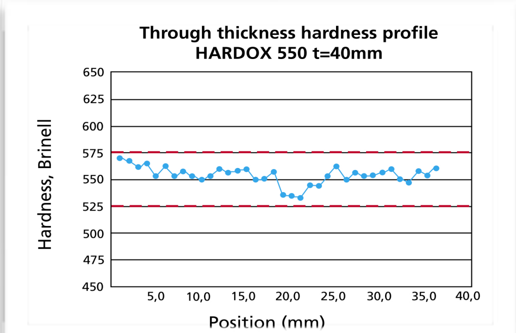
Figure 58: Mechanical Properties of hardox 550

Hardness [HBW], guarantee	550 [+/- 25]
Impact toughness, typical 20 mm	30 J/-40C, 22 Ft-lb -40F
Yield strength, typical	1400 N/mm^2, 205 ksi
Tensile strength, typical	1700 N/mm^2, 250 ksi
Elongation [A5], typical	7 %
Carbon equivalents, typical	CEV= 0.72 / CET= 0.48

CEV= C + Mn/6 + [Cr+Mo+V]/5 + [Cu+Ni]/15
CET= C + [Mn+Mo]/10 + [Cr+Cu]/20 + Ni/40

In the same brochure, Hardox 550 is compared against 12% manganese steel, and Standard 500 HBW plates in wear parts. As result of the comparison, it has been noted by consumers that selection of Hardox 550 steels is more economical. It is so, because of less frequency of maintenance, longer lifetime of machine parts, truth of promised properties, simplified and reliable logistics, customized components, and easy handling in workshop. Furthermore, Hardox 550 brings more healthier work environment, in comparison with 12% manganese steels, since welding and cutting are performed without heavy fume emission.

Figure 59: Hardness deviation in Hardox 550

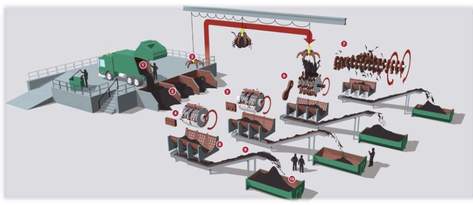


50 HBW increment over Standard 500 HBW steel plates yields elongation of up to 60% of service life depending on wear situation. This enhancement attributes extra hardness as well as surface quality of the Hardox steels. Hardox 550 gets an extra grain refinement - homogenous mircostructure in combination with a low level of impurities by additional plate processing. Through the additional process, plates are handled by improved plate handling routines which secure an outstanding surface finish. This essentially reduces the number of potential points of crack initiation.
By the producers of Hardox steel, it is recommanded to substitute Hardox 500 with Hardox 550. This is economically sound since the extra 50 HBW brings up to 60% enhancement of service life. In other words, **the additional 60% of service life far outnumbers the minor cost difference.**

The additional 60% of service life of machine part brings a recycling company a save more than 100.000 Euro a year by decreased costs for maintenance and stocks, shorter lead time, and improved productivity.

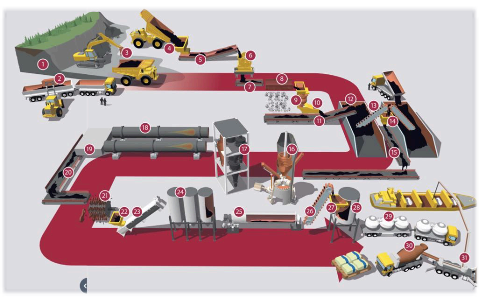
Hardox 600 is the world's hardest wear plate with a hardness of 600 HBW that makes it possesses uniquely high impact strength. It is inteded specifically for extreme wear conditions and is mainly inteded to replace case steels, chromium-alloyed white cast iron, and hard facing. Abilities to be cut, machined, welded are preserved in the mark of product.

Hardox in recycling [R25]



Recycling processes, such as the fragmentizing of waste, places enormous demands on equipment. in Order to stay productive and competitive it is vital to use Materials that withstand the abuse. Hardox wear plate is the solution. Developed specifically for Tough demands, hardox wear plate allows recyclers and recycling Equipment manufacturers to cut costs, improve service life, and optimize production.

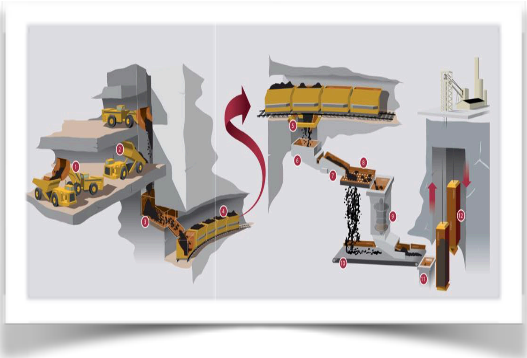
Hardox in cement production [R25]



While Hardox is made on the purpose of possessing high mechanical properties, it is also coated so that the steel plates are resistant to corrosive agents. Even the nature of the material shows a certain amount of anti-corrosion behavior - carbon and magnesium.

The cement production process finds use for Hardox wear plate all the way from the limestone quarry to loading and transporting the final products. The abrasive applications include excavating, crushing, screening and grinding the stone.

Hardox in underground mining [R25]



Its outstanding weldability and workshop-friendly behavior makes the products favorable for underground application. Mobile and immobile machines, without having need to be taken on surface and get repaired, can get repaired still under the ground. This method keeps production up and maintenance costs down.

Quarrying and open-pit mining [R25]

Quarrying and open-pit mining operations deliver some of the world's toughest wear challenges. Throughout the whole process of processing rocks and ores, hardox material promises longer service lifetime of machines than commercial wear resistant steels.

Hardox in road building [R25]

A variety of equipments, from trucks that transport heavy material over long distances to machines that withstand extreme wear when breaking ground is needed for road building operation. Superior strength of Hardox allows machines to be equipped with lighter shields which allows more payloads.

Hardox in agriculture

In sector of agriculture, typical actions encompasses preparing ground by means of cutting, ploughing, ripping, then planting, ultimately harvesting, storing, spreading, and transporting. For each activity pops up in the context of agriculture work, Hardox material is best suited. Most of the processes involve abrasive and impact wearing, for which Hardox is made.

Alloying elements

Chemical composition of steel is of Great importance since it determines the Potential mechanical Properties of the finished steel product and controls the degree of corrion resistance and weldability of the material. For that reason structural steel specifications always provide a table of chemical composition limits which challenges the steel Maker.

About twenty different elements are used in various proportions and combinations in the manufacture of both carbon and low alloy structural steels. Some are used because they Impart specific Properties to the steel when they Alloy with it, or when they Combine with carbon, wholly or partly, to form compounds known as Carbides. Others are used because they are beneficial in controlling the steel of impurities or rendering the umpuritites harmless. The effects some common allyoing elements are breifed in this section.

Sulphur, S 0.08-0.19%
- Undesirable content
- Improves machinability
- Decreases weldability
- Its detrimental effects are Offset by Manganese
- MnS has higher Melting

Phosphorus, P
- Increases strength at very Low amount
- Decreases ductility and toughness
- Should be kept at minimum

Nitrogen
- Increases austenitic stabilities, yield strength
- Efforts are made to eliminate hydrogen, oxygen, nitrogen as much as possible

Carbon, C
- Cheapest hardener
- High carbon Leads to britleness and Weaker weldability
- Carbon increment follows decrease in ductility, toughness, impact properties annd increase in Abrasion resistance

Boron, B 0.001-0.003%
- Good additive in Low carbon steel
- A hardenability Agent that improves deformability and machinability

Silicon, Si 0.2-2%
- Deoxidizer
- Increases strength up to certain limit, Oxidation resistance, elasticity, strength, grain size
- Decreases ductility at high amount

Manganese, Mn up to 1%
- Deoxidizer and desulphurizer
- Increases Tensile strength, hardenability, ductility at high temperature
- Substitutable of Nickel
- Eliminates iron Sulfides
- Mn + C makes steel highly resistant to Abrasive wear

Nickel, Ni 2-20%
- Increases ductility, notch toughness, impact resistance at Low temperature
- Improves Corrosion and Oxidation resistances
- Often comes with chromium

Lead, Pb
Although virtually insolubele in liquid or solid steel, lead is sometimes added to carbon steels via mechanical Dispersion during pouring in Order to improve machinability

Copper 0.1-0.4%
- Increases Corrosion resistance at high temperature
- Promotes precipitation hardening
- High Cu content decreases weldability

Aluminum 0.95-1.3%
- deoxideize, often promotes formation of nitrides
- Small amount of Al restricts grain growth
- Increases drawability, Hardness

Tungsten, W
- At high temperature, increases strength and refines grain size
- Tungsten + Carbides is exceptionally hard, increasing wear resistance

Cobalt, Co
- Improves strength at high temperat ure and magentic permeabil ity

Columbium
- Austenite stabilizer
- Increases Corrosion resistance , Tensile properties

Zicronium, Zr around 0.1%
- Increases strength at Low temperat ure
- Limits grain size

Niobium, Nb
- Promotes precipitation hardening
- Increases strength in Small amout at high temperature

Vanadium, V around 0.15%
- Mild deoxidizer
- At high temperature, refines grain size and increases strength
- Improves fatigue limit
- Increases depth of hardening

Chromium, Cr
- Cr + C is a powerful hardener
- Increases Corrosion resistance, strength, abrasion resistance at high temperature and hardenability
- Its Carbides are very stable

Molybdenum, Mo 0.2-5%
- Increases depth hardening, corrosion resistance, hardenability
- Improves Corrosion and creeping

Titanium, Ti 0.25-0.6%
- Effective Carbide Former
- Coating Agent
- Improves strength and Corrosion resistance, refines grain size

Methodology

Intoduction

From Oyu-Tolgoi LLC mining company, a thesis topic was provided and named „Elongation of service time of transfer chute“. Transfer chute is lined inside so that rock flow does not harm the chute. Due to constant and abrasive bombardment of rock flow, the liners fail causing, at worst cases, a fiercing of wall. Through the fiercing spillage occurs. The topic is studied by a group of mechanical students, from different aspects so that a complete solution is supposed to be developed. Within scope of this study, the topic is studied from material science perception. Therefore, main attention was paid to failure mechanisms that are involved in wear process.

Among the literatures, there were not many, alomst no studies regarding mechanisms of how wearing occurs in the operation of coarse ore handling through transfer chute. Wear mechanisms are often studied in softwares whose fundamental concepts lie on DEM (discrete Element anaylsis). Due to incapability of buying a licensed software such as „Wear“, analytical calculations were made by hand and followed reference from work of „Experimental Research on the Determination of Coefficient of Sliding Wear under Iron Ore Handling Conditions“ by G. CHen, Y. Liu, G. Lodewijks, D.L. Schott. Number of powerful assuptions were taken in order to make calculation feasible by hand.

By the company, two pieces of worn liner samples (Hardox 500) shown in figure 60,61 came with a bag of caorse ore. For comparing purpose, a same purposed liner piece (110Г13Л) was requested from Erdenet mine LLC. Erdenet mine produces its liner by casting. All the procedure, from smelting, alloying to casting is performed in its maintenance department. The requested piece was provided and is shown in figure 62.

Figure 60: A worn side wall liner made of Hardox 500

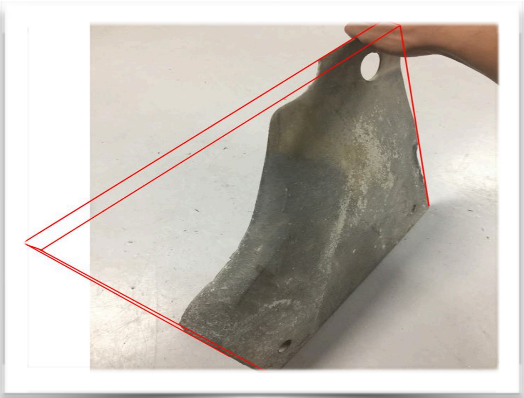


Figure 61: A worn skirt liner made of Hardox 500

Figure 62: Erdenet liner

After numerous literature review was made, and an analysis on the case was made. By visual inspection, it was understood that wearing occurs majorly by abrasion type. In such type of wearing, rubbing of liners with rocks cause volume loss. Volume loss estimation, according to literature [S8] (G. Chen et al.), is linearly proportional to applied force, rubbed distance, and inversely proportional to hardness.

$W_v = \frac{k}{H} * F * L$, Archard's equation

,where W_V - volume loss, k - coefficiet, F - Applied force, L - rubbed distance

By common sense, the formula makes a lot of sense because harder the material lower the volume loss. And if applied force or rubbed distance is greater, then it follows higher wearing. Time derivative of the formula would yield to wearing rate.

$$\frac{dW_v}{dt} = \frac{d(\frac{k}{H} * F * L)}{dt} = \frac{dk}{dt} * \frac{1}{H} * F * L +$$

$$k * \frac{d(\frac{1}{H})}{dt} * F * L + \frac{k}{H} * \frac{dF}{dt} * L + \frac{k}{H} * F * \frac{dL}{dt}$$

$$= \frac{k}{H} * F * \frac{dL}{dt} = \frac{k}{H} * F * S$$

,where S - speed.

To simplify the complexity of derivation, some assumptions and approximation can be made. indeed, every term is time dependent except for, probably, the coefficient. During a period of wearing process, applied force will most likely deviate as force is induced by impacts of rocks. The same is true for hardness; perfectly homogenous hardness over the volume is impossible, there must be a hardness deviation as a new surface gets generated. However they can be set to constant over the period, so time derivative of them merges to zero. This makes wearing rate dependent upon time derivative of distance which is speed.

$$\frac{dW_v}{dt} = \frac{k}{H} * F * S$$

To conclude, wearing rate is dependent upon how fast a particle is sliding on the study material which in this case Hardox 500 liner. The concept is also mentioned in a [S14], meaning that the simplification makes sense.

To study wear and wear rate, the referenced formula was applied for Hardox 500, but not for 110Г13Л steel. This is due to lack of knowledge of conditions under which the 110Г13Л steeled liner works.

All the efforts are dedicated for calculating wear rate. Wear rate defining is crucial because, then, a reliable prediction can be made on replacing a liner. Reliability level of prediction is dependent upon truthness of collected data.

At Darkhan Tumurlug, the Hardox 500 worn liner and 110Г13Л steel are examined. Eximanitaions were hardness test, chemical composition test, and microscopic image analysis.

The given coarse ore is examined for size distribution. However, amount of the sample rock was not sufficient enough for a relaible size distribution to be estimated.

Hypothesis and Research questions

Hardox steels are well appreciated by their mechanical properties. The steels hold excellent mechanical properties at extreme conditions, i.g. highly abrasive and/or corrosive environment, cold and hot temperature etc,. On top of these mechanics, the steels are workshop-friendly meaning that they can be formed by means of conventional forming machines such as: bending, cutting machines. Hardox steels are low alloyed steels having much less amount of carbon than its contemperary steels. This fact makes welding possible for this highly durable steel. Table # summarizes chemisty of Hardox steels supplied from its proudcer. To compare its chemistry, chemistry of steel 110Г10Л is shown in table 5. Hardox 500 chemistry is compared against chemisty of 110Г10Л steel in figure 63 (element contents at their Maximum value).

It has been said by producers that Hardox 500 retains hardness of 500 with deviation amplitude of 30 consistently under 250 temperature [R24]. Brinell hardness of 500 is near to extreme; the hardest in market is 600 HBW. While being excellent hard, the steel is concurrently bendable. In practice, dump trucks armor themselves by Hardox steels, an example is shown in Figure 64.

Figure 63: Hardox steels, compared in chemistry

HARDOX Mark	Thickness, mm	C% Max	Si% Max	Mn% Max	P% Max	S% Max	Cr% Max	Ni% Max	Mo% Max	B% Max	CET (CEV)
400	80-130	0.32	0.7	1.6	0.025	0.01	1.4	1.5	0.6	0.004	0.5 (0.76)
450	80-130	0.26	0.7	1.6	0.025	0.01	1.4	1.5	0.6	0.005	0.41 (0.67)
500	40-103	0.3	0.7	1.6	0.02	0.01	1.5	1.5	0.6	0.005	0.47 (0.75)
550	8-65	0.37	0.5	1.3	0.02	0.01	1.4	1.4	0.6	0.004	0.51 (0.76)
600	25-51	0.47	0.7	1	0.015	0.01	1.2	2.5	0.7	0.005	0.61 (0.87)

Figure 64: A truck armored with Hardox steel

Facts that high harndess and bendability are contrasting in some sense, because hardness itself is ability to resist deformation whereas bending is deformation. This contradiction origins a hypothesis that the Hardox material is inner soft but outer hard. Soft core having covered by a hard layer could make bending possible while being hard at surface.

Hypothesis 1: Hardox material is martensite-bainitic structured steel containing various alloying elements. The microstructure is achieved by careful control of heat treatment as its producers state [R25]. Heat treatment is usually done over the whole volume. In the case of study, heat treatment is believed covering a swallow depth, leaving some material at core without metamorphism. In this scenario, material could exhibit different hardness values over its thickness. In other words, wearing rate may advance as volume loss exposes inside material out.

Table 5: Chemistry of 110Г10Л marked steel

Elements	Percent
C	1.5
Mn	1.5
Si	1
Ni	1
Cr	1

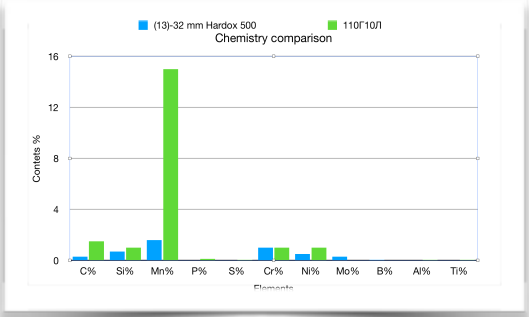
P	0.12
S	0.05
Al	0.05
Ti	0.05

Wear occurs through micro mechanical interactions (cutting, ploughing, breaking, fatigue etc.,). In any case, wearing rate is increased if its surface gets oxidized. Through the preparation of liner sample for hardness test, it was noticed that newly exposed surface, cut by sawing with water cooling, is forming a red layer of material, presumed oxides, rapidly. The cut samples having a red film are shown in figure 65. Metal oxides are mostly brittle, meaning that they are easily collapsible.

Figure 65: Red layer

Hypothesis 2: coarse ore that are being conveyed contains water #% by weight. Origin of the water is from primary crusher. # l/h of water is sprayed for purpose of extinguishing dust in the crusher. Sharp asperities of the coarse Rocks abrading the Hardox 500 create virgin surface of steel. Water content in the rock flow has potential to spread over the surface and oxidize it, making the surface to be brittle. Wearing rate might be getting accelerated by this surface alteration. the measured chemical composition analysis is graphically shown in figure 66.

Figure 66: Comparison of Hardox steel agaisnt 110Г10Л steel in chemistry



In the figure some element values cannot be seen because of their infitisemal amount.

The research is studying wear rate happening on Hardox 500 under given conditions from perspective of material science. The main question addresses to at what rate wearing occurs at the surface? How is hardness over the volume? What is chemistry of Hardox steels? The research questions certainly accentuate the hypothesises.

Study Plan

To answer the research question as much as possible, the following study plan was proposed and approved by superivsors Gunther Stehr and Ariunbolor Purvee.

1. Build a comprehensive knowledge of transfer chutes, and tribology by doing literature review.
2. Estimate the current wearing rate, apply the estimation for different steels, then compare.
3. Conduct hardness, chemical composition Tests, and microscopic image analysis.
4. Analyze the test, explain the wearing mechanism.
5. Draw a conclusion, then make (a) recommendation(s)

During the study, it has been known that determination of the coefficient (in Archard's equation) is of high importance, because it is unique from case to case. A prime advantage of accurately determining the volume loss rate is that later, the complete formula can be used for assessing other type of Liners such as Hardox 550, 600, and Alloy from Erdenet - 110Г10Л liner.

Data Analysis

Data collection and analysis

Throughout the study, various sources of information is used. The problem introduction was given by Oyu-Tolgoi mine. To study the case following knowledge were required:

What sized rock are bombarding? What contour do rocks form on conveyor belt at troughed and flattened section? geometry of the transfer chute? inclination, dimension and location of head pulley, rock parameters: density, angle of repose, water content, Poison ratio, shear stress and so on? And what is Hardox? Why are they hard? simply everything related to physics of the study was needed to be understood and found.

Data is accumulated collectively from the following sources:

Reports:

Visual insepction reports on transfer chutes made by Oyu-Tolgoi maintenance team were provided generously. From the reports, liner thicknesses, resulted after a certain period of time transfer operation, have been studied. Rock box locations, built-up pile were recognized. Also technial drawings of the transfer chute #CVB-003 gave all the required spatial sense.

Management supplying companies Rio Tinto, and Turqouise Hill resources publish quarterly reports on the progress and achievement of the project Oyu-Tolgoi. Their reports provided thorough understanding of current achievements, and where the company is in its development plan.

http://www.turquoisehill.com/s/Home.asp

A report done by SANDVIK, who is technical supporter of the project, on calculation of conveyor belt was found and provided by Oyu-Tolgoi maintenance team. From the report, contour of rocks on troughed and plattened sections of conveyor belt, and parameters of belt conveying operation were studied.

Experiments:

Size Distribution

To roughly estimate applied force on chute wall by pressure of flowing rocks, rock size distribution is needed to be studied. Its test was made in Processing Laboratory of German-Mongolian Institute for Resource, and Technology. Conventianal vibrating seiving machine, with sieves from 0.063 to 4 millimeter, was used. Majority of the given Sample was, apparently too big to be analysed by the sieving machine. Instead, the lump (specially used in this context) sizes varying from 5 mm to 100mm, were weighed individually. There were 55 lumps in total, plus debris sieved by the sieving machine. Associated pictures are shown in figure 67,68.

Figure 67: Sieved debris

Figure 68: Lumps

Given the size distribution, for calculation purpose, a mean particle diamter was needed to be derived. Fact that the given rocks account total mass of 6.70158 kg, of which 6.1095 kg is lumps, gives a hint to approximate mean particle diameter.

Assuming, in the simplest ideal case, particles are spherical, the mean diamter was estimated by the following calculation.

$$m_m = \frac{M}{N} = \frac{6701.58}{55} = 121.8gr$$

$$V = \frac{m_m}{\rho} = \frac{121.8}{2947380} = 0.00004132m^3$$

$$r = (\frac{3 * V}{4\pi})^{\frac{1}{3}} = 21.44mm$$

So, the given rocks are translated into uniform sized spheres of 21.44 mm diameter. For Illustration purpose, figure 69 is showing the translation.

Figure 69: Comparing ideal mean diameter with actual particles

Hardness test

The test was done at Darkhan Tumurlug laboratory under supervision of researcher and worker Tsend-Auysh.D.

From the skirt liner, a test Sample was made. Cut planes are shown in figure 70. Conventional electric cutter was used. And it was anticipated that over 250 Celcius, the liner material would not necessarily retain its promised properties. Thus, water cooled cutting was performed. Water is sprayed to cutting saw. The cutting is presumed under 250 celcius. Due to difficulties of selecting a sample from around center of the provided worn liner, it was cut from edge.

Figure 70: Sample preparation

It was hypothesized that hardness inside the liner might be less than that of outside. Therefore, lateral and planar hardness tests were conducted by using RSS-560 machine.

The measured hardnesses are shown in Table 6. The RSS-560 machine is capable of examining both Vicker and Brinell hardness at a time. The measured hardness values are double proofed by conventional Brinell hardness. The values agree with each other with a small difference.

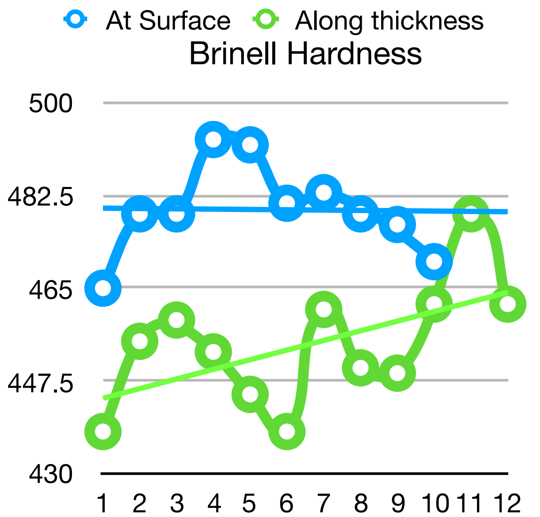
Table 6: Hardness of Hardox 500 (Brinell)

Point #	Hardness, at Surface	Hardness, along thickness
1	465	438
2	479	455
3	479	459
4	493	453
5	492	445

6	481	438
7	483	461
8	479	450
9	477	449
10	370	462
11	-	479
12	-	462

The measured values are illustratively shown in graph 4.

Graph 4: Hardness on Hardox



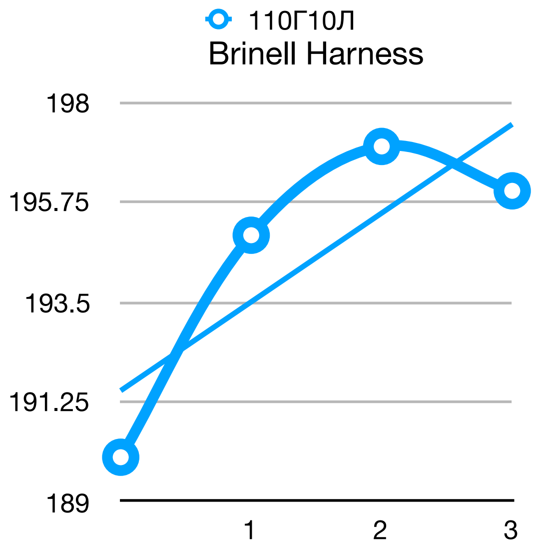
For comparison purpose, the same test was conducted on steel from Erdenet mine, but with small number. Measured results are tabulated in Table 7.

Table 7: Hardness of 110Г10Л steel (Brinell)

Point #	Hardness
1	190
2	195
3	197
4	196

The measured values are illustratively shown in graph 5.

Graph 5: Hardness on 110Г10Л



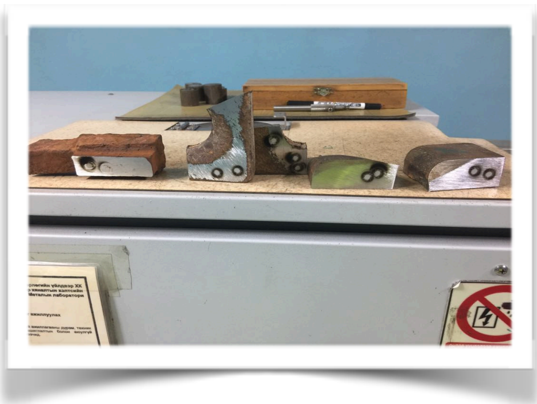
Hardness, by Brinell, values differ from the supplier Information for Hardox. Intended hardness value of 110Г10Л steel is unknown.

Hardness value really fluctuates as can been seen in from the test result.

Chemical composition analysis

The same research facility hosted chemical composition Analysis. The test was made by Optic Emission Spectrometer PDA-7000. The device has been being used since 2004, and still performing accurate, as was said. the test was done under supervision of Battulga.Ch - laborant. Figure 71 shows scars left by the emission spectrometer analysis.

Figure 71: Scars, from spectrometric analysis



The test was made on several hardox sample cut from different liners, and on 110Г10Л steel. The table 8 summarizes the chemical compisition anaylsis.

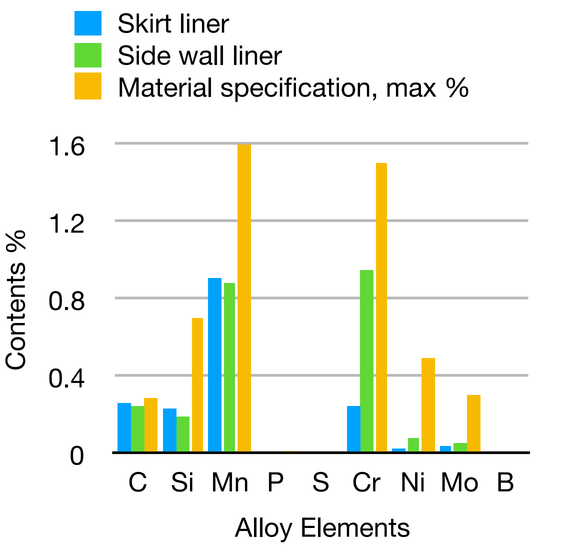
Table 8: summarization of chemical composition analysis

Elements	Side liner	Skirt	110Г10Л
C	0.248	0.2635	1.315
Si	0.198	0.228	0.0553
Mn	0.8835	0.9115	13
P	0.0065	0.008	0.046
S	0.00065	0.00075	0.025
Cr	0.9555	0.247	0.831
Ni	0.0775	0.0315	0.176
Mo	0.0605	0.036	0.089
B	0.004	0.004	
Ti	0.0145	0.0225	0.029
Pb	0.006	0.013	0.149
V	0.017	0.013	0.065
Al	0.043	0.0225	0.127
W	0.0125	0.0075	0.062
Sn	0.007	0.0095	0.013
Nb	0.0105	0.018	0.019
Cu	0.01195	0.0255	0.285

Measured Manganese content in 110Г10Л steel was outside the equipments reach; in it specification sheet it is mentioned that the steel contains Mn 11-15%. The Equipment does not recognize Boron. In Hardox specification sheet it is mentioned that Hardox steels, disregard to mark, contain B 0.004%.

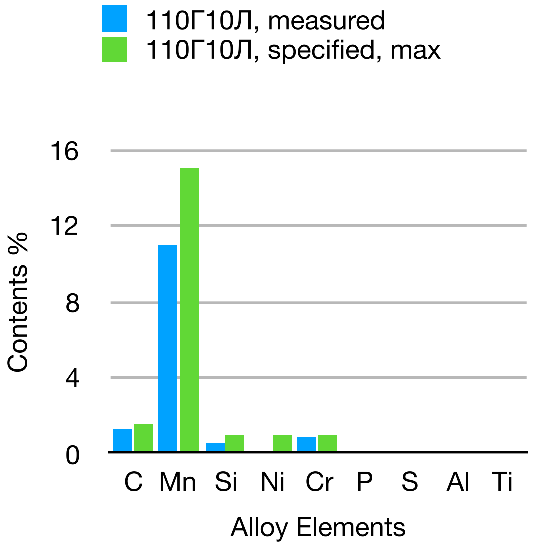
Graph 6 compares the measured values of each skirt and side wall liners against its indicated chemistry.

Graph 6: Composition comparison for Hardox



For Hardox steels, measured elements are always lower than its indicated values. Differences in content span from 6.25% for Carbon to 116% for Lead. The same intended comparison for 110Г10Л steel is shown in graph 7.

Graph 7: Measured vs indicated chemistry for 110Г10Л steel



From the chemical composition analysis of skirt and side wall liners, it has been noted that they have elements in different quantities, however they both are said made of Hardox 500 mark steel.

All the measured chemistries are compared in graph 8 for comparing purpose. Most of the elements were found richer in 110Г10Л steel except for Chromium.

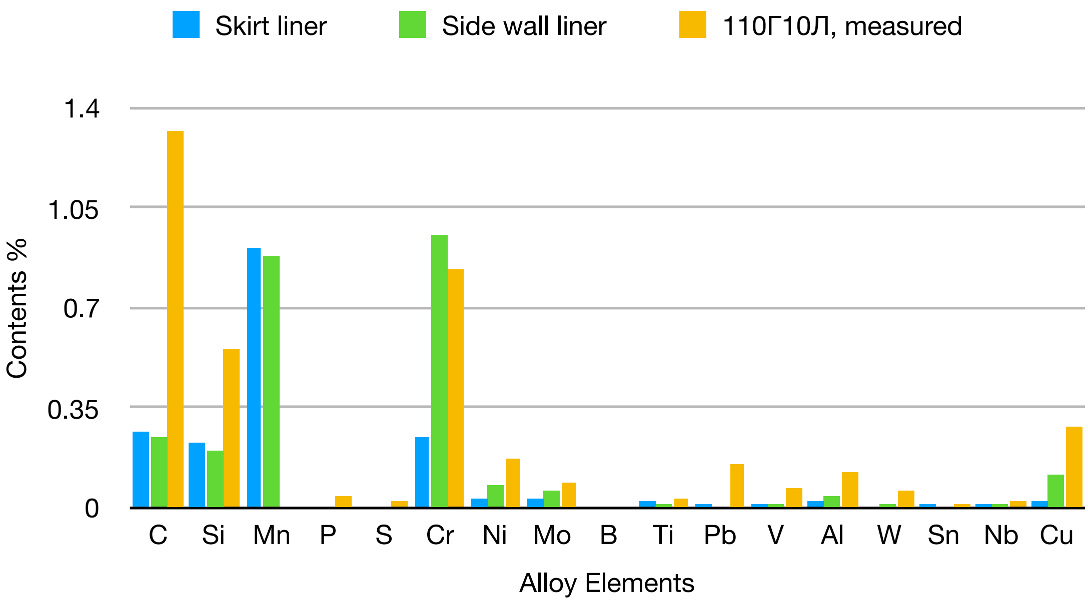
Graph 8: Comparison of measured chemistries

In the graph 8, Manganese content is not included due to its exceeding amount that is beyond the measuring limit of the equipment. Its value, as indicated, spans between 11 to 15%. This means that Manganese in 110Г10Л is around 14.5 times that of in Hardox 500 steel.

Every element is contained more in 110Г10Л steel than in Hardox, except for Copper and Chromium.

110Г10Л steel contains undersirable elements such as sulphur and phosporus at high value. The elements have negative influences on mechanical properties. All the favoring elements are contained much higher in 110Г10Л steel, yet the steel is much softer than Hardox as can been seen from hardness test results.

This fact brings attention to the microstructures of the steels.



Microscopic image analysis

From the cut sample for hardness test, before hardness test preparation was made, two thin pieces were cut. The pieces were first examined by microscopic analyze. But due to incapability of reaching desired magnification, the samples were provided for more stronger Optic microscopic analysis - ML1000 optic microscope. Moreover, the 110Г10Л steel also accomodated the test. Cutting processes were done by arc wire cutter with water cooling, explanatory picture is in figure 72. Images are taken from center and around circumference after they are embedded for polishing, etching. Figure 73 shows the hardox pieces embedded.

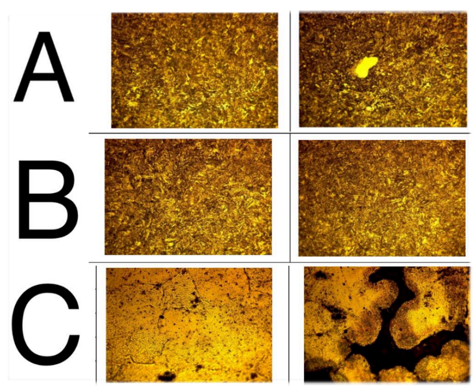
Figure 72: Arc wire cutting

Figure 73: Embedded hardox pieces

The test was hosted by Darkhan Tumurlug and conducted by J.Ulziibadrakh, a researcher at the company. The test procedure was in accordance with ISO 643-1983, ASTM E 112, ГОСТ 8233 standards.

The examination's results are reported, shown in figure 74 as compared.

Figure 74: Microscopic image results compared, a: hardox - longitudinal, b: hardox - cross sectional, c: 110Г10Л - random; left - around edge, right - at center



Result says that hardox steel microstructure consists of martensite structure and remained austenite structure from austenite to martensite transformation. The remained structure is estimated to be 10-15% by area.

Microscopic image analysis for 110Г10Л steel shows empty voids, colored black in the image. Without the test, this fact was expected from hardness test, and from cutting of the sample. During hardness test, spheric indentation dept was considerably deep. Cutting process passed a void in 110Г10Л steel, shown in figure 75.

Figure 75: 110Г10Л having void cut

The hardox steels are seen very dense comparing to 110Г10Л image. Dark color indicates void, or non-material in the pictures. Not much difference was observed between two Images of hardox steels, meaning there is homogenous microstucture over the volume. However, by long observation by naked eyes, it seems more darkish at the center. If that is the case, then emptiness around the center is higher than that of around surface.

Because of the fact that 110Г10Л steel contains much more voids, it is not as resistant as hardox steel in abrasion wear. While wearing erodes the steels from surface, empty voids will enhance the wearing process as it will take nothing for volume loss to advance.

In hardox image, fine grains are apparantly observable. This fineness in that material brings the promised mechanical properties. Because the material is compression of fine grains, wear takes place so slow than coarse grained steels. In context wearing, effort is made to deteriorate hardox steel grain by grain. A big goldish yellow spot is present which is believed to be austenite structure.

Hardox steels are stated to be of martensite-bainite structure. The test result partially disagrees with the statement. For both test samples, 10 to 15 percent austinite was found. Austenite, comparing to Bainite, is inferior. This fact can ascribe to higher wear rate.

In contrast, microscopic image of 110Г10Л steel does not necessarily show fine grains. Its grains are so big that volume loss can happen much bigger at a time. However the steel contains alloying elements much higher than Hardox steel, its microstructure shows quite coarse grains and voids. That facts attribute its inferior hardness.

The result for hardox steels does not support the hypothesis 1. The hypothesis was that wear rate advances as inner material gets exposed to wear - meaning that Hardox is soft inside and hard outside. The origin was from the materials behaviors that Hardox steels are easily foldable by common forming machines, concurrently so hard that is withstands high abrasion.

The formed red layer does not necessarily ascribe to oxidation. Chemical composition analysis shows that in both steels, there are many anti-corrosion elements. The formed red layer happened probably because of cutting with tape water cooling. The developed temperature might have enchanced formation of the red layer. Therefore, hypothesis 2 is not necessarily supported by the test results.

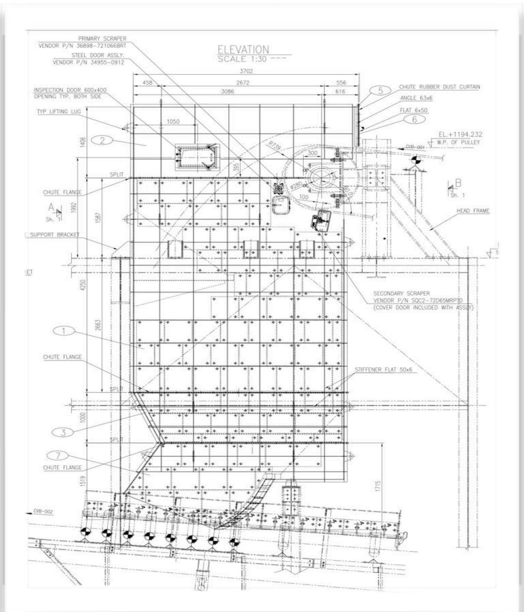
However the test results do not support the hypothesis, that does not necessarily mean the taken hypothesis are wrong.

Case analysis

After having processes in the coarse ore transportation are realized, and data is analyzid, the problem is well understood and converted into a new problem set.

Uniform sized particles, having diamter of 21.44 mm, are wearing Liners made of Hardox 500. Wearing occurs non-homogenously over the liners, having highest at bottom middle. 110000 tonnes of ore with bulk density of 1750 kg/m3 is flowing daily. And figure 76 showing the worn liners that are after operation of 2 months as its date refers. Belt is loaded 52.4 kg/m by material and running at speed of 3.78 m/s. Chute geometry is not changed as it is in its technical drawing shown in figure 77.

Figure 77: Technical drawing transfer chute, side view



Wearing coefficient, and wearing rate were calculated according to Archard equation, and its time derivative, respectively.

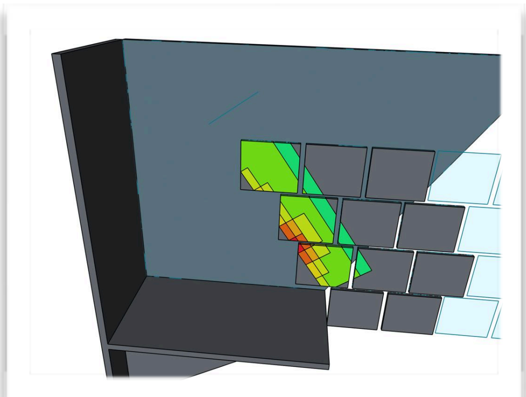
Quite many assumptions were made to simplify the complexity of the reality. Assumptions are A#-A# in the assumption topic.

Formula derivations for estimating applied force.
Figure 76: Worn liners

Liners wear higher at bottom center.

Wearing intensity decreases as it gets away from bottom center. For Illustration purpose, the wearing Pattern is shown in figure 78. In the figure, wearing rate is color-coded. Redish color indicates higher wear rate, whereas greenish color indicates lower wear rate.

Figure 78: Wearing pattern in side wall liners



The Illustration vaguely visualizes the actual wearing pattern. Dimensions are approximated from the Chute's technical drawings.

Volume loss is higher at botton center as shown in figure 78. This radial volume loss Gradiant is Motivation to guess forces that caused the loss. Dynamic is that there is the material flow that is impacting on the bed rock. When material pile becomes more than the pile can hold, they collapse. the flow Impact induces forces on Side walls. on top of that static Pressure of bed rock. That means deeper the particle in bed rock, and closer the particle to flow impact, the force is higher. This makes sense because, assuming material impact acts on a triangular area, the highest material impact induced force will be at bottom of the triangular.

The radial Gradient of wearing rate follows a conclusion that there is in-homogenious wearing rate over the rubbing area. Once the Most intense wearing Zone (red) reaches to its limit, a maintenance work is provided. Liners around the worn one get replaced too, however they have potential to shield more due to in-homogenious wearing. This brings Inefficiency to the Usage of those liners.

The figure 78 gives motivation to approximate volume loss. The picture is from visial report in Oyu-Tolgoi on 4th of May, 2018. The shown liners are installed on 24th of February, 2018. And it has been reported that the chute run for 1463 Hours in total. In table 9, thickness left from the operation is summarized.

Table 9: Remained thickness

#	RHS	Life, days	LHS	Life, days
1	Max 49	1525	Max 48	762.5
2	48	762.5	44	254.166
3	47	508.333	45	305
4	46	381.25	Min 42	190.625
5	42	190.625	46	381.25
6	45	305	47	508.333
7	43	217.857	43	217.857
8	44	254.166	45	305
9	45	305	46	381.25
10	46	381.25	45	305
11	Min 40	152.5	44	254.166
12	41	169.444	47	508.333
13	42	190.625	45	305
14	46	381.25	-	-

By average, at RHS

$\frac{76}{14} \approx 5.428mm$ thickness is lost, and at LHS

$$\frac{63}{13} \approx 4.846mm$$

From this, it can be concluded that the flow was more to the right (by 5.66%) as there is more volume loss at right side.

At RHS, Maximum loss is 10mm, Minimim is 1mm. This means that the maximum wearing rate, at extreme points, is 10 times the minimum. Whereas at LHS, Maximum loss 8mm and minimum 2mm, yeilding 4.

From operation Hours

$$\frac{1463}{24} \approx 61days$$

And from Installation and Inspection Dates

$4/May/2018 - 24/Feb/2018 = 68days$

It means

$$availibility = 61/68 \approx 89.7\%$$

The Liners are marked as „Plate mark 373: PL 25x450x450“. Its mass is 39.19kg. By knowing this, wear Rates can be actually calculated.

At RHS, Maximum wear rate is:

$$\frac{10*450*450mm^3}{61days} = 33196.72\frac{mm^3}{day} = 0.257\frac{kg}{day}$$

At LHS:

$$\frac{8*450*450mm^3}{61days} = 26557.37\frac{mm^3}{day} = 0.206\frac{kg}{day}$$

At this wearing rate, the liner can last

$\frac{39.19}{0.257}days = 152.5days$ at RHS

$\frac{39.19}{0.206}days = 190.6days$ at LHS

To be completely worn out. In table #, life time of each liner is attached.

If a maintenance were to be provided, because the Most worn Liners are considered disquilified, Liners that are in lower layer will definitely be replaced.

Colored in Green in table # will be ones to be replaced.

That means the liners are being replaced at their

$$\frac{254.12-61}{254.12} = 74.8\% \text{ life at RHS}$$

$$\frac{381.25-61}{381.25} = 84\% \text{ life at LHS}$$

If threshold to replace the Liners is Set to at

$\frac{152.5-61}{152.2} = 60\%$, it means just for the named liners, 14.8% and 24% Potentials are wasted. These wastes are only for the 2 named liners. From the table #, it can been Seen that total of 27 Liners are replaced at the first rock box.

Liner life wastes was estimated as 512% when replacement threshold is Set to at 20%. 512% can be perceived as 5 new Liners are being wasted due to in-homogeniuty wear rate. So different wearing rate brings Inefficiency in use of liners.

In the literature, Archard's equation is derived for Single particle.

$$W_v = \frac{k}{H} * F * L$$

W_v, H are known, and F, L can be analytically found, then experimently proven.

The formula explains that volume loss is resverly related with hardness. Harder the liner, lesser the volume loss. Applied force and rubbed distance will not change substantially. And current wearing is resulted from usage of Hardox 500 which has Brinell hardness 500. So if the usage gets completely replaced by hardox 550, the wearing rates decrease by 10% according to the formula. However, in one of the supplier's brochures, it has been stated that improvement in life is 60%. the respective life time will also increased by the respective percent as the relation between volume loss and hardness is in order of one.

This means in practice, the shown volume losses which happened in 61 days will occur in 67.7 days for 10% improvement, and 152.5 days for 60% improvement. Since life days will also be extended, 512% of waste is still valid. Here, only service is increased.

The story will be a lot changed when the usage combines hardox 500 with hardox 550. Higher hardness for area where wearing is higher. Its purpose is to harmonize the wearing rates, so at the end homogenious wear would result. The service time estimation was made on this scenario. Table 10 shows the scenario as applied.

Table 10: Combined use of Hardox 500 and 550

Combination	Days until threshold	Maximum wearing, gr/day	Liners waste, %
current	122	0.257	512
10% improved	135.5	0.2312	487.1
60% improved	244	12.84	364

When chute is lined with combination of Hardox 500 and 550, its maintenance period, and waste is improved by 11%, 4.86% for 10% slower wearing and 100% , 28.9% for 60% slower wearing, respectively.

Results and discussion

Graph 1,2,3 were created on some assumptions and delimitations.

The followings have beed assumed:

- When the first liner reaches 20% of its thckness by wearing, all the liners are expected to be replaced by new ones
- The visual inspection report results were main references: the measured volume losses occured in 61 days of opretion, from which wearing rate is calculated for each liner, and is believed to be constant. Life of each liner is estimated based on the calculated wearing rates.
- Duration of 61 days is assumed to be length of chute service time, however the report mentioned that wearings over 61 days were minor.
- It is also assumed that every chute shutdown involves 4 workers for 12 hours a day. Shutdowns last for 2 days.

Delimitations

- Charts and estimations are made for only one side wall. Right wall of the first rock box, where 14 liners were highlighted. And there are similar 3 more walls, plus skirts only in the chute under attention. This implies that the estimation does not cover all chutes.
- System restart frequency considered only one chute. This may make the frequency seem too small.

Hardox steels are found having lesser hardness than it is specified. However calculations were relied on value from the specification. This is due to a chance of inaccurate hardness measurement. Having the liner hardnesses varied, particularly decreased over thickness from the work surface means wearing rate becomes higher as old surface gets removed. Only one line of hardness measurements on planar and lateral sides were done. Therefore, for further studies, multiple lines of hardness tests are recommended. On top of that, sample preparation method, as mentioned in literature, should not create temperature over 250C. Cutting, polishing works should be done under cooled condition. Grinding in the test was made by abrasive sand paper which were creating shooting particles. The continuously running sand paper is shown in figure 79. The procedure was accordance to the laboratory's regulation.

Figure 79: Spinning sand paper

The attempted method, mentioned only in abstract, was not finished due to absence of possibilities of on-site investigations and access to softwares. The method is based on logical derivation. An iterative evolution is the key for its reliability. The method applies Archard's equation, of which each parameter can be studied individually. Discrete element modeling is what has potential to check the method's reliability. For determining of, for example, applied force, very complete and comprehensive knowledge was required which is achievable through many complex experiments and simulations. With the given reality, it was not feasible to determine.

In the chemical analyses, it has been noted that both alloy contain number of corrosion resistant elements such as Ni, Mo, Cr, Al, Cu, Si, Ti. Both steel are corrosion resistant, especially the hardox 500 mark. It is a guess that the observed red layer came because cutting process used conventional cutter with tape-water cooling. The water, as it is not pure, may have potential to oxidize heated and newly formed surface.

On the provided rock sample, a size distribution analysis has been conducted. The analysis covered only a fraction of the sample that is not too bulky. This ascribes to the fact that maximum sieving plate is the way smaller than most of the big particles. Major fraction is lumps. Even with bigger sieved plates that is capable of analysing the whole sample, the provided sample was not enough for a reliable material size representation to be concluded.

Comparison between usage of Hardox steels are made on data found from many sources. Validity of some data is questionable. By knowing this, the main aim of the study was to roughly estimate liner's service life. More accurate data, rather than approximations or average values is recommended for further researches, or for evolution for this study. The provided liner samples' locations in the chute were uncertain.

Experimental procedure & setup

Sieving analysis

Sieving analysis was conducted at processing laboratory of GMIT, borrowing its sieve analyse machine, shown in figure 80. Bigger particles (named lumps) are selectively separated from the sample simply due to their apperent big sizes. The remaining grits are sieved and then weighed. Later it was realised that the lumps were holding dusts covering their concave surfaces. This fact implies that the test result is not necessarily reliable. The intention of the test was to gain an impression of sizes of rocks flowing through transfer chutes.

Figure 80: Vibrating sieve

The equipment was set to a configuration where L 5, H 45, F 50, C 1.

55 lumps were weighed individually, the biggest lump has linear dimensions of 10.7mm, 7.1mm, 4.6mm, shown in figure 81.

For weighing the fractions, an electron weigher is used. Some error must be present because some particles were stuck at the sieve holes. This means that the measured weighs are smaller than the actual.

Figure 81: Largest rock

Microscopic analysis

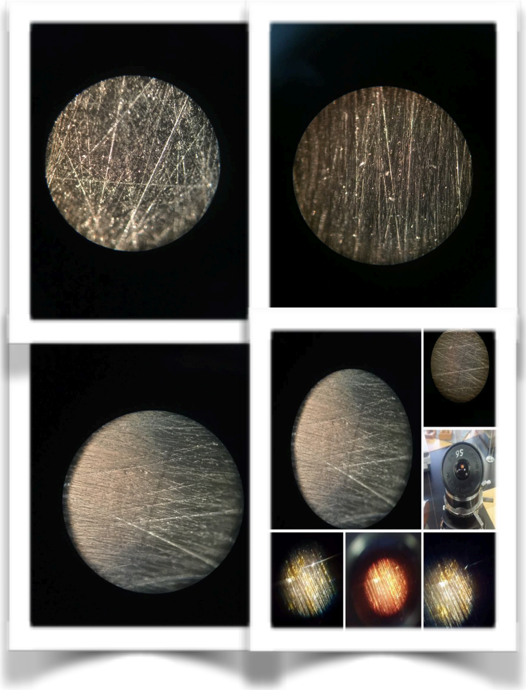
The provided liner Sample was cut, and a thin piece was prepared for microscopic picturing. Conventional electric cutting was done with tape water cooling. The cutting action was producing flying flashes while being cooled by water spray. Heat developed may created temperature over 250C. The cut pieces were then polished by conventional sand papers which made for woods. Polishing grits were of sizes AA120, AA240, AA320, AA400, AA600, and metal pieces passed the sand papers from the coarsest to finest progressively.

Sample was cut in way that it allows its lateral and planar sides are visible for microscopic watch, cut pieces are shown in figure 82.

Figure 82: Cut pieces

The prepared samples were seen by microscope, results are grouped and shown in figure 83. The intended microscopic image was not achievable. Its reason is believed to be improper sample preparation. Also the microscope's capability of magnifying the image was not sufficient for micostructures to be observable. Therefore, microscopic analysis was conducted by stronger microscope.

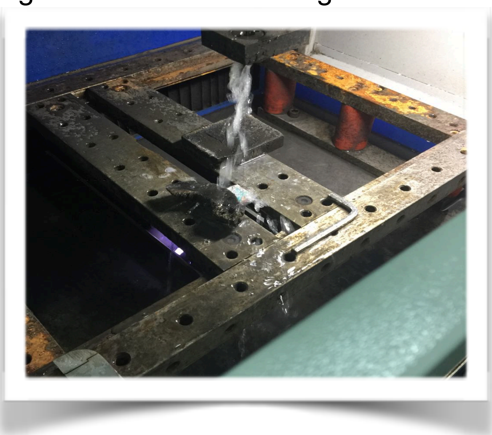
Figure 83: Images from first microscope



Electron microscopic analysis

The test was hosted by Darkhan Tumurlug's research laboratory. The previously prepared samples were used and cut by arc wire cutter with water cooling, shown in figure 84, to fit in embedding compressor.

Figure 84: Arc wire cutting



The same cutting was done for 110Г10Л steel from Erdenet mine. After each cutting, samples were embedded for further polishing and actual imaging.

All test procedures were in accordance with the laboratory's regulation.

Hardness test

The block from which samples for second microscopic analysis were made did undergo Brinell Hardness test. The piece was carefully prepared in a way that its sides are parallel. It is requirement for accurateness of test, the sample material to have parallel and planar edges.

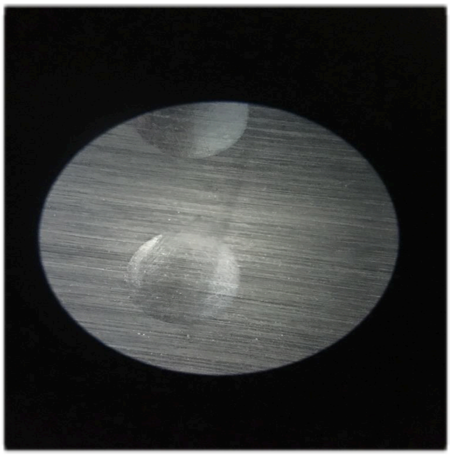
Before hardness examination, surfaces are cleand by grinding. Created heat may have resulted regional alteration in metal properties. Hardness test was performed when the subject was cooled down in air.

The hardness measuring equipment was electronic and automatic. It can evaluate Brinell hardness, and directly convert the result into Vicker's Hardness. So, two hardness values come out of each test. The equipment is shown in figure 85.

Figure 85: RSS-560

The Same test was conducted on 110Г10Л steel. Results were proven by Brinell hardness test performed by another machine. The demonstration measurement hired spherical indent, and used a table to read associated hardness values for given diameter of indentation. The indentation is shown in figure 86 through a microscope. 150 kN force was Applied for every measurement.

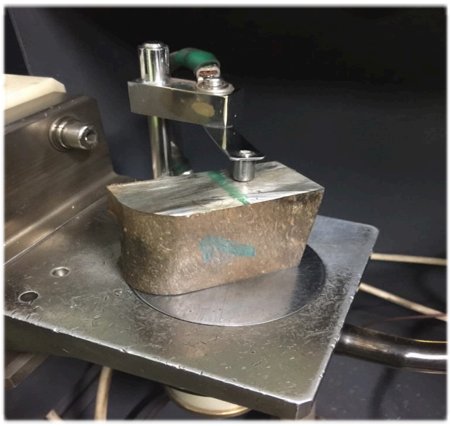
Figure 86: Spherical indentation



Chemical composition test

As it was the quickest among all other tests, multiple samples from Hardox steel were examined. In addition, of course, 110Г10Л steel was examined. Optic emission spectrometer PDA-7000 was used. Samples are grinded in the same way samples prepared for Hardness test. In this test, developed heat will not likely influence to test results much. Figure 87 Shows mounting of test subject onto measurement machine.

Figure 87: Mounting on spectrometer



For each sample, two measurements were performed and average values are taken for final result.

Conclusion and Suggestion

Conclusion

The steel Hardox 500 is tempered martensite steel. The liners are various in dimensions.

The study focused on wearing mechanism and its intensity. Their wearing rate, depending on location inside chute varies from 263.23 to 372.41gr/day. Wearing takes place in form of abrassion dominantly. Heterogenous wearing rate over liners causes inefficient use of liners because at shutdown, the most worn liner is replaced with lightly or medium worn liners.

Chemical analysis of the given samples indicated the measured composition is lower than it is specified. Many anti-corrosion alloy elements are included in composition. However, for further studies, temperature effect from both environment, and rock impact is proposed to be studied. Temperature effect can enhance corrosion which, in this study, is believed to be negligibly small. And dust extinguishing liquid at the pimary crusher is believed to be pure water bubbles. However, water without any additive cannot produce bubbles as required for the purpose. Thus, exact chemistry of the spraying liquid should be studied in detail on wear with temperature effects.

Hardnesses over the measured areas were showing lower values than it is specified. A hardness gradient is observed, increasing toward the work surface. According Archard's equation, and by common logic, softer material will wear out faster. However this was not supported by microscopic image analysis much. According to hardness test result and Archard's equation, the wear rate increases over ore transportation duration. High hardness and high toughness was the main motivation to extend the study reach to this point.

A solution emphasizes combined use of Hardox steels. It is idealized that Hardox 550 steel replaced liners where wearing rates are higher among them. Corresponding estimations made and the combined use could, at the Most optimistic scenario, increases chute service time by 100%, decreases liner deficiency by 28.9%.

The aim of study was analytically define wearing rate. A method was attempted to be developed. However due to lack of scientifically proven methods and knowledge, and required data, the development was not finished. Therefore, it was not explained at all.

Suggestion

According to the producers of Hardox steels, there is a small price difference between Hardox 500 steel and Hardox 550 steel which can be easily compensated by elongated machine life. The substitution, indeed, benefits industries and companies.

It does not make sense to study hardox steels of Hardox brand that are softer than 500 HBW.

Three possible ways are there to introduce Hardox 550 in the transportation. One is to fully replace, the other is to partially replace where wearing intensity is higher, the last is to have the same life of Transfer chute with thinner liners. The fundamental goal is to bring to extremes of wearing rate closer to solve the problem. By consequence of doing that, chute service life time will be elongated, and efficiency in liner usages will increase.

Complete replacement substantially increases chute service time, however heterogenouty is kept. It must cost more than partial replacement by logic. In contrast, partial replacement fulfills the two requirement. It increases chute service time and decreases Inefficiency. Table 11 compares the two scenarios.

Table 11: Partial and complete replacement comparison

	Service time	Liner inefficiency	Cost comparison
Current	122	512	Low
Complete replacement	305	512	High
Partial replacement	244	365	Medium

To decide for better option, the below formula is applied.

$$cost \approx \frac{service - time}{year - time} * inefficiency$$

433 for complete, 247 for partial replacement. Thus, partial replacement is suggested as a final conclusion of this study.

Furthermore, three more possbile wear reduction scenarios are proposed for further studies: Effects of dusts between liners and impacting rock, studded liner texture against abrasion wear, retired conveyor belt application in transfer chute for reducing wear.

The last possible option is to order Hardox 550 steels that are thinner than Hardox 500 liners. It is logical that thinner but harder material should age equal to thicker but soft material at a certain point. The service time of Hardox 500 liners having 25mm thickness can be realized by 19.4mm thick Hardox 550 liners. This can bring advantages without exacerbating the situations.

- Thickness reduced Hardox 550 liners will not cost as much as Hardox 550 Liners of 25mm thick. Its price may be cheaper than cost buying Hardox 500 liners of 25mm thick.
- 19.4mm thick liners are 33% lighter. This means 39.19kg of hardox 500 liner will age as good as 30.48hg of hardox 550 liner.
- Lighter liners benefit workers in shutdowns
- Over 5mm of thickness reduction will ensure more space for material stream, decreasing probability of plugging

To define optimum combined use of Hardox 500 and 550, on-site tests and observations are highly recommanded. Accurate knowledge of rock and liner parameters key to define the optimum combination.

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