IRD Spring Meeting - April 21st -24th

Scrap Diameter of a Profiled Roll, Why It is Important to Understand This

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Jiangsu Kaida Roll

About Kaida Roll

- Founded in 1951 46 years roll manufacturing experience
- Over 480 employees Company occupies: 10 hectares
- Designed annual production capacity: 50,000 tonnes, at present 40,000 tonnes
- Kaida Roll is the third largest roll manufacturer in China
- But is the largest in terms of section mill rolls produced in China.

Presentation structure

1. Introduction to long product roll failures

2. Low cycle high stress fatigue – how this determines the discard diameter

3. Conclusions

1. Introduction to long product roll failures

Rolls are by their nature undergo cyclic loading, where the selection of the material is down to optimising the following key properties :

Wear resistance - keep profile
Toughness - do not crack easily
Strength - Do not break
Hardness - Do not indent
Price - are affordable

However, often higher toughness is low hardness, higher strength is more expensive alloying / heat treatment.

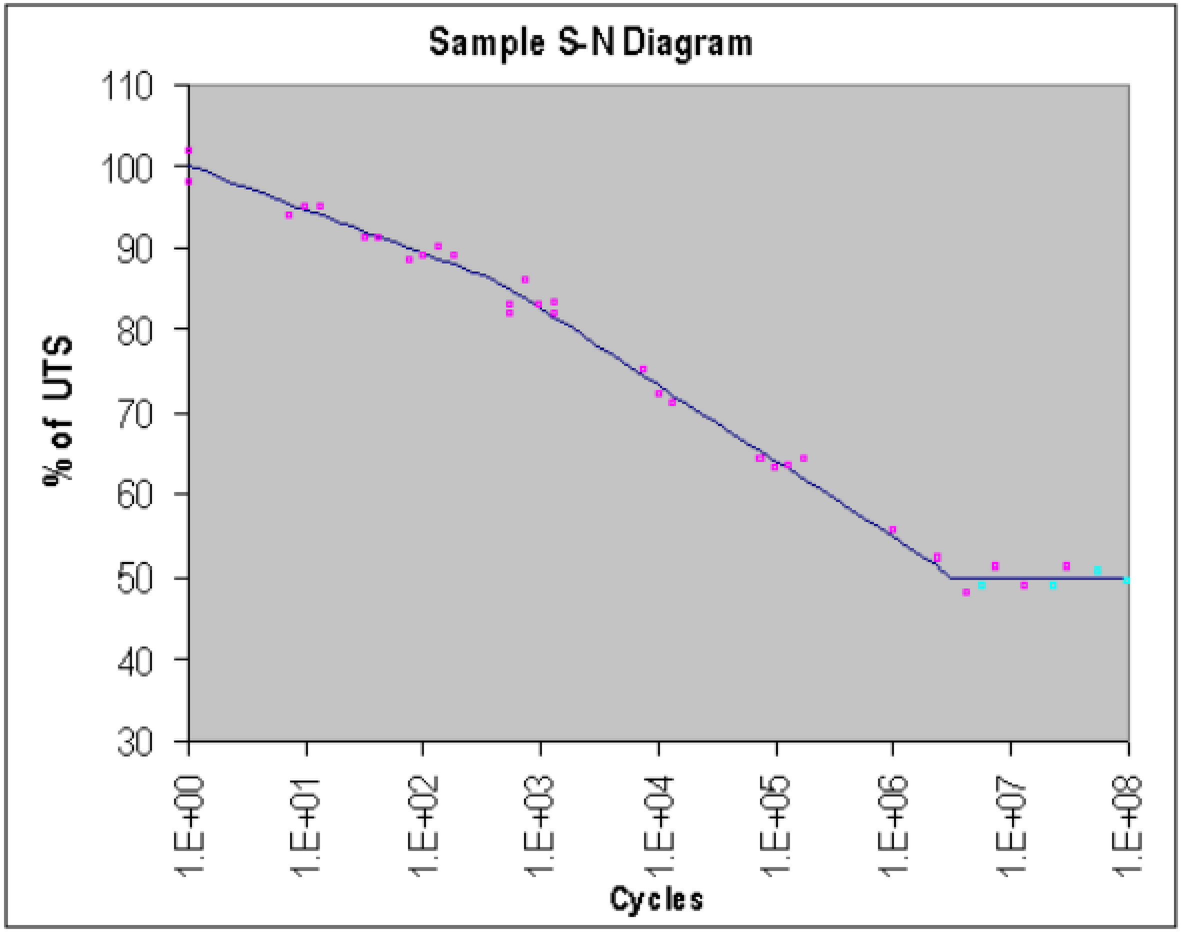
The aim is to select a roll grade that lasts the longest for the expense (value in use), won't break – within design usage.

Rolls are designed to work within their endurance limit – for crack initiation and crack growth.

Within the pass there are always thermal cracks – prevention of high stress, low cycle fatigue.

Roll design is used to avoid too deep passes and high rolling loads at the central passes of a two high roll.

Endurance limits for steels



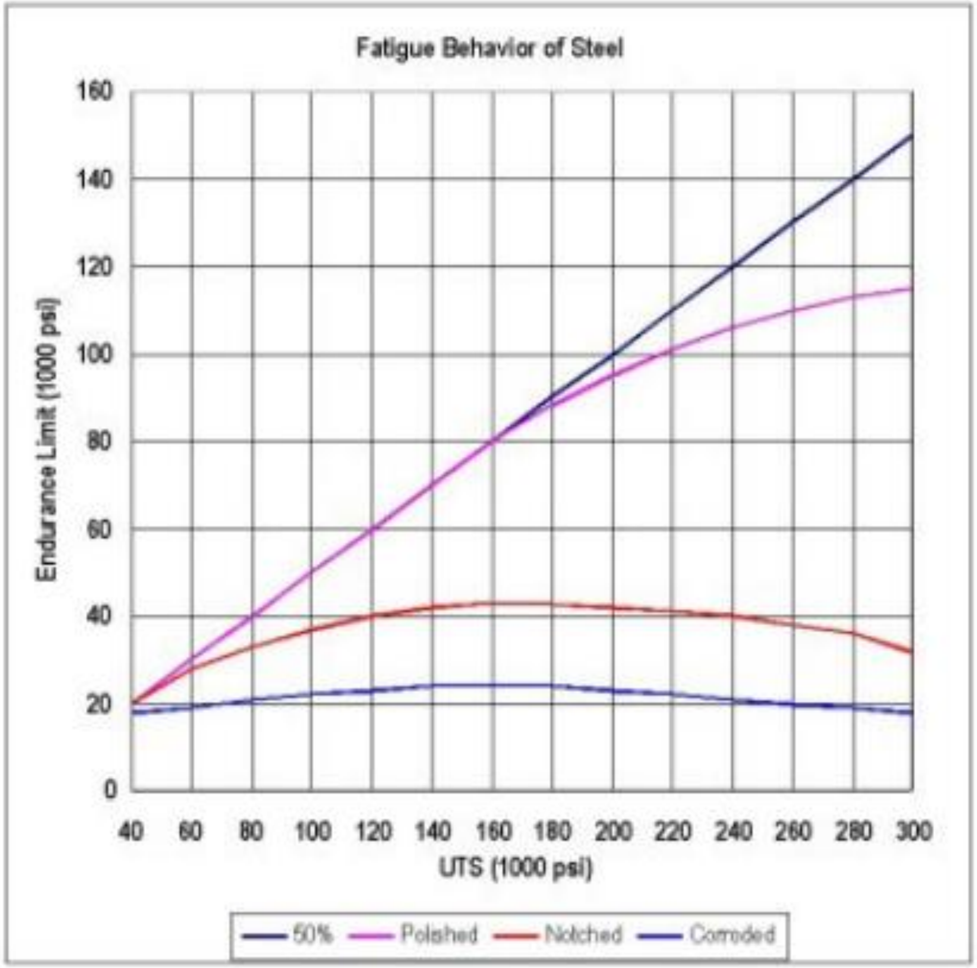
Here it appears that the endurance limit should be 50% of the UTS.

Approximate definitions are :-

low cycle fatigue < 10^4

High cycle fatigue > 10^4

There are other factors as well for a roll in service – Mainly for high cycle low stress fatigue



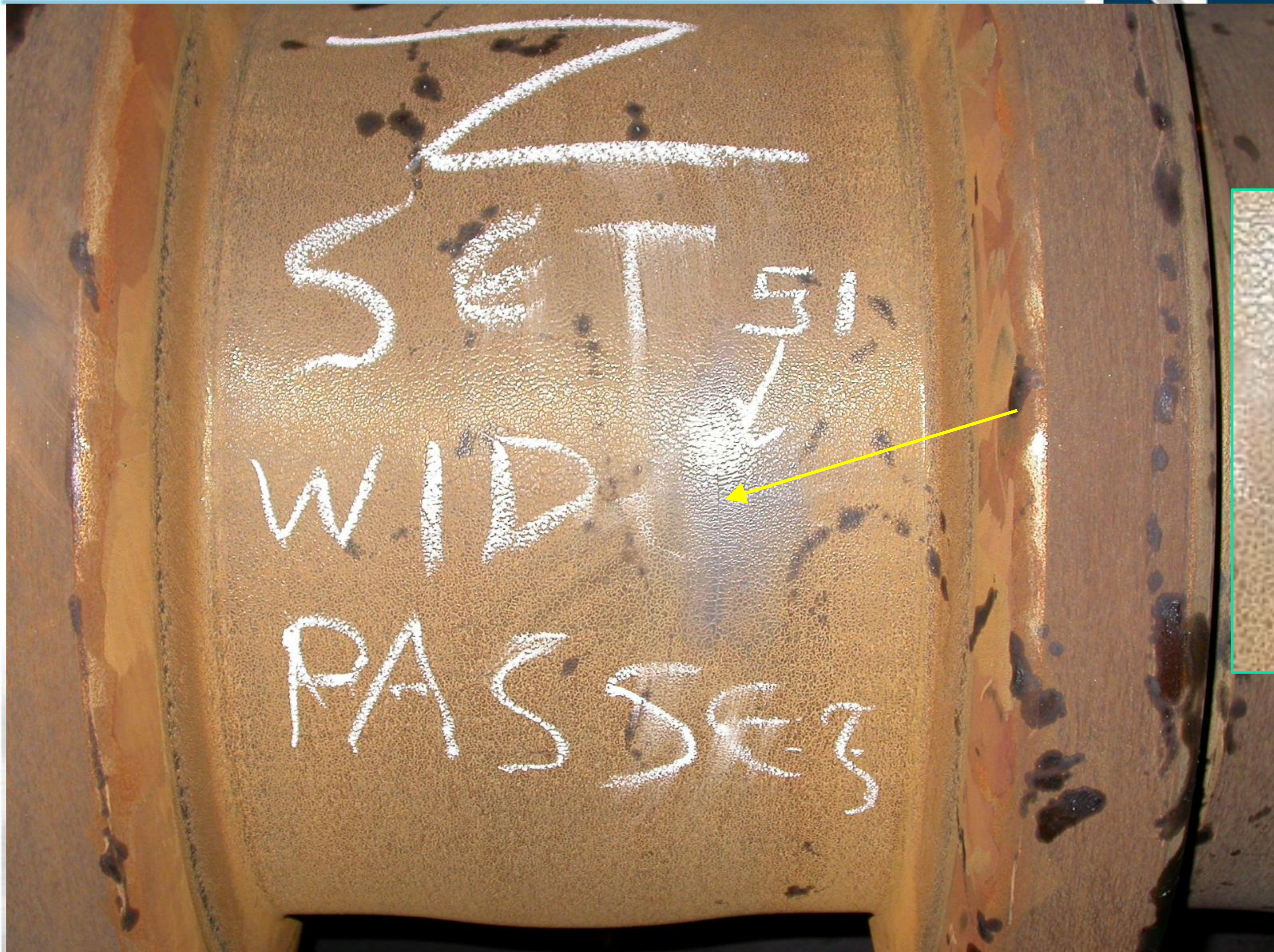
In addition, rolls are not polished surfaces – see this schematic from EPI Inc

1. Surface Condition (ka): such as: polished, ground, machined, as-forged, corroded, etc. Surface is perhaps the most important influence on fatigue life;
2. Size (kb): This factor accounts for changes which occur when the actual size of the part or the cross-section differs from that of the test specimens;
3. Load (kc): This factor accounts for differences in loading (bending, axial, torsional) between the actual part and the test specimens;
4. Temperature (kd): This factor accounts for reductions in fatigue life which occur when the operating temperature of the part differs from room temperature (the testing temperature);
5. Reliability (ke): This factor accounts for the scatter of test data. For example, an 8% standard deviation in the test data requires a ke value of 0.868 for 95% reliability, and 0.753 for 99.9% reliability.
6. Miscellaneous (kf): This factor accounts for reductions from all other effects, including residual stresses, corrosion, plating, metal spraying, fretting, and others

Real-World Allowable Cyclic Stress = ka * kb * kc * kd * ke * kf * EL

Box pass of roughing roll with 51mm deep stress crack

KAIDA ROLL



A roughing roll failure in a box pass showing a 50mm deep pre-crack (same roll type as previous roll)

At 750mm collar diameter, but crack = 50 mm depth, where discard calc = 690mm, however, with crack depth implies <650mm effective diameter. Note beach marks to 200mm depth, but these high stress low cycle fatigue.

2. Low cycle high stress fatigue – how this determines the discard diameter

Requirement is high enough fracture toughness **(K_1C),** which is is a Material's resistance to crack propagation :

$$K_{1c} = Y \times \sigma \times \sqrt{(\pi \times a)}$$

Where:

- K_1C is the fracture toughness,
- Y is a geometric factor,
- σ is the applied stress, and
- a is half the crack length.

The stress and geometric factors may be bending or tensile stress or both added together.

Relation between strength and toughness – product of microstructure

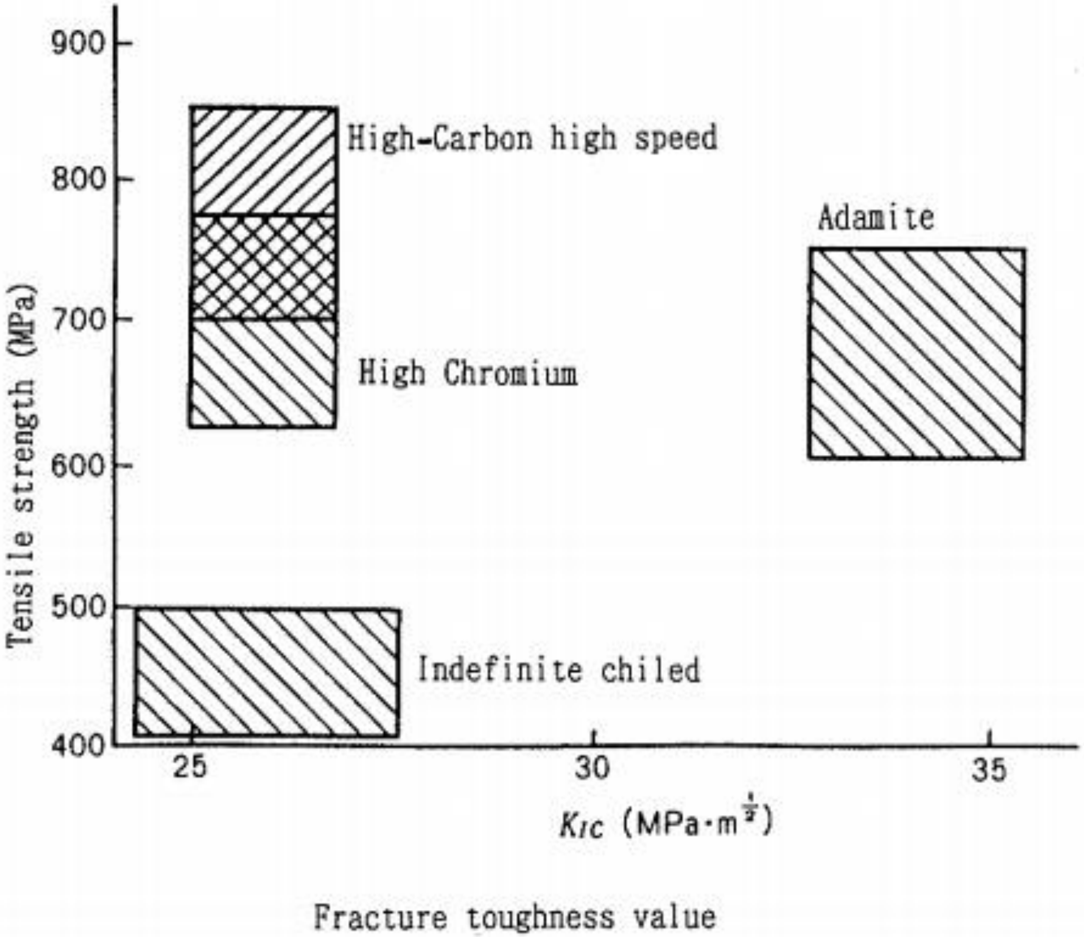
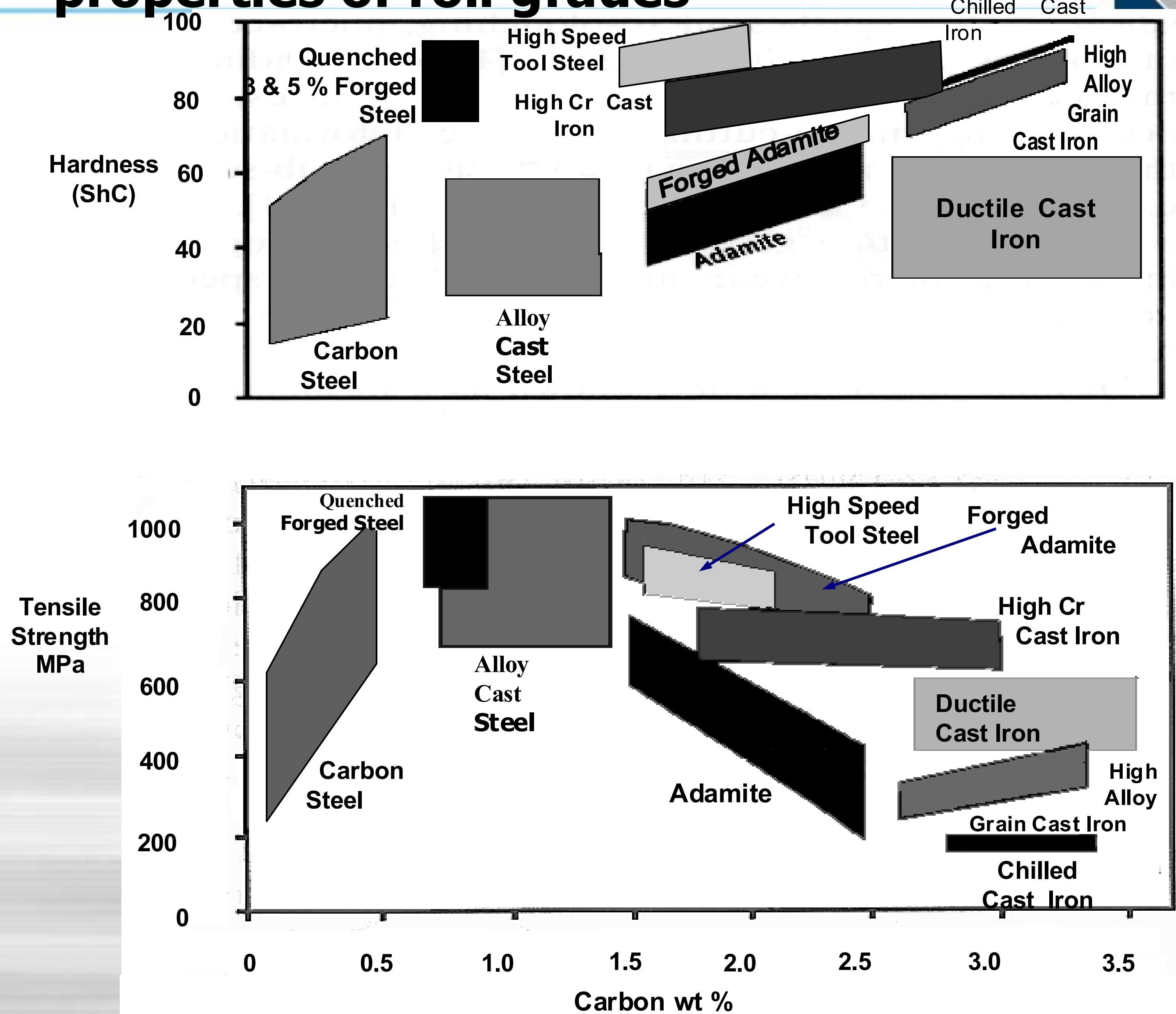


Fig. 6. Tensile strength and fracture toughness value of roll materials.

From : Y. SANO.T. HATTORl,and Mi. HAG, 'Characteristics of High-carbon High SpeedSteel Rolls tor Hot Strip Mill ', ISIJ International, Vol. 32 (1 992), No. 11, pp. 1194-1 201

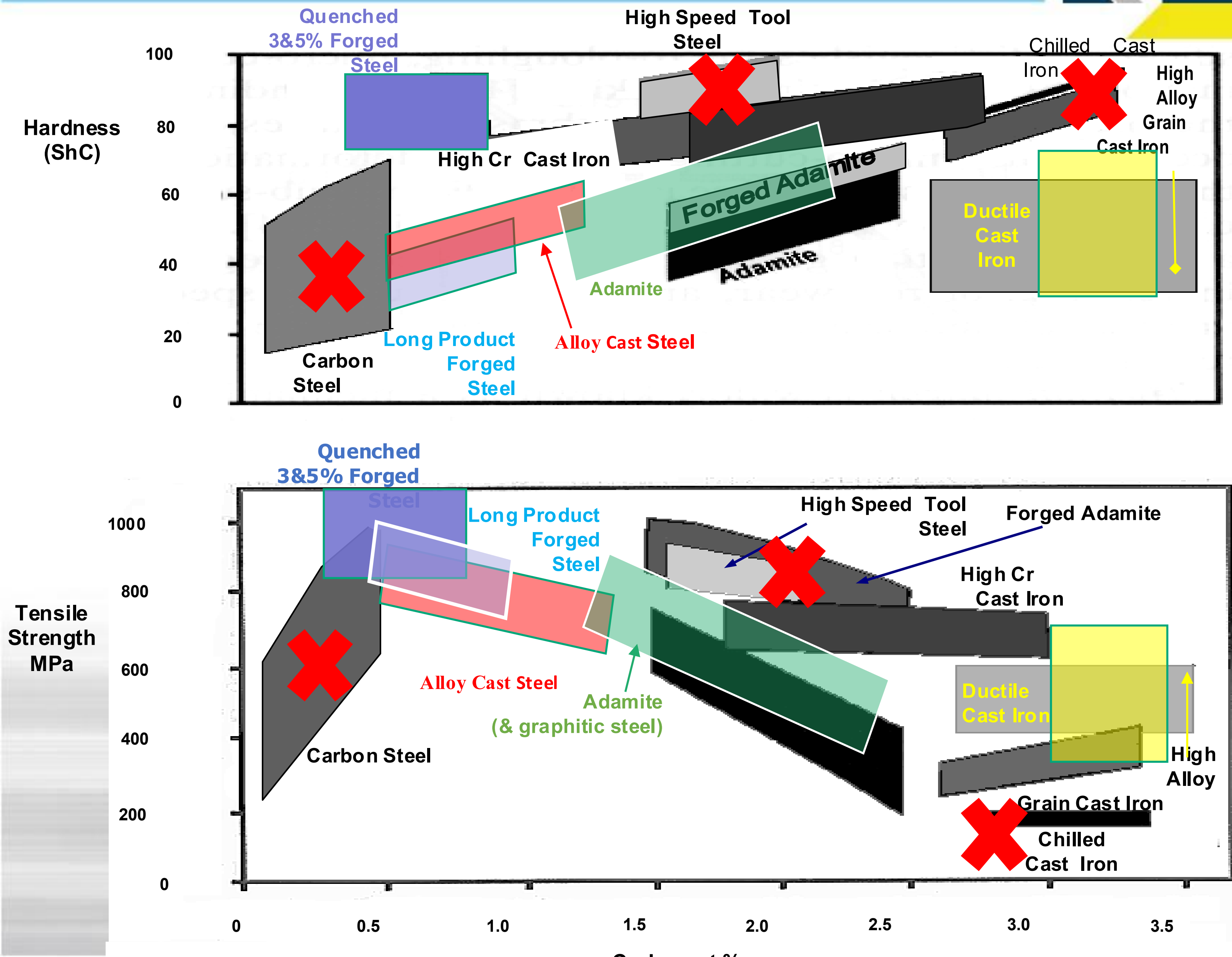
However, crack growth calculations for long product rolls very time consuming – too many parameters and surface condition may be poor.

General schematic of mechanical properties of roll grades

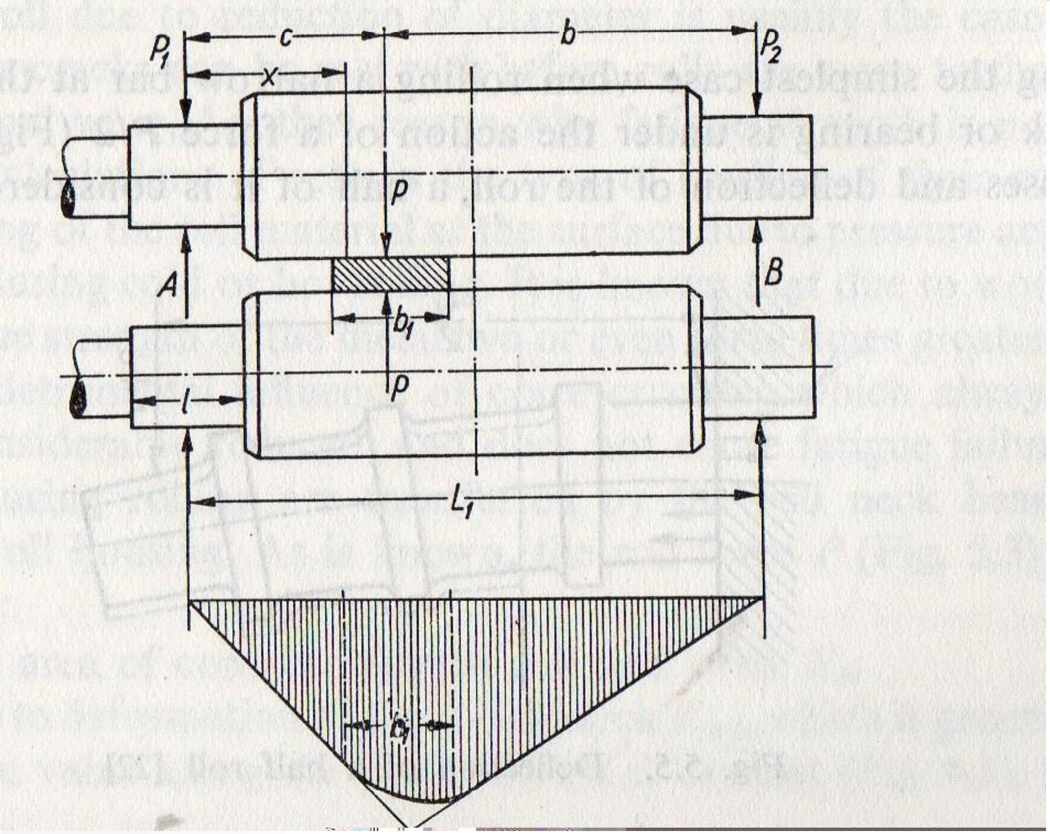


Original Figure from S Spuzic et al; Published in Journal WEAR Volume No 176 (1994) pp 261 - 271

Same schematic as previous but updated for modern long product rolls



Rolls and their permissible loading



There are several basic equations for the bending moment at any point of the barrel.
For this application $x \leq c - b_1/2$

A few of these equations are hereby stated:

$$M_b = \frac{P}{2} \cdot \frac{L_1}{2}$$

Maximum stress dependence on the moment and round cross-sectional bending modulus:

$$\sigma_b = \frac{M_b}{W_b}$$

Where moment of intertia $I = W_b = \frac{\pi D^4}{64}$

and $M_b = B(L_1 - x) = Pc/L_1 \, (L_1 - x)$

The roll when grooved and not plain barrel has an increase in the bending moment due to the concentration of stresses depending on radii of curvature etc, so becomes
$M_b = 0.1 D^3 \sigma_b \alpha_b$

Where α_b takes into account stress concentrations and dependent on such factors, inter alia, D/d and r/d – radius at the smaller diameter, d for long products where there are multiple grooves or passes.

Taken from Z. Wusatowski, 'Fundamentals of Rolling', Pergammon Press, 1969, p396

Equations of moments of inertia

This becomes for point b_1

$$\sigma_b = \frac{M_b}{0.1\mathrm{d}^3}$$

Torques are taken into account using the equation:

$$\tau = \frac{M_t R}{Moment\ of\ inertia\ of\ cross-section} \doteq \frac{M_t\, {}^{D}/_{2}}{0.1D^4} \doteq \frac{M_t}{0.2D^3}$$

If the roll is subject to simultaneous bending and torsional moments, then the equivalent moment used for strength calculations is for steel rolls:

$$M_b' = \sqrt{M_b^2 + \frac{3}{4}M_\tau^2}$$

Correspondingly the formulae for calculation of compound stresses under simultaneous action of bending and torsion are :

$$\sigma_b' = \sqrt{\sigma_b^2 + 3\tau^2}$$

The lever arm rule for the torque is taken as:

$$M_t \doteq P\frac{l_d}{2} \doteq 0.5P\sqrt{R \triangle h}$$

Equations for discards

$$\sigma_b' \sqrt{\sigma_b^2 + 3\tau^2} = \sqrt{\frac{100 M_b^2}{D^6} + \frac{3\,M_b^2}{0.04 D^6}}$$

Expanding

$$\sigma_b'^2 = \frac{100 P^2}{D^6} . \left[\frac{x(L_1 - c)}{L_1}\right]^2 + \frac{3}{4} . \frac{P^2 D \Delta h}{0.08 D^6}$$

Which when simplified leads to

$$D^6 = \left[\!\left[\left(10 P \frac{c}{L_1} (L_1 - x)\right)^2 + P^2 \frac{300}{32} D \Delta h \right]\!\right] \frac{1}{\sigma^2}$$

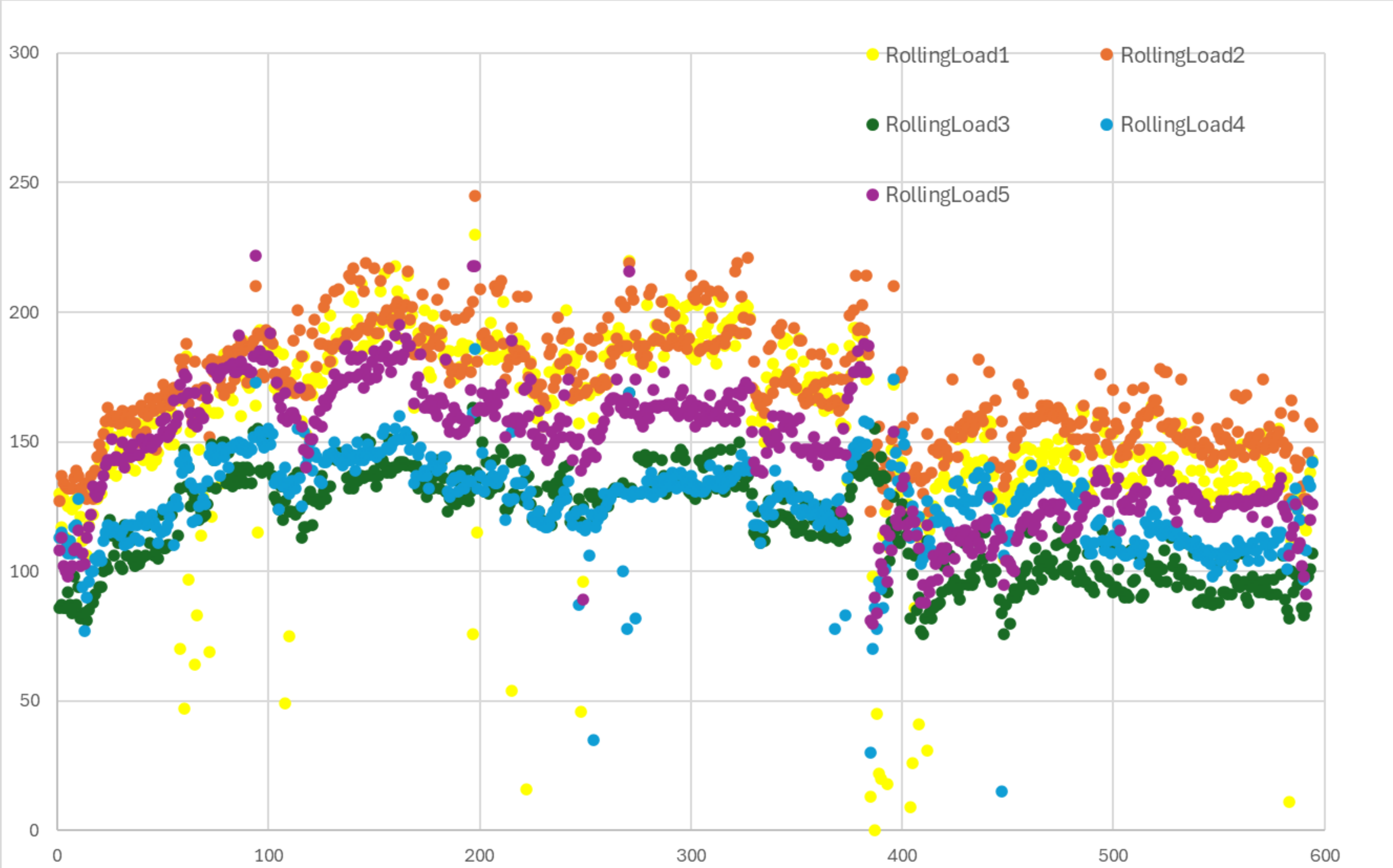
Solving for the discard diameter gives:

$$D_{min} = \left[\!\left[\left\{ \left\lfloor 10 \frac{c}{L_1} (L_1 - x) \right\rfloor^2 + \frac{300}{32} D \Delta h \right\} . \frac{P^2}{\sigma^2} \right]\!\right]^{1/6} + D_{st} - D_{Bpt}$$

In practise the second group is largely substituted by a semi-empirical factor, where for D the break point diameter is used and the factor 300.Δh/32 by 8.5mm. The result is an accuracy within 1 - 2mm.

Note the 6th root for this equation gives the result a reasonable accuracy even for 5 to 10% inaccuracy of any of the parameters.

Practical assessment of rolling loads



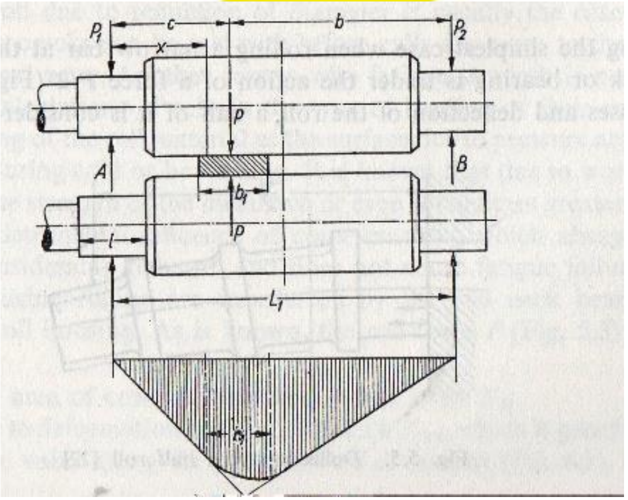
Load 1 ≈220t
Load 2 ≈230t
Load 3 ≈160t
Load 4 ≈170t
Load 5 ≈190t

(W set)

Example spreadsheet – Simplified W set

Four adjacent box passes 1- 4

ROLL IN	GROOVE	1	2	3	3
DISCARD IN	GROOVE	1T	2T	3T	4T
BARREL TO	MID-PASS	275	656	799	509
BARREL TO	BREAK PT.	376	699	829	524
LOAD	tonnes	245	222	288	176
CENTRES	(MAX)	800	800	800	800
DIAM. at B	POINT	605	620	660	583
Discards (mm)	FORGED	575	580	581	582
	CAST 0.9%C	585	590	592	591
	CAST 1.3%C	607	613	618	612
	Adamite 1.6%C	644	652	661	647
	ST. BASE	686	696	710	688

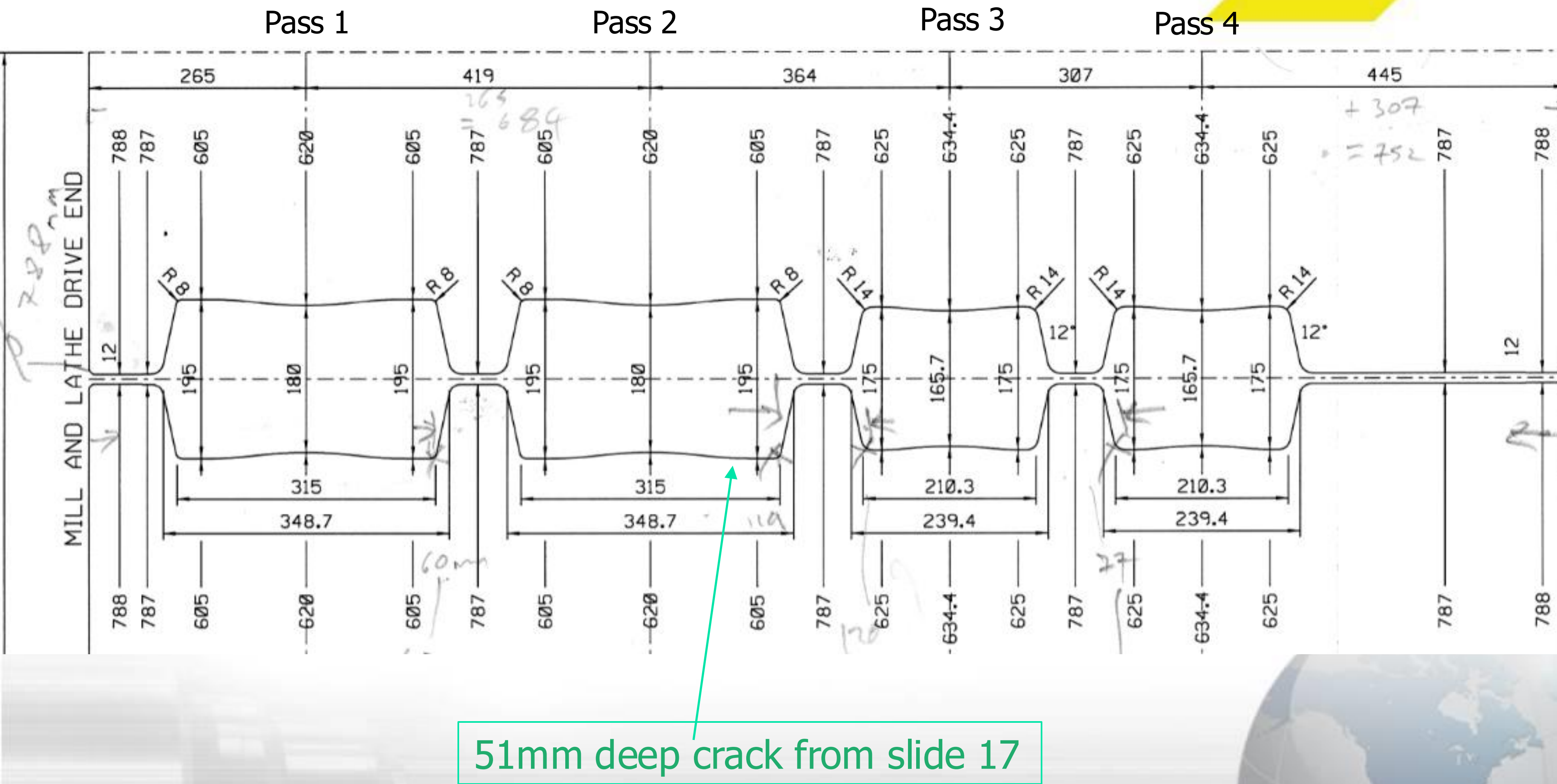


Note mill limit minimum = 690mm Rail roughing set

$$= \left[\left[\left\{\left[10\,\frac{c}{L_1}\,(L_1 - x)\right]^2 + 8.5.D\right\}.\frac{P^2}{\sigma^2}\right]\right]^{1/6} + D_{st} - D_{Bpt}$$

The above roughing roll – to show calculation methodology

Z set Rougher

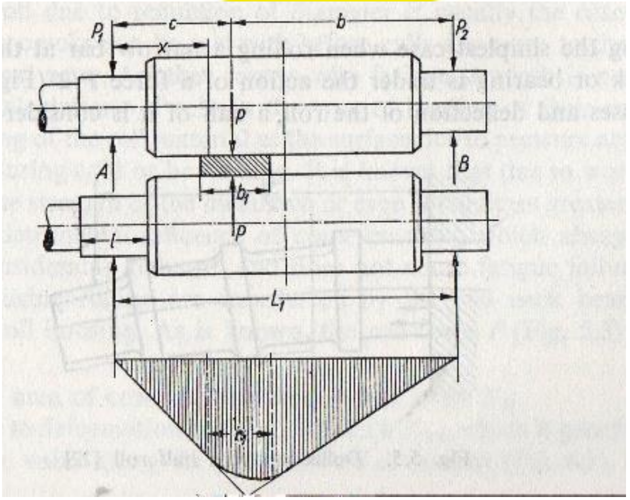


Example spreadsheet - Simplified

Four adjacent box passes 1- 4

Z set

ROLL IN	GROOVE	1	2	3	3
DISCARD IN	GROOVE	1T	2T	3T	4T
BARREL TO	MID-PASS	265	**684**	752	445
BARREL TO	BREAK PT.	463	**857**	864	554
LOAD	tonnes	440	**440**	250	250
CENTRES	(MAX)	800	**800**	800	800
DIAM. at B	POINT	605	**605**	625	625
Discards (mm)	FORGED	649	**684**	587	574
	CAST 0.9%C	673	**709**	609	595
	CAST 1.3%C	694	**733**	628	614
	Adamite 1.6%C	731	**772**	662	646
	ST. BASE	835	**884**	756	737



Note mill limit minimum = 690mm Rail roughing set

$$= \left[\left\{\left[10\frac{c}{L_1}(L_1 - x)\right]^2 + 8.5.D\right\}.\frac{P^2}{\sigma^2}\right]^{1/6} + D_{st} - D_{Bpt}$$

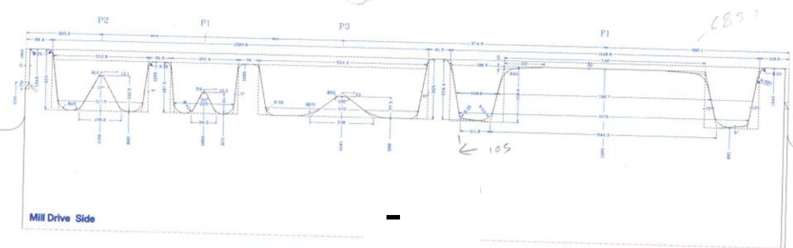
Example spreadsheet - Simplified

Three knifing then one forming pass

Cogging 914x419

ROLL IN	GROOVE	1	2	3	3
DISCARD IN	GROOVE	P2	P1	P3	F1
BARREL TO	MID-PASS	280	664	1183	685.1
BARREL TO	BREAK PT.	397	710	1453	1219
LOAD	tonnes	400	310	500	1400
CENTRES	(MAX)	1340	1340	1340	1340
DIAM. at B	POINT	965	965	965	891.2
Discards (mm)	FORGED	901	890	984	1260
	CAST 0.7%C	929	917	1016	1302
	CAST 1.3%C	954	941	1046	1341
	Adamite 1.6%C	997	983	1095	1406

P2 P1 P3 F1



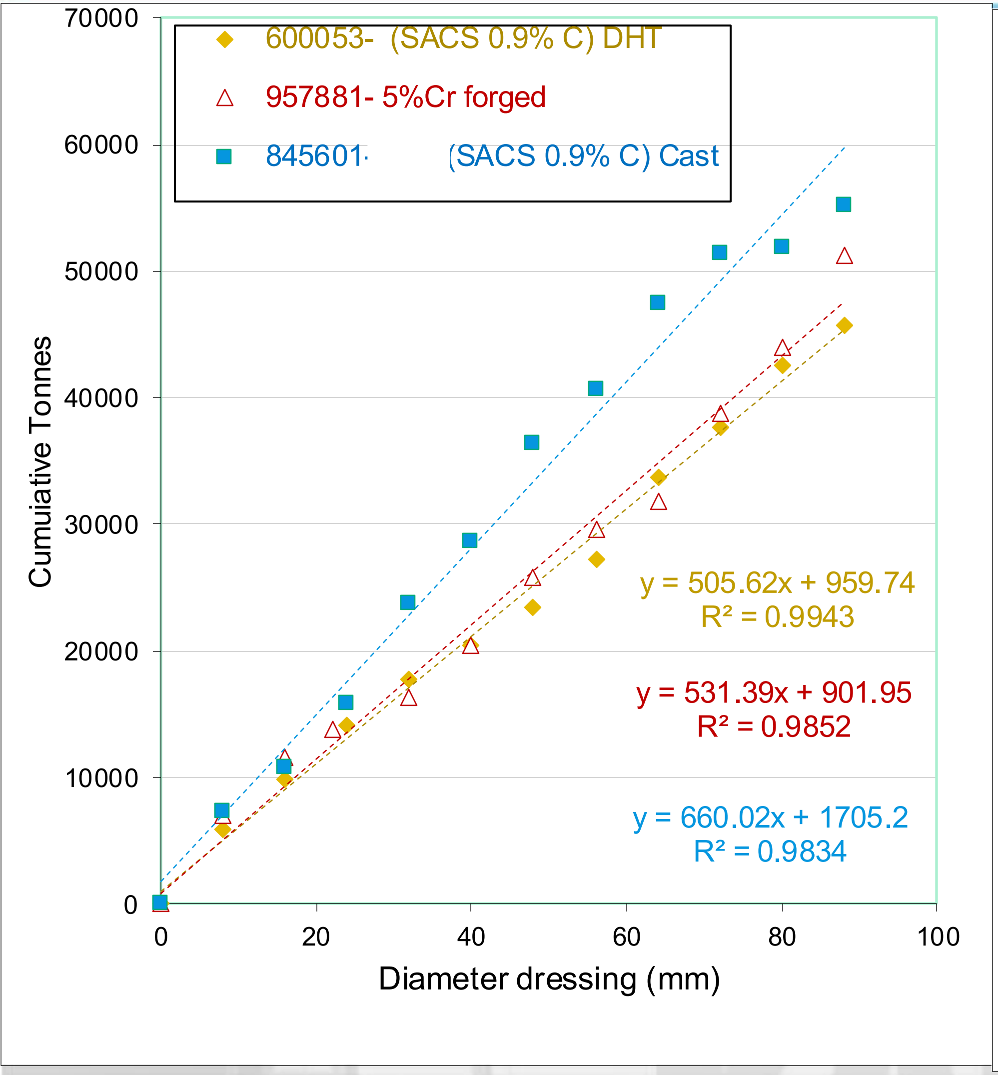
Note mill limits
minimum = 1130mm
Maximum = 1340mm
Jumbo column
Note 12.5mm
drafting not 2.5mm

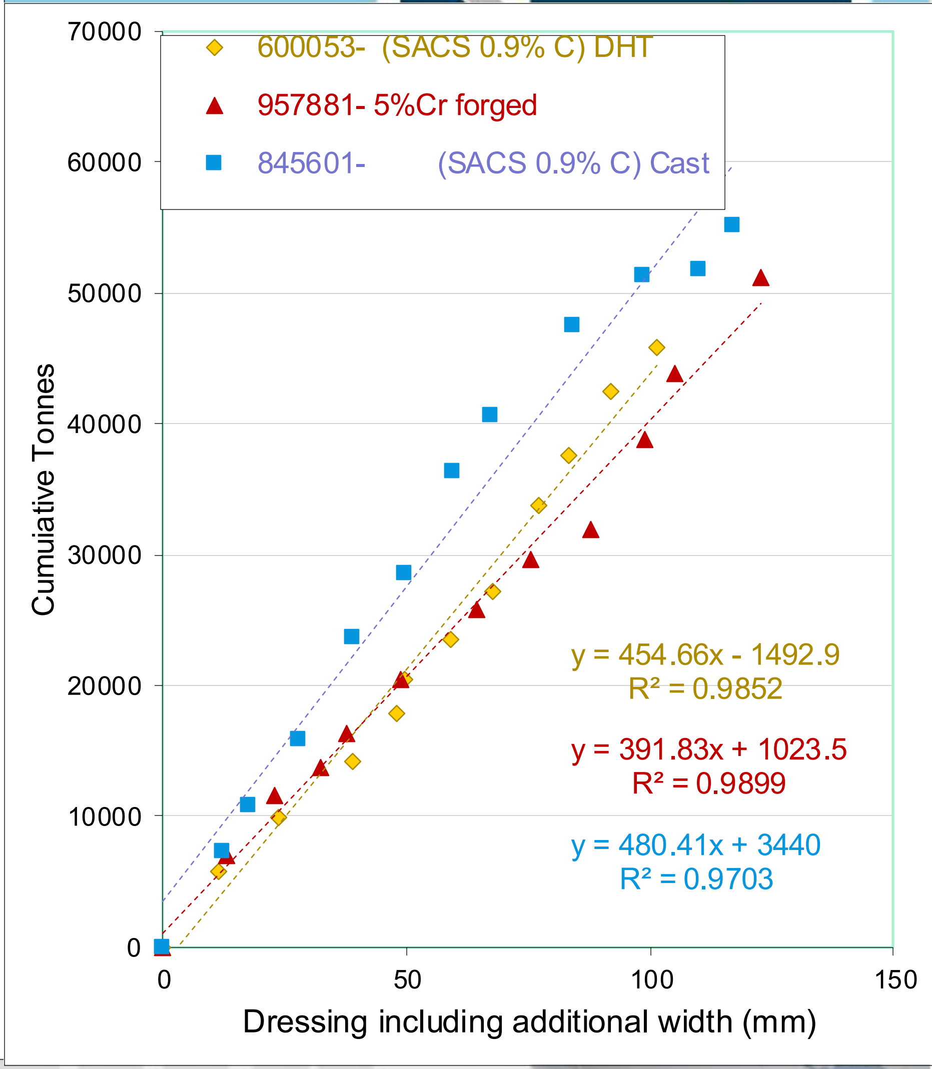
$$= \left[\left\{\left[10\frac{c}{L_1}(L_1 - x)\right]^2 + 46.D\right\}.\frac{P^2}{\sigma^2}\right]^{1/6} + D_{st} - D_{Bpt}$$

Material strength to fatigue limit comparison

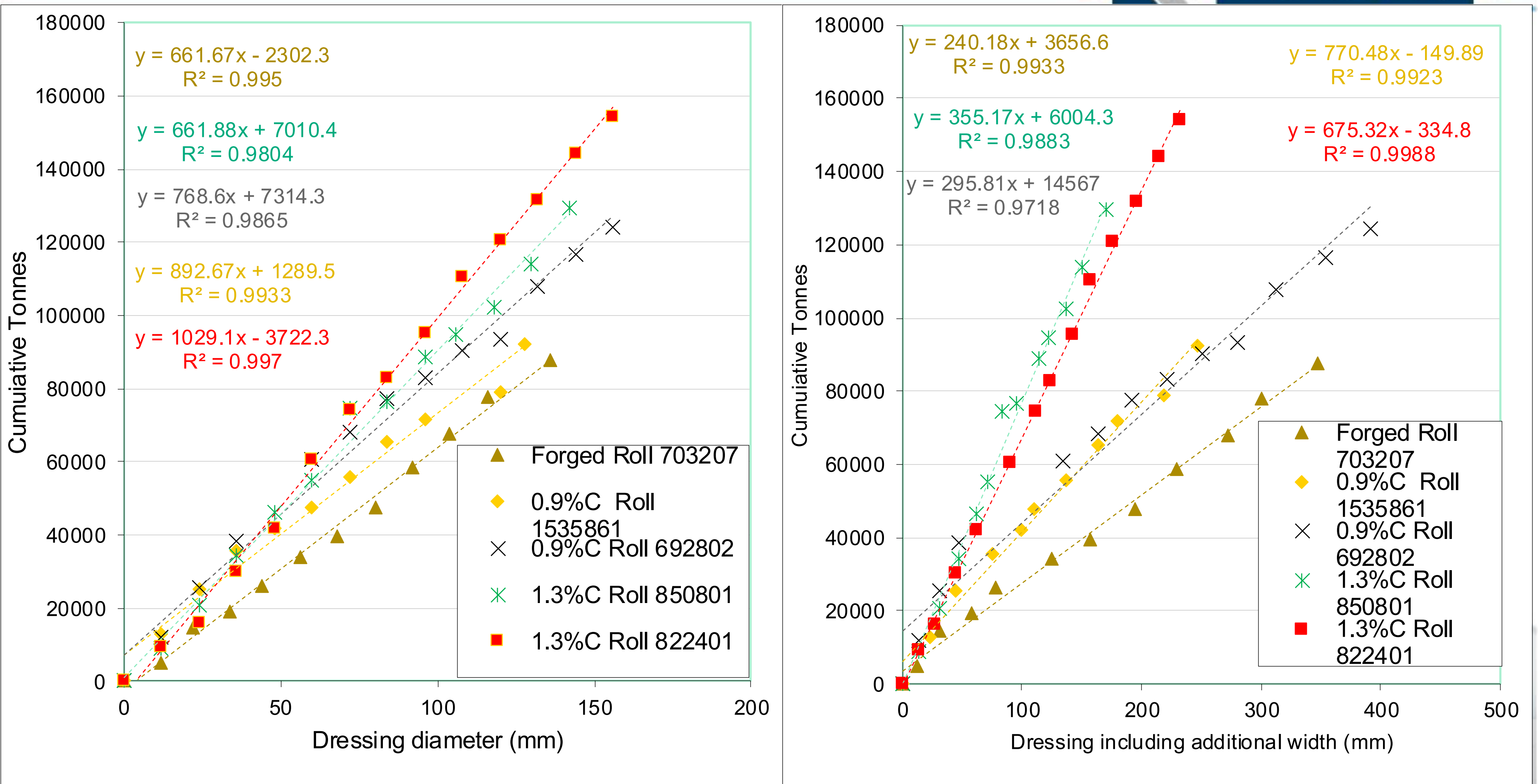
Roll grade	Fatigue Limit	~UTS	Ratio
	MPa	MPa	
FORGED (0.6%C)	213	1200	0.18
CAST 0.7%C	198	1100	0.18
CAST 0.9%C	182	1000	0.18
CAST 1.3%C	160	900	0.18
AD120	137	750	0.18
AD160	122	600	0.20
AD180	99	500	0.20

Performances when rolling identical bloom shape, schedule and steel – forged and ACS – Z set





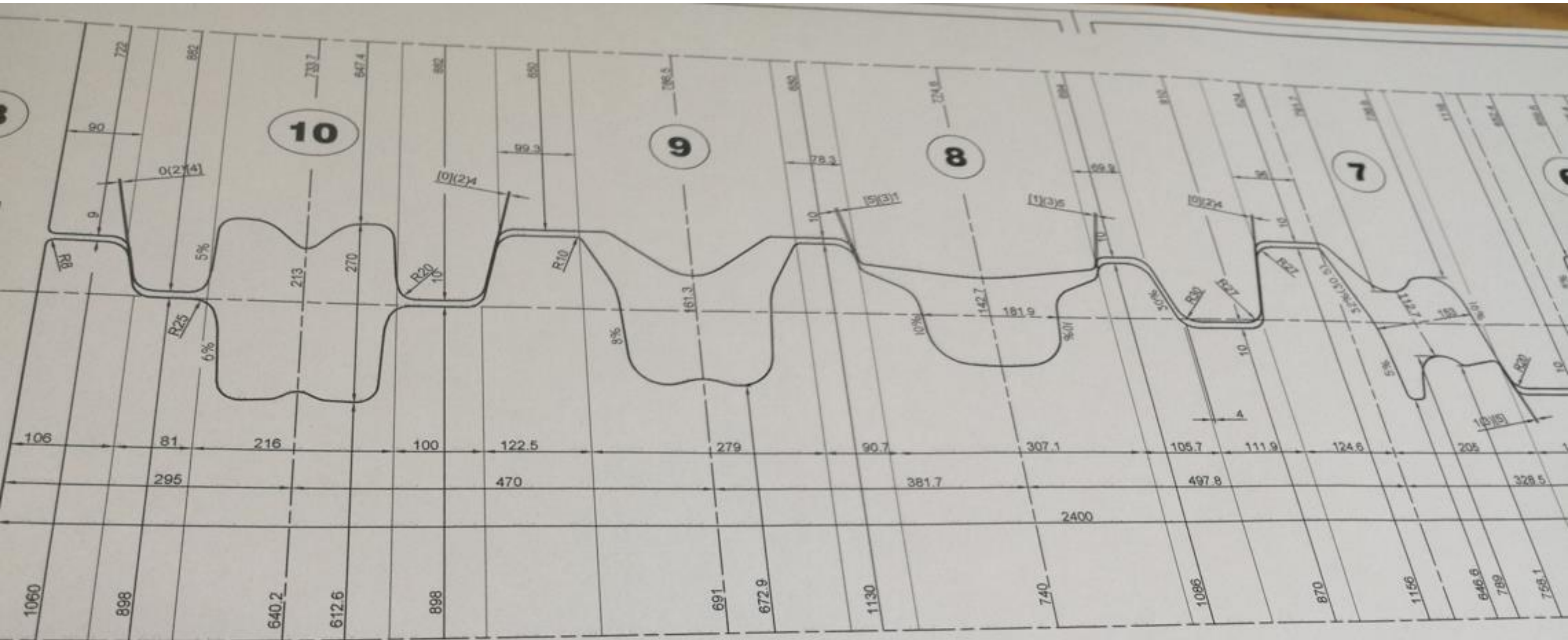
Performances when rolling with different forged and ACS types



Case study 1 for example of discard diameter decision making

Bottom Roll of a 2 high section roll pair

Roll pass design shows a much less profiled top roll than bottom roll



Roll discard diameters in mm compared for rolling two steel grades

Discards were at 800mm Centres, so for adamite bottom rolls not ideally suitable for the more alloyed stock material. Note top roll – roll grade always 0.9%C cast steel, due to lower wear rate (shallow grooves).

Pass ->	P9	P9	P8	P8
Roll grade	9Top	9 bot	8 top	8 Bot
FORGED	606	**718**	612	666
CAST 0.9%C	632	**744**	638	694
CAST 1.3%C	656	**768**	661	718
Adamite 1.5%C	695	**808**	700	760
Adamite 2.1%C	809	**922**	810	878

Standard R260 steel

Note 900mm = starting centres

Pass ->	P9	P9	P8	P8
Roll grade	9Top	9 bot	8 top	8 Bot
FORGED	622	**734**	628	683
CAST 0.9%C	649	**761**	654	711
CAST 1.3%C	673	**785**	678	737
Adamite 1.5%C	714	**827**	718	779

Grade R260Mn steel
(+10% loading to 440t)

Roll Manufacturers roll grades outcomes

Different roll manufacturers choices of roll grades was based on previous experience

Manufacturer	Carbon content %	Ni	Si	Successful ?	
A	1.55	1.3	1.0	Yes	
B	2.06	1.6	1.3	No	First time in mill
C	1.55	1.1	1.3	Yes	
D	1.55	1.2	0.8	Yes	
E	1.56	0.6	1.5	No	Near to discard

4. Conclusions

- **A common failure mode of Long Product Rolls is through mechanical fatigue at the most highly stressed part of a roll groove.**
- **There is a limit below which stress cracks do not grow in long product roll passes, fatigue cracks grow too slowly, which can be calculated from the theory presented.**
- **Optimisation of roll grades can then proceed, where an increase of 0.4%C content in an ACS grade roll can double the roll performance.**
- **Roll selection can be evaluated using the above theory to determine the most suitable material for the given design and other key parameters.**
- **The key to optimum usage is through maximising wear resistance without compromising the roll integrity.**

Acknowledgements

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Thank you for your kind attention.