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Iron and Steel
Metal Rolling

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TECHNICAL SESSION
32

Organized by
Naczelna Organizacja Techniczna w Polsce

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ЦИФРОВАЯ СИСТЕМА СЛЕЖЕНИЯ ЗА СЛЯБАМИ И УЧЕТА РУЛОННОЙ ПРОДУКЦИИ НА НЕПРЕРЫВНОМ СТАНЕ ГОРЯЧЕЙ ПРОКАТКИ

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Повышение требований к качеству горячекатанного листа, значительное увеличение производительности станов привели к необходимости автоматизации всего технологического процесса на широкополосных непрерывных станах горячей прокатки с применением управляющих вычислительных машин /УВМ/[1,2,3]

Системы управления непрерывным широкополосным станом горячей прокатки должны располагать информацией о местоположении слябов на всей технологической линии стана. Решение этой задачи может быть осуществлено системой автоматического слежения за продвижением слябов на стане. Система слежения, определяя местоположение каждого сляба, выдает необходимые данные в системы дистанционной перестройки стана, регулирования толщины полосы, регулирования теплового режима печей, учета рулонной продукции и т.п., для нормального функционирования которых требуются сведения о расположении слябов как в пространстве, так и во времени.

1. Система слежения за слябами

Рассматриваемая система слежения за слябами и учета рулонной продукции относится к непрерывному широкополосному стану "1700" горячей прокатки Карагандинского метзавода [4].

Функциональная схема системы показана на рис.1.

На технологической линии стана одновременно находится около 400 слябов, относящихся примерно к 70 партиям. Под партией понимается группа слябов одной плавки, начальные геометрические размеры которых и заданное сечение прокатанной полосы одинаковы. Переход от прокатки одной партии к другой требует перестройки технологических агрегатов.

на определенный промежуток времени / на 3-4 часа/ программа работы стана. В программу вводится следующая информация; номера партии, заказа и плавки; марка стали и фактический химсостав; геометрические размеры и вес сляба, заданное сечение полосы; количество слябов в партии; отличительный признак сляба / "короткий" или "длинный", горячий или холодный/. Исходная программа подготавливается на перфокартах в планово-распределительном бюро цеха и затем передается для ввода в УВМ.

Ввод новой исходной программы в УВМ производится в тот момент, когда останется одна партия предыдущей исходной программы. Если новая исходная программа своевременно не подготовлена, то об этом сигнализируется старшему посадчику, а на посты загрузки поступает сигнал запрета на дальнейшую загрузку слябов в печи после окончания загрузки последней партии предыдущей программы.

Заранее составленная исходная программа может быть нарушена в связи с изменением режима работы слябинга и т.п. В этом случае старший посадчик со своего пульта вносит изменение в программу подачи слябов на загрузочный рольганг. Поскольку о вновь поступающей плавке к этому моменту времени не будут известны все её данные, то старший посадчик указывает лишь номер плавки и количество слябов в ней, а УВМ присваивает ей внутрисистемный номер партии. Ввод же остальных данных этой плавки в дальнейшем осуществляется с поста оператора УВМ.

Для слежения за металлом линия стана делится на ряд зон: загрузочный рольганг, печи, приемный рольганг, каждый рольганг между черновыми клетями, промежуточный рольганг, рольганги между чистовыми клетями, отводящий рольганг, моталки и участок от моталок до поворотного стола / рис.2/.

Слежение за каждым слябом начинается с момента поступления его на загрузочный рольганг. Затем определяется номер печи, в которую загружен сляб и далее осуществляется слежение за слябом по мере продвижения его через печь, на приемном рольганге, на участках черновой и чистовой групп клетей вплоть до поворотного стола.

Для того чтобы сократить время перестройки стана при переходе на прокатку новой партии, сигнал в систему дистанционной перестройки стана поступает при покидании последним слябом данного заказа каждого механизма, требующего перестройки. В этом случае можно начинать прокатку нового заказа до полного завершения прокатки предыдущего заказа.

Для отдельных технологических участков составлены алгоритмы слежения за слябом. На рис. 3 в качестве иллюстрации приведена блок-схема алгоритма слежения за слябом на участке загрузочного рольганга. x/

При составлении указанного алгоритма приняты следующие условия.

1. В зависимости от того, находятся ли на загрузочном рольганге "длинные" или "короткие" слябы, определение места загрузки сляба производится или по печам P_j, или по рядам R_q.

2. На загрузочном рольганге в районе каждой печи / каждого ряда/ может находится лишь один "длинный" /"короткий"/ сляб.

3. В зависимости от направления вращения рольганга сляб может перемещаться как в прямом, так и в обратном направлениях.

4. Если сляб остановлен в районе какой-либо печи / под остановкой сляба у печи будем понимать нахождение сляба на загрузочных брусьях печи/, то он может быть загружен только в эту печь.

На приведенной блок-схеме приняты обозначения:

$1ФП_j$ /$1ФП_j'$/ -срабатывание любого из датчиков продвижения сляба по рольгангу;

1ДРР -срабатывание датчика реверса рольганга;

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x/ Слежение за слябами на участках загрузочного и приемного рольгангов является наиболее сложным, т.к. только на данных участках возможны перемещения слябов как в прямом, так и в обратном направлениях, а также изменение первоначальной последовательности слябов.

$n_{vi}\ HP_j\ (n_{vi}\ HR_q)$ -сляб n партия V_i находится в районе печи P_j /ряда R_q /;

$n_{vi}\ OP_j\ (n_{vi}\ OR_q)$ -сляб n плавки V_i ; остановлен у печи P_j / ряда R_q /.

Для определения перемещения слябов как между зонами стана, так и внутри отдельных зон, установлены различные датчики. В качестве датчиков выбраны фотореле, реле активного тока прокатных двигателей, контакторы включения различных механизмов и т.п. Для увеличения надежности системы в целом в каждом месте, где необходимо фиксировать прохождение металла, установлено по три датчика.

В процессе работы возможны случаи, когда по тем или иным соображениям сляб / раскат/ будет снят с какого-либо технологического участка стана. Исключение этого сляба из программы работы стана производится вручную, путем ввода сигнала с пульта соответствующего технологического участка.

Проверка правильности работы системы производится на участках загрузочного и приемного рольганга, т.к. именно на этих участках наиболее вероятен сбой в работе системы из-за неверно введенных данных. Проверка производится путем ввода ручного сигнала окончания подачи на загрузочный рольганг / или выдачи из печей на приемный рольганг/ последнего сляба заказа. Если данные УВМ и ручного ввода не совпадают, то подается соответствующий сигнал о необходимости проверки работы системы.

2. Система учета рулонной продукции

Учет рулонной продукции производится системой по количественным и качественным показателям. Вся исходная информация поступает из системы слежения за слябами и от различных датчиков технологического контроля, в частности от толщиномера и ширинометра полосы, измерителей температуры конца прокатки и смотки полосы, длины полосы и веса рулонов. Некоторая учетная информация / даты, номера бригады, заказа, плавки, химсостав стали и др./ выводится на печать без предварительной обработки. Другая информация выводится на печать после соответствующей обработки данных.

В частности определяется теоретический вес рулона G_T, как произведение удельного веса стали γ на требуемую ширину S_T и толщину h_T и фактическую длину полосы ℓ_{ϕ}:

$$G_T = \gamma S_T h_T \ell_{\phi} \qquad /2.1/$$

и отношение фактического веса рулона к теоретическому

$$\varepsilon = \frac{G_{\phi}}{G_T} \qquad /2.2/$$

Кроме того, определяется суммарная длина и относительное расположение участков полосы, на которых параметр /толщина, ширина, температура конца прокатки или температура смотки/ выходит за заданные пределы. Отсчет параметра производится через каждые 0,5 м по сигналу от измерителя длины полосы. Для каждого отсчитанного значения производится проверка выполнения неравенства

$$U_{min} \leq U_i \leq U_{max} \qquad /2.3/$$

где: U_{max} и U_{min} – максимальное и минимальное допускаемые значения параметра;

i – порядковый номер отсчета.

Совместное рассмотрение выполнимости неравенства /2.3/ при произвольном i и при $i-1$ позволяет выделить те номера отсчетов, при которых это неравенство нарушено и указать признак нарушения / больше или меньше допуска/. Выделенным номерам отсчетов присваивается признак нарушенной части неравенства.

Например, если в точке l_i /рис.4/ происходит отклонение параметра в сторону превышения допускаемого значения, на печать необходимо вывести " Ol_i^+ ". В рассматриваемом примере на печать будет выведено:

$Ol_i + l_i + .0$ Ol_{i+2}^- $^- l_{i+3} 0$

Блок-схема алгоритма классификации полосы показана на рис.5.

На основе указанной выше информации система составляет паспорт на каждый прокатанный рулон.

3. Функциональная часть системы слежения и учета

В системе слежения за слябами и учета рулонной продукции используется универсальная вычислительная машина М2000 агрегатной системы средств вычислительной техники /АСВТ/. Применение этой вычислительной машины позволяет решать не только задачи слежения за слябами и учета рулонной продукции, но и задачи управления нагревом слябов в печах и механизмами стана.

Ввод позиционных сигналов системы слежения производится через устройства ввода дискретной информации /УВДИ/ и далее через устройство связи эти сигналы поступают в вычислительную часть системы. Ввод технологической информации от датчиков системы учета производится через индивидуальные нормирующие преобразователи. Для увеличения надежности системы слежения ввод информации осуществляется параллельно через два УВДИ. В вычислительной части системы используются два процессора - специализированный и универсальный. На спецпроцессор, работающий совместно с логической системой слежения, возложены только функции слежения и учета, а универсальный процессор, наряду с выполнением этих же функций, используется и для решения задач управления.

Дублирование вводных и функциональных устройств системы слежения вызвано повышенными требованиями к её надежности, действительно при отказе системы слежения утрачивается информация о программе работы стана и обслуживающему персоналу не будет известно на какие окончательные размеры должен быть прокатан очередной сляб. В то же время выход из строя универсального процессора или какихлибо других устройств связанных лишь с выполнением функций управления, приведет лишь к необходимости ручного ввода заданий в локальные системы управления, а продолжение функционирования системы слежения и учета обеспечит возможность нормальной работы стана.

В связи с тем, что общее количество информации, которая должна сопровождать каждый прокатываемый сляб, весьма велико / суммарное количество информации по каждому слябу составляет около 80 десятичных знаков/, непосредственная передача всей информации по системе слежения путем сдвига массива практически нецелесообразна, так как такое решение влечет за собой очень большие аппаратурные затраты.

Поэтому по логической системе слежения передается только информация позволяющая идентифицировать отдельные слябы, а остальная информация, необходимая для работы стана, хранится в памяти специализированной УВМ. Слежение за прохождением слябов по технологической линии, ввод в память необходимой информации и вывод информации на табло осуществляется по условным / внутрисистемным/ номерам партий. Блоксхема системы, реализующей этот принцип, приведена на рис.6. Система слежения работает следующим образом.

При поступлении на вход технологической линии /загрузочный рольганг/ новой партии слябов вся необходимая исходная информация о слябах из блока автоматического ввода данных /Б1/ /при автоматическом вводе/ или с пульта старшего посадчика /П1/ /при ручном вводе/ вводится в систему. Одновременно этой партии автоматически присваивается очередной внутрисистемный номер. Вся информация вместе с присвоенным ей внутрисистемным номером, который играет роль адреса, поступает в вычислительное устройство системы учета и запоминается в оперативной памяти /ОЗУ/, допускающей многократную выборку. Условный номер партии присваивается каждому слябу данной партии и при поступлении сляба на загрузочный рольганг передается в блок слежения за слябами на загрузочном рольганге /Б2/. Блок слежения за слябами на загрузочном рольганге осуществляет слежение за положением сляба и при поступлении сляба на загрузочные брусья печи соответствующий сигнал вводится в приемный регистр блока слежения за слябами на участке печей /Б3/. Одновременно с номером партии по системе слежения передается признак сляба, состоящий из трех двоичных разрядов и несущий информацию о самом слябе / горячий, холодный, "короткий", "длинный"/.

При загрузке сляба в печь номер его партии и следующая с ним информация вводится в блок слежения за слябами на участке печей. При появлении на выходе печей новой партии происходит обращение по номеру партии в ОЗУ системы учета и вывод необходимой информации на табло пультов операторов загрузки /П2, П3/, старшего сварщика /П4/, оператора черновой группы /П5/, оператора ножниц /П6/ и оператора чистовой группы /П7/. Номер выданного из печи сляба поступает на пульты операторов загрузки и старшего сварщика, а также передается в блок слежения за слябами на приёмном рольганге /Б4/ вместе с признаком сляба. При выдаче из печи первого сляба новой партии в блок слежения за слябами на приёмном рольганге передается также информация о количестве находящихся в печах слябов данной партии / или о количестве выданных из печей слябов/.

В блоке слежения за слябами на приёмном рольганге производится слежение за продвижением слябов по приёмному рольгангу, учет снятых с приёмного рольганга слябов и числа слябов находящихся на приёмном рольганге, последнее передается на пульт старшего сварщика. При поступлении первого сляба новой партии на участок рольганга перед вертикальной клетью из блока слежения за слябами по номеру партии производится запрос в ОЗУ системы учета и выдача необходимой информации на табло пультов операторов черновой группы, ножниц и чистовой группы. Информация о номере каждого сляба при поступлении его на рольганг перед вертикальной клетью передается в блок слежения за слябами на участке черновой группы.

Блок слежения за слябами на участке черновой группы /Б5/ обеспечивает слежение за продвижением слябов по черновой группе, выдачу на пульт оператора черновой группы информации о положении каждого сляба, а также определяет местоположение раздела между партиями и выдачу сигналов на перестройку в соответствующие точки системы дистанционной перестройки черновой группы. Блок слежения производит также / по номерам прокатываемых в черновой группе партий/ запрос в ОЗУ системы учета и вывод информации на табло пультов операторов черновой группы, ножниц и чистовой группы, а также оператора моталок /П8/. Номер каждого выходящего из черновой группы сляба передается в блок слежения за слябами на промежуточном рольганге /Б6/.

Блок слежения за слябами на промежуточном рольганге следит за прохождением слябов через ножницы и по промежуточному рольгангу и осуществляет исключение из системы слежения снятых на промежуточном рольганге слябов. Этот блок по номеру первого сляба партии, поступившего на рольганг перед чистовым окалиноломателем, производит запрос в ОЗУ системы учета и вывод информации на табло пультов операторов чистовой группы и моталок, а также передает в систему перестройки чистовой группы номер поступающих на вход чистовой группы раскатов и номер раската в партии.

Блок слежения за слябами на участке чистовой группы /Б7/ следит за прохождением сляба через чистовую группу, осуществляет запрос в ОЗУ и вывод информации на табло операторов чистовой группы и моталок, исключение из системы слежения снятых в чистовой группе раскатов и присвоение порядкового номера за сутки выходящим из чистовой группы полосам. При выходе полосы из чистовой группы в блок слежения на участке моталок /Б8/ из блока слежения в чистовой группе передается номер партии сляба, из которого прокатана полоса, порядковый номер сляба в партии и порядковый номер полосы. Эти номера также присваиваются в качестве адресов в системе учета всей полученной о данном слябе информации.

Блок слежения на участке моталок по номерам партий и номерам слябов в партии следит за прохождением полос до маркировщика. При прохождении первой полосы новой партии на участок моталок по номеру партии осуществляется вызов в ОЗУ и вывод информации на табло пульта оператора моталок. При поступлении первого рулона на поворотный стол по номеру партии и номеру рулона осуществляется вызов в ОЗУ и вывод информации на табло. Из блока слежения на участке моталок в блок слежения на участке маркировщика /Б9/ поступает номер партии, номер сляба в партии и номер рулона.

Блок слежения участка маркировщика по полученным номерам осуществляет запрос в ОЗУ и выводит необходимую информацию на табло /П9/ и на цифропечать. Одновременно с выводом информации на цифропечать в системе учета происходит стирание в ОЗУ всей информации, относящейся к данному рулону. При выводе на цифропечать информации о последнем рулоне партии в ОЗУ стирается вся информация относящаяся к данной партии слябов.

В системе используются четыре печатающихся устройства, на двух из них / скорость печати - 10 знаков/сек/, расположенных в районе нагревательных печей, фиксируются загружаемые и выдаваемые из печей слябы, а на двух других / скорость печати - 400 строк/мин. по 128 знаков в строке/

расположенных в помещении УВМ, печатаются паспорта рулонов с указанием их качественных и количественных характеристик.

Информация выводимая на табло различных постов, а также информация о загруженных и выданных из печей слябах и учетная информация о рулонной продукции отражены в таблице.

Табло оператора загрузки	34 десятичных	8 двоичных
Табло старшего посадчика	53 десятичных	7 двоичных
Табло старшего сварщика	95 десятичных	10 двоичных
Табло оператора черновой группы	85 десятичных	33 двоичных
Табло оператора ножниц	34 десятичных	4 двоичных
Табло оператора чистовой группы	63 десятичных	5 двоичных
Табло оператора моталок	63 десятичных	5 двоичных
Табло маркировщика	8 десятичных	3 двоичных
Цифропечать паспорта рулона	от 168 до 600 десятичных знаков в зависимости от качества рулона	
Цифропечать поста старшего сварщика / два устройства/	около 180 десятичных знаков на каждый сляб	

Вывод информации, необходимой обслуживающему персоналу для ведения технологического процесса, производится на табло расположенное у операторов различных участков стана. На табло старшего посадчика в десятичной форме индицируются номера трех ближайших к загрузке плавок и количество еще не поданных на загрузочный рольганг слябов загружаемой плавки. При поступлении на загрузочный рольганг последнего сляба каждой плавки на табло появляется сигнал "Проверка" и если сигнал системы совпадает с действительным окончанием плавки, то посадчик нажатием кнопки фиксирует его совпадение.

Для того чтобы обеспечить выдачу всех слябов данной плавки из печей и предотвратить несвоевременную выдачу слябов другой плавки, на табло оператора загрузки индицируется количественное расположение в печах слябов данной плавки в текущий момент времени. Это же расположение слябов индицируется и на табло старшего сварщика. Кроме того, на табло сварщика появляется сигнал "Проверка" при выдаче из печей последнего сляба плавки.

На табло операторов черновой и чистовой групп, ножниц и моталок индицируются данные относящиеся к прокатываемой плавке: заданное сечение прокатываемой полосы, остаток непрокатанных к данному моменту слябов / несмотанных полос/, марка стали и т.п. Для возможности подготовки к перестройке стана к прокатке следующей плавки на табло также индицируются все данные необходимые для перестройки стана. В связи с большой протяженностью черновой группы стана / около 300 м/ на табло оператора черновой группы осуществляется световая индикация положения слябов на рольгангах этого участка стана.

На табло маркировщика рулонов выводится номер рулона за сутки и в плавке, номер плавки и дата.

Во всех блоках осуществляется контроль правильности передаваемых номеров по модулю два. Контрольный разряд присваивается при вводе номера партии в систему слежения.

в ОЗУ системы учета вся информация хранится вместе с адресом. Сравнение адреса запроса выданной информации позволяет контролировать правильность работы устройства ввода и вывода информации. Эти операции выполняются блоком контроля исправности системы слежения /Б10/, который в случае обнаружения ошибки в информации,передаваемой в любом из блоков слежения, подает на табло всех пультов / или пультов связанных с этим блоком/ сигнал о неисправности системы слежения.

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AUTOMATIC PLATE ROLLING AT OXELOSUNDS JARNVERK

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INTRODUCTION

On March 13, 1968 operating personnel at Oxelosunds Jarnverk's 3650 mm Plate Mill began production use of a computer directed Process Control System. This marked the end of a 14 month installation and check-out period and the beginning of a 3 month period of transition from manual to full automatic operation.

The preparations for this change and the resulting effects on mill operations and plate quality are the main subject of these remarks.

THE PLATE MILL AT OXELOSUND

The plate mill in Oxelosund is a 3650 mm wide four-high mill with 925 mm work rolls and 1550 mm back-up rolls. The main rolls are driven by twin 3100 kw motors, each capable of a maximum torque of 200 ton-meters. The screwdown is controlled by two 150 kw motors.

Slabs are heated in two pusher furnaces which provide a total heating capacity of 160-200 ton/hour. Each furnace is designed to handle two rows of slabs 1700 mm to 3000 mm in length and up to 400 mm in thickness. Illustrated in figure 1 are the furnace depilers which accept stacks of slabs from an overhead crane for charging into the four furnace rows. The heated slabs pass through a high pressure water descaler on their way to the rolling mill.

The layout of the four-high mill is illustrated in figure 2.

Slabs may be turned on either side of the mill by tapered rolls located between sideguides which open to accommodate a maximum diagonal of 4750 mm.

Finished plates under 40 mm are hot levelled in route to one of the three cooling beds, which transfer plates up to 30 meters long to the finishing area.

PURCHASE DECISIONS AND OBJECTIVES

Since the start of Oxelösund's plate mill operations in April 1960, operating management had been considering mill automation. Some results and experiences with automated mills were published in the early 60's. Oxelösunds' first positive action was the appointment, in 1963, of an outside consultant charged to investigate and report on what could be automated and in what form.

The result of that report was a decision to concentrate on the plate rolling area and, specifically, to investigate further the possibilities of on-line process computer control. Two main alternatives were considered: Oxelösunds Järnverk could form a process control group charged to prepare detailed specifications and to coordinate the manufacturing and installation functions; experienced vendors could be invited to propose their versions of an appropriate turnkey offering. After some evaluation, it was decided that the second alternative would produce the best result in the shortest time.

Proposals were solicited in 1964 and the balance of that year and early 1965 were spent in discussions and evaluation of the competitive offerings.

In parallel with this activity, an Oxelösunds study team visited most of the hot mills in the U.S. and Europe which had at that time achieved or attempted any significant degree of automation. Though not always encouraging, the information gained during these visits was very useful in evaluating the vendors as well as the functional alternatives. In spite of the evident risk, several functions looked economically attractive and prompted a decision to invest about 1.0-1.5 million dollars in a process control system. It appeared essential, however, that the supplier guarantee his system's production rate and gauge and width control accuracy.

Comparison of the guaranteed performance with the corresponding manual performance permitted calculation of the economic return. If the guarantees on gauge and width could be met, slab to plate yield would be raised 1-2%, and the investment returned in 2 to 4 years.

But how would production be affected? Lacking useful experience from other mills, Oxelösunds' study team was forced to rely on sample rolling schedules submitted for typical products and on an evaluation of several related factors. It appeared that process computer control could give higher production, probably not on a short time basis. Higher production of salable plates would be the result of:

- less downtime because of improved treatment of the mechanical equipment
- fewer rejected plates
- fewer passes on the heavier gauge plates

The final major decision involved the main mill pulpit. Although it was possible to add the computer related devices to the existing desk arrangement, a complete redesign of the mill operator's station was chosen as, by far, the most desirable solution. Installation of the new pulpit, illustrated in figure 3, thus became a critical point in the hardware installation phase. Oxelösunds' staggered vacation system provides only five days of downtime twice a year, and the installation had to be phased into one of these periods. The full changeover was successfully completed without production loss.

SYSTEM DESCRIPTION

The Process Control System employs a GE/PAC 4060 Computer which performs both supervisory and direct control functions. The Central Processor, peripheral devices, and associated control equipment are grouped in five locations as illustrated in figure 4. The primary source of slab identities and processing instructions is punched cards submitted by the furnace operator during slab charging. Manual corrections to slab dimensions and identities can be made through an Auxiliary Input Panel in the mill pulpit. In the photograph of the mill operator's station (figure 3) this panel is the central insert in the left desk. The station is arranged for one man control of all drives. The display panel at his right (figure 5) indicates the state of all drives and sensors associated with automatic operation.

The flow of processing information through the system is illustrated in figure 6. A primary data card is prepared for each slab at the Data Processing Center. The cards arrive at the furnace pulpit along with the scheduled slabs. The furnace operator submits these cards in groups as the corresponding slab stack is lowered onto the depiler. A record of slab identities and dimensions is typed on charging.

Each slab's progress through the designated furnace row is tracked and displayed on its arrival at the rolling area, at which time all primary data are typed on the mill operator's typer. Vital process data are added to this log on completion of each plate. Summary information is printed on demand and at shift changes on the same typer. Punched tapes duplicate all typed information and supplement it with greater detail on productivity and delays.

These data flow back to the Data Processing Center where they serve as the basis for reporting and changes in providing standards.

Figure 7 lists the major control functions performed by the system.

Width Control

The width control function relies on the initial sideguide measurement to identify variations from planned slab width. While variations in cast slab widths are negligible, rolled slab width variations of 20 to 30 millimeters are common. Predictive control based on measured incoming width is adequate where table speeds are well matched to the mill and between sections, particularly at the tapered roll turning tables. Slab skewing due to poor table synchronization reduces the elongation resulting from the planned reduction. The length gage provides in-process correction of these errors. Remaining negative errors are caught by the post broadside squeeze measurement and corrected if excessive. The entire sequence, including slab turning, is automatic.

Pattern Control

The pattern, or plan view, of the plate after broadside rolling is dependent on rolling force level, and on the position of the cross-rolling phase within the rolling schedule. The force level is calculated to produce an approximately rectangular pattern after cross-rolling. The operator notes deviations and informs the control system by coded manual inputs which adjust the system's choice of force target. The operator may elect, in an alternative mode, directly to specify the broadside force target. On 4-high mills pattern is influenced more by the position of the broadside phase than on force level. In this system, cross-rolling is deferred until further pre-broadside elongation would exceed the roll face width.

Gage Control

Final plate gage is controlled by proper setting of roll opening to reflect in-process variations in temperature and resulting deformation resistance. Variations in mill dimensions resulting from thermal and roll wear effects are monitored by plate thickness measurements following the last two forward passes. This feedback is essential where badly worn rolls may present mill dimension variations exceeding 0.5 millimeters across the roll face.

Crown Control

Finished plate profile is established by the finishing roll force and the effective roll crown. The finishing force is set by the system to reflect desired plate crown, roll crown, and mill and plate deformation characteristics. The finished plate is traversed by the plate thickness gage to provide a crown measurement. Corresponding adjustments are made in the roll crown data to correct the force target selected for subsequent plates.

Flatness Control

Plate flatness is controlled by the choice of plate crown relationships during the final rolling passes. Coded flatness observations submitted by the mill operator are the source of feedback. In response, the system changes the finishing phase drafting pattern. To illustrate, figure 8 indicates the planned force pattern before and after the operator had submitted a "center buckle" verdict for one millimeter plate. In this case two such observations were made by the operator before the condition was completely corrected.

SYSTEM DESIGN AND SIMULATION

Although the system was functionally specified prior to the transaction's close, additional system definition was required to relate these functional objectives to specific Oxelösund operating practices. This, and the related task of defining the hardware interface with existing controls, was essentially complete after three meetings totalling 20 days. Unfortunately, system requirements are dynamic and vary with changes in the user's market, plant, and organization. Thus, minor changes continued through the entire project.

To verify the accuracy of supplier-user communications in the design phase, two techniques were used: preliminary off-line rolling schedule generation and factory simulation. The rolling schedules, covering a large group of typical products, were evaluated by Oxelösund operating personnel for reasonableness and for compliance with operating rules previously established. The factory tests included methods of data entry and simulation of all operating sequences including the time shared position regulators. Oxelösund personnel participated in the simulation testing and in the system check-out which preceded it. The simulation equipment was shipped with the system to assist in field installation.

TRANSITION FROM MANUAL TO AUTOMATIC OPERATION

The first try in automatic took place November 2, 1967 when 13 plates were finished successfully. During this first phase of operations, the auxiliary input panel and all peripheral devices were connected in the computer room. Thus, actual control of operations was from the computer room, with management actively involved in communications between the computer room and the mill pulpit. After a few months, when most of the necessary modifications in the software had been made, the auxiliary equipment was moved to its final location in the pulpits. Shortly after that, card flow arrangements were completed and the tracking function kept operating 24 hours a day.

Automatic rolling for the first few months was limited to plates over 15 mm final gauge. The gauge limit was gradually lowered as model adjustments permitted processing thinner plates without rejects for flatness.

Operator Training

Training of the operators started shortly after the system specifications were resolved. At that time, the main principals of operation were introduced and discussed. Courses on the theory of operation started just before the computer hardware was installed making it possible to study and try some of the equipment in conjunction with the theoretical presentations. These courses occupied ten 2-hour periods.

Complementing these courses were visits by all operators and foremen to another mill with several automatic features. As the computer hardware and software were installed and the sensors and displays connected in the pulpit, the operators could begin to follow the information flowing to and from the computer during manual operations. In that phase and throughout the whole project, the operators and mill management met frequently to discuss those steps last completed and next planned.

Perhaps the most important part of the operators training is the information given him in the pulpit during actual automatic rolling. Every new system function was reviewed just prior to testing. Taking one small step at a time, the operators gradually became familiar with the automatic operation and leaned how and when to intervene, make corrections and return to automatic.

Support Personnel Training

Support personnel include two maintenance engineers and two programmers who attended General Electric Company training courses in the United States. Course timing was planned to permit their participation in hardware and software checkout of the factory.

During the entire field installation period, Oxelösunds' support personnel actively participated in solutions to hardware and software problems.

The present maintenance staff includes 2 engineers and 2 technicians who work the day shift but are "on call" 24 hours a day.

Operating Practice Changes

From the operators' point of view the transition from manual to automatic operation has required few changes, none of which was drastic.

The furnace operator did use a card reader even before transition to automatic rolling. The card reader was part of an IBM-357 system comprising two typewriters, one each in the main pulpit and the leveler pulpit, and a card punch in the planning department. For each slab pushed the operator submitted the corresponding card through that card reader. The card contained rolling and leveling instructions and provided a record of what had been rolled to the planning department. Cards were read after the slab was successfully pushed and moving towards the mill to avoid false documentation in case the slab had to be lifted off the table for reheating.

Present practice is to read the cards before the slabs enter the furnace and give a push complete signal when the slab slides down on the roller table or before. When he has used the cards to submit primary data to the computer, the operator puts them into a file arranged for manual tracking.

After the completed reading cycle, a type-out of slab identity and dimensions indicates in which order and in which furnace row the slabs were entered. The procedure is thus to:

1. Read identities from slabs
2. Sort the cards in right order and enter them through the card reader
3. Read the type-out and check that the order agrees with the physical order of the slabs

The push complete signal initiates typeout of the identity of the slab just pushed, which the operator uses to check that his manual tracking agrees with the computer tracking. The procedure has considerably improved reliability with little increase in operator effort.

The mill operator has several new routines to follow, which are associated with initialization, record keeping, and feedback functions. Before every shift the operators must:

a) enter date/turn/crew identification

b) check the calibration of the sideguides (this is of vital importance for accurate width control

After every roll change they must:

c) enter new roll diameters and crowns

d) calibrate the roll opening

e) enter draft limit (if changed)

f) enter finishing force targets (if in force target mode)

g) enter plate crown limit

h) run a display test

During operations they must:

i) enter delay reasons for delays exceeding 5 minutes

j) enter reasons for slab or plate rejections

k) enter occasional manual thickness measurements when the thickness gauge is unavailable

Leveling operations are essentially unchanged, but information transmittal is improved. Previously, the plate data were typed when the slab was pushed from the furnace. Since two or three slabs could be pushed before the first reached the leveler, the situation in case of rejections could be confusing and result in incorrect plate marking.

The present system transmits data to the leveler pulpit as the completed plate leaves the mill.

SYSTEM PERFORMANCE

Width Control

It was apparent early in 1968 that the basic width measurement approach was suitably accurate and reliable. Minor sideguide modifications were required to insure contact at the slab's bottom edge when squeezing. Prior to this, 15 to 20 mm width measurement errors resulted from variations in incoming slab thickness. The calibration procedure duplicates the normal width measurement sequence thus eliminating the effects of sideguide wear and changes in the applied thrust at stall.

Underpowered feed rolls presented the only serious width control problem. The feed roll drives were unable to match the front and rear table accelerating rates. This resulted in occasional severe skewing as the slab was passed from tapered turning rolls to multiple disk feed rolls. The skewing reduced the useful elongation resulting in underwidth plates. This deficiency was partially compensated by the combining of reduced mill speed and increased table speeds to provide some squaring on impact. Zero entry speed, effectively employed for squaring at some plate mills, was considered detrimental to the mill bearings.

Width control accuracy has met objectives in spite of this compromise. Figure 9 indicates deviations from target width for plates rolled in June of 1968. The measurement used is that made by the sideguides after broadside rolling. The allowance for shrinkage and spread is included in the target width. Its accuracy has been verified by comparison of hot and cold measurements. The observed standard deviation of 10 mm is less than 1/4 the standard deviation experienced on this mill when under manual control. The distribution is asymptotic to -30 mm, since greater negative errors automatically call for an additional turn and correcting pass. At this setting only about one piece in 50 requires correction.

Pattern Control

The effect of deferred broadside rolling is illustrated by the photographs in figure 10. The slab in figure 10a was rolled manually following conventional practice of starting to cross roll after one scalebreaking pass. The slab of figure 10b, rolled automatically, received 2 added passes before cross rolling began.

The pattern superiority is evident in the straighter sides and squarer corners.

Gage Control

Accurate control of plate gage requires the ability to predict rolling force and the associated mill deformation. Errors in these predictions are the major source of gage inaccuracy. Uncertainty concerning mill dimensions is largely removed by the calibration procedure and by feedback of plate thickness. Where work rolls are badly worn, however, the effective roll opening will vary across the roll face. Fortunately, uneven roll profile presents no problem at this installation. The demand for minimum gage variation across the plate width has forced Oxelosund gradually to lower the number of tons rolled between grindings.

The gage control function has been evaluated on the basis of comparisons between ordered thickness and the final thickness measured manually. Figure 11 indicates the distribution of gage errors for plates rolled in June of 1968. The distribution indicates that 95% of the sample was within 0.3 mm of target gage. Prior sampling of manually produced plates had indicated a standard deviation of 0.25 mm, or 95% within 0.5 mm of target gage. The distribution exhibits a .08 mm bias, reflecting the tendency of the gage to read low by that amount.

Crown Control

Thickness measurements are made at the center and edge of each finished plate. These measurements are made near the plate end, so that processing of the next plate may start before the gaging sequence is finished.

The measured plate crown is compared with that calculated for the measured force and the difference attributed to a change in effective roll crown. A low gain is applied to the roll crown correction since changes are slow and since some attentuation of the gaging inaccuracies is necessary.

The system attempts to obtain a plate crown of 5×10^{-5} mm per mm of plate width, or about 0.1 mm crown on a two meter plate. If this would require too low a force, due to the current roll crown condition, the target crown is automatically raised, but not above the crown limit which is dictated by the operator. When the crown limit cannot be met with the current roll crown, the system signals the operator to raise the crown limit or switch to manual operation.

Thus, the target crown changes with roll condition as well as plate width. The measure of the system's ability to control crown is the deviation from target crown rather than the crown produced. In figure 12, deviations from target crown are plotted. The distribution exhibits a standard deviation of about 0.09 mm, and a mean deviation of -0.04 mm. No comparable statistics exist for manual operation.

Flatness

Flatness, the absence of edge or center waviness, is the most elusive of the controlled characteristics. Such distortions result from unequal elongation across the plate's width. Maintaining a constant percentage crown during finishing would prevent these distortions but would increase the average number of finishing passes. The extent to which a plate can accommodate unequal elongation across its width depends largely upon its thickness, width, and deformation resistance.

During finishing, this system attempts to utilize the steepest possible descending force pattern which will not violate limits which have been established for various combinations of plate dimensions and hardness.

Lacking a flatness sensor, the system relies on operator feedback to close the flatness control loop. His coded defect observations are used to adjust the slope of the finishing force pattern so as to prevent defect recurrence in the next plate.

There is no convenient index of system effectiveness in controlling flatness. Our experience indicates that the results are roughly comparable to those obtained manually. In critical situations, however, an experienced operator is often better able to assess the current plate condition and choose an appropriate correction strategy.

RELATED BENEFITS

Although it was yield improvement which made this system economically attractive, several related benefits are worth mentioning.

Reduced Slab Identity Errors

When defining the data input procedures, a major objective was to minimize the risk of assigning the wrong card to a charged slab. If the dimensions on the card and the slab were different the exchange would be discovered in the dimensional check prior to rolling, but if the dimensions are approximately the same the situation is more critical.

The following procedure was selected:

a) Only the depiler selected by a 4-position switch can be operated

b) Limit switches indicate when each depiler is raised to accept a new slab stack

c) Card reading is initiated by one of four "Read Card" pushbuttons designating which row is being charged

d) The "Read Card" pushbutton, depiler limit switch, and depiler selector switch positions must correspond before data can be entered. When this condition is met, the cards corresponding to the slabs on the depiler are read.

This system has virtually eliminated the two most common manual tracking errors: charging the wrong row and charging in reverse order. Combined with the pre-rolling dimensional check, it has reduced the incidence of mixed orders to a negligible level.

Improved Providing Practice

The system tests several dimensional relationships before accepting an item for automatic rolling. Changes in production planning practices can thus be monitored. For example, current providing practice dictates that cross-rolling be limited to 200% elongation. If the system notes that planned plate width exceeds 3.0 times slab width for a double turned item, this fact will be alarmed at the mill operator's typer. A full record of deviations from proper providing practice is, thus, immediately available.

Improved Mill Capacity and Scheduling Information

In order to minimize elepsed time from input of material in one end of the production line to output of finished product at the other end, it is of vital importance to know accurately the capacity of each processing area. Capacity of the rolling mill is particularly important at Oxelosund, since it is the limiting facility for most products. Mill capacity varies with dimensions, weight, and steel grade. Typically, mill capacity estimates are based on simple relationships involving one or more of these factors.

Oxelösunds Järnverk uses relatively complex mathematical models for scheduling its production facilities. The added complexity is only justified, however, where sufficient data are available for model adjustments. The GE/PAC system provides off-line as well as on-line generation of rolling times for all products, permitting precise adjustment of the production scheduling models.

Increased Heating Capacity

Although the process control system does not include any direct control of the furnaces, it has helped raise furnace productivity in a very simple way.

During the years of manual operation, push rate had been defined by a relationship which expressed the minimum time between consecutive pushes from one row as a function of maximum slab thickness in that row. For simplicity, the function employed 20 to 30 mm steps of slab thickness. The computer, by substituting a continuous function for the previous step function, has removed some of the remaining conservatism. "ROW READY" lamps indicate when the calculated time has elapsed since the last push of each row. These assist the operator in obtaining maximum capacity from each furnace and in balancing the loading between furnaces.

CONCLUSION

The closer tolerances of width and gage as a result of the automatic rolling have made it possible to review the providing practice system. As an average Oxelösunds Järnverk have been able to raise the slab to plate yield %.

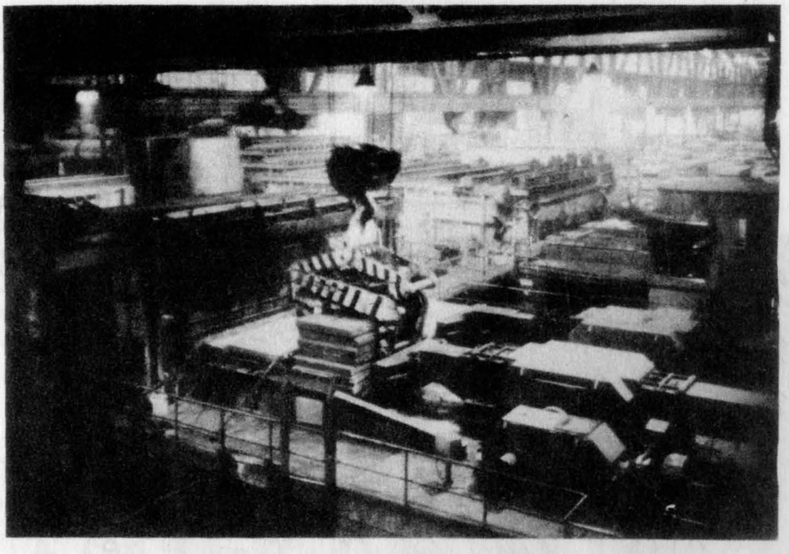


Figure 1 "Furnace depilers accept slabs from an overhead crane for charging into the four furnace rows".

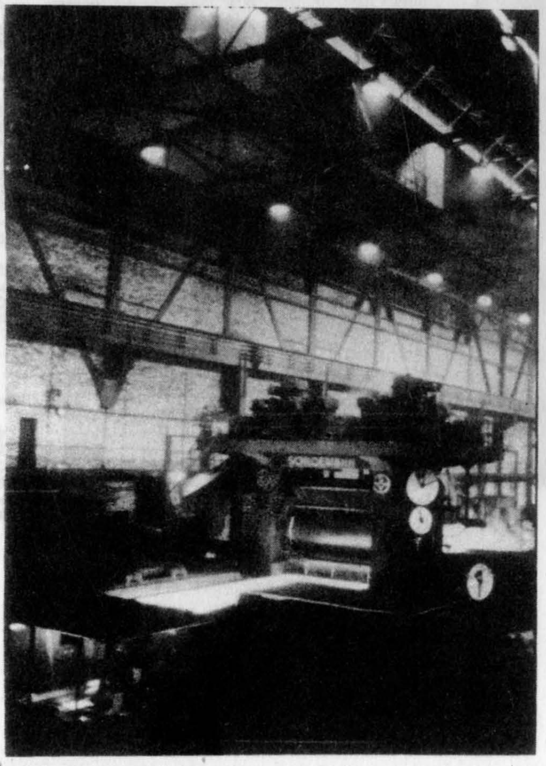


Figure 2 "The plate mill is seen here as viewed by the operator".

Figure 3 "Both right and left operators desks were redesigned for automatic operation".

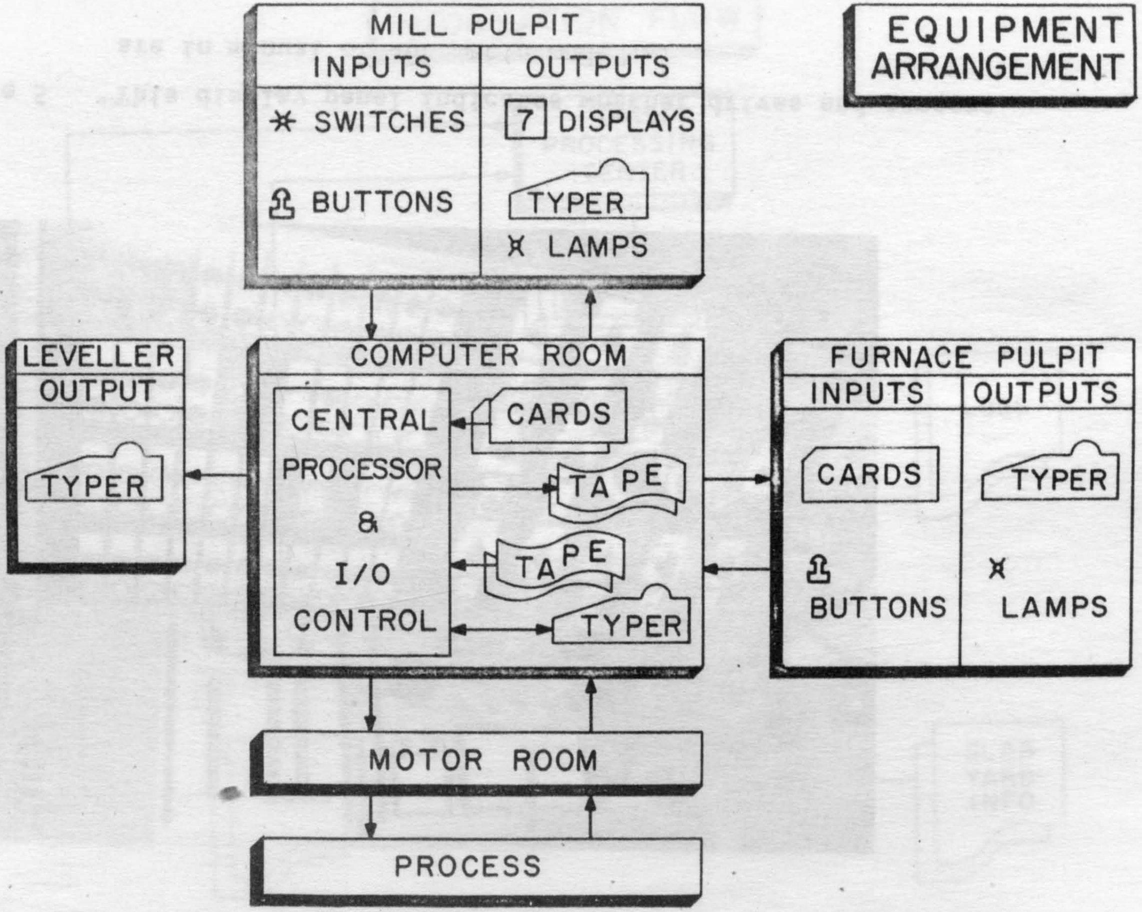


Figure 4 "The equipment associated with automatic operation is shown here".

Figure 5 "This display panel indicates whether drives and sensors are in manual or automatic mode".

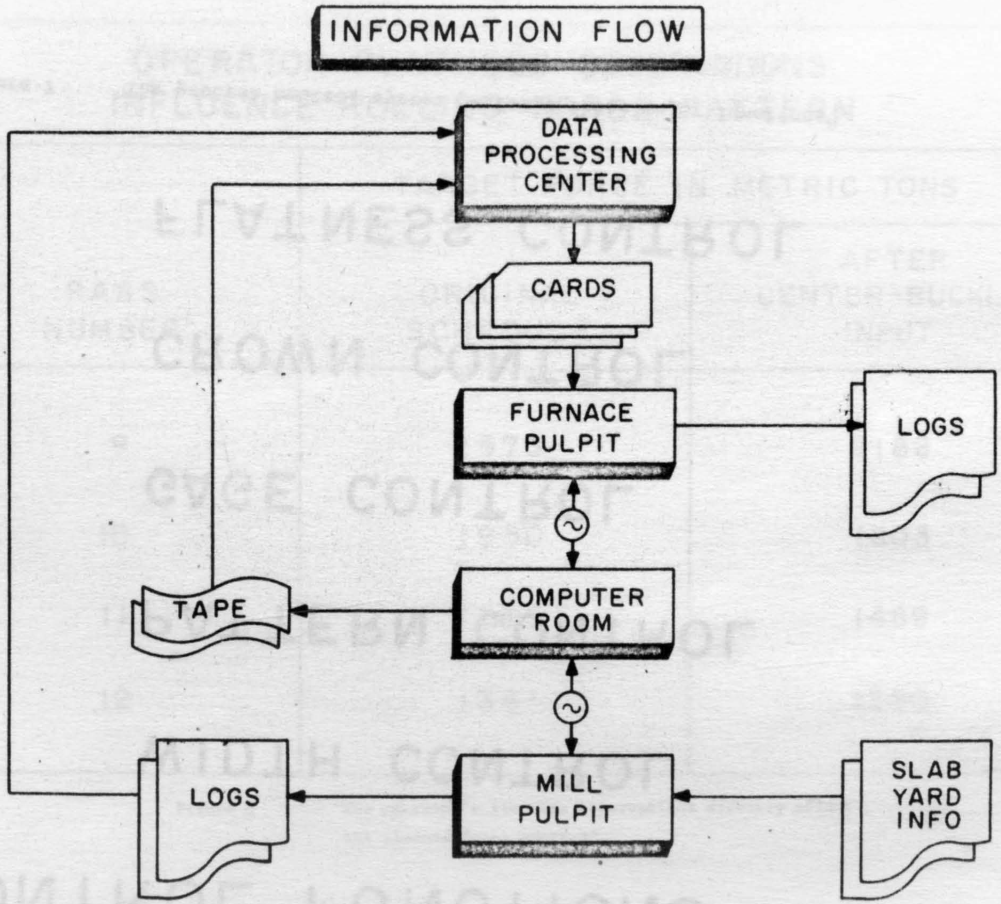


Figure 6 "The flow of processing information is shown here".

CONTROL FUNCTIONS

WIDTH CONTROL

PATTERN CONTROL

GAGE CONTROL

CROWN CONTROL

FLATNESS CONTROL

Figure 7 "The process control system performs these major functions".

OPERATOR FLATNESS OBSERVATIONS INFLUENCE ROLLING FORCE PATTERN		
PASS NUMBER	TARGET FORCE IN METRIC TONS	
	ORIGINAL SCHEDULE	AFTER CENTER-BUCKLE INPUT
9	2573	2188
10	1950	1803
11	1563	1489
12	1361	1380

Figure 8 "The operator's flatness observations directly affect the planned force pattern".

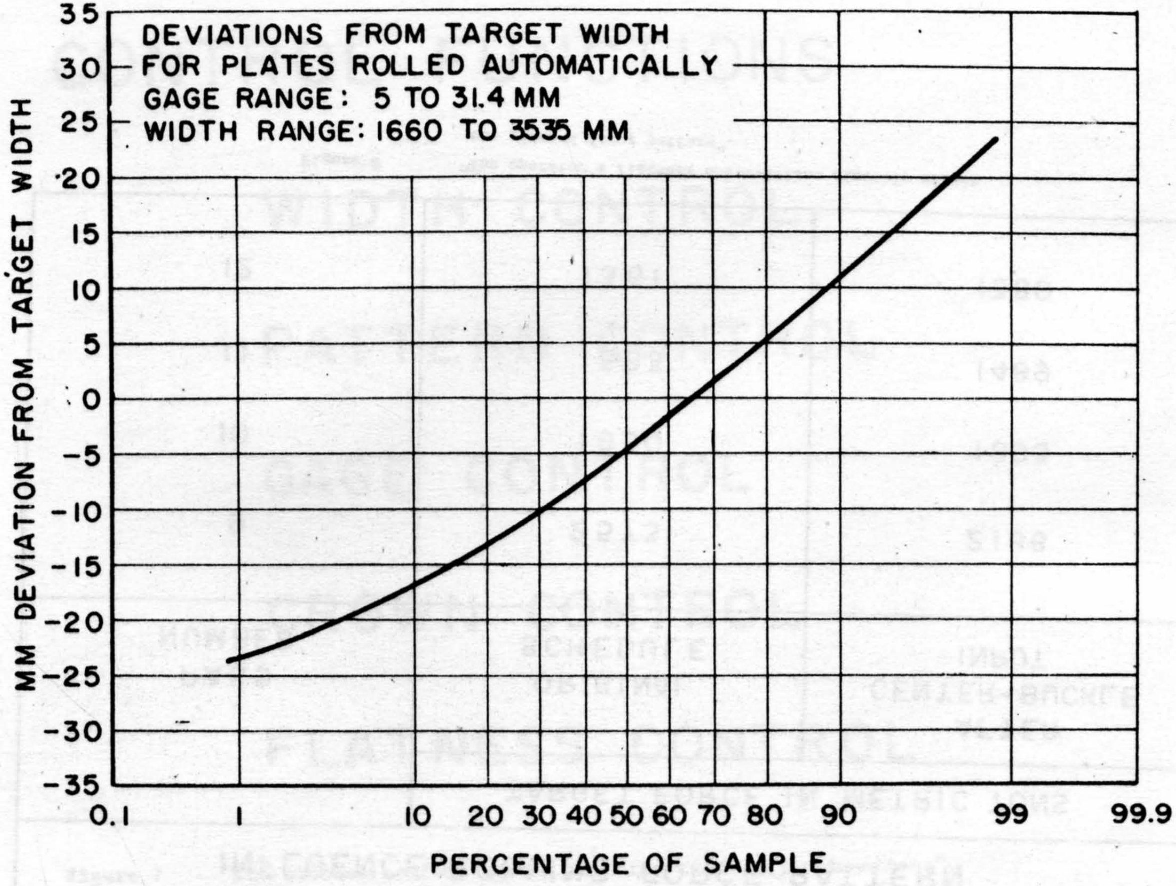
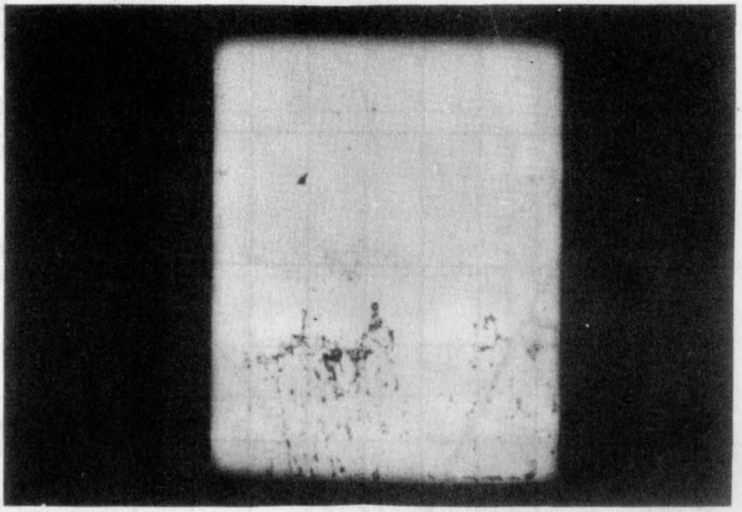


Figure 9 "The automatic width control function was performing at this level by March 1968".



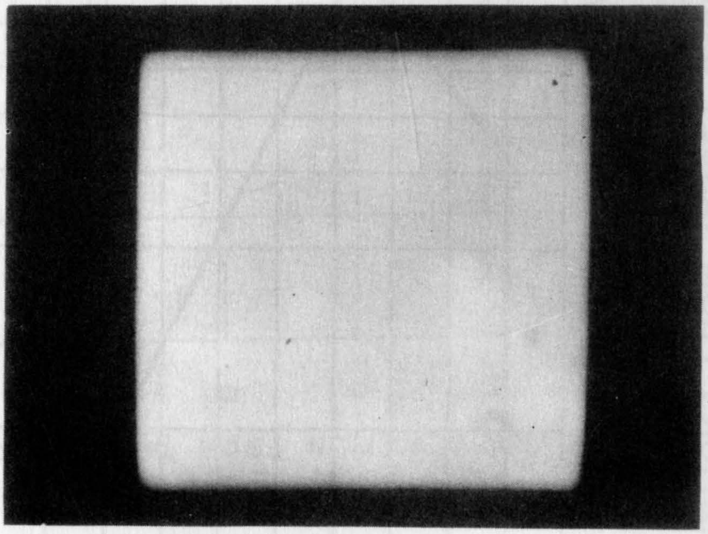


Figure 10a,10b "Pattern after cross rolling is improved by automatic operation".

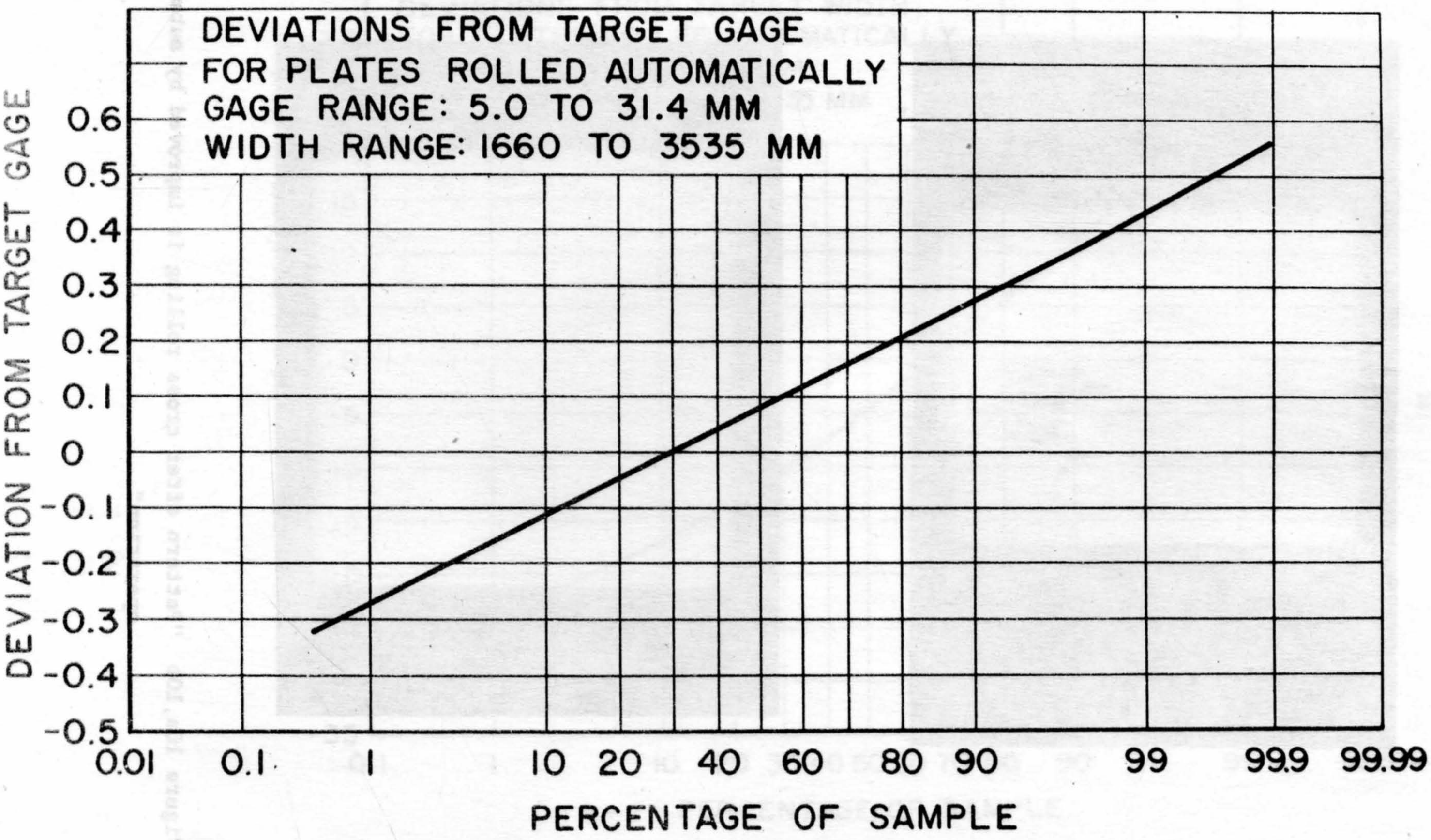


Figure 11 "Plate produced automatically exhibit this gage error distribution".

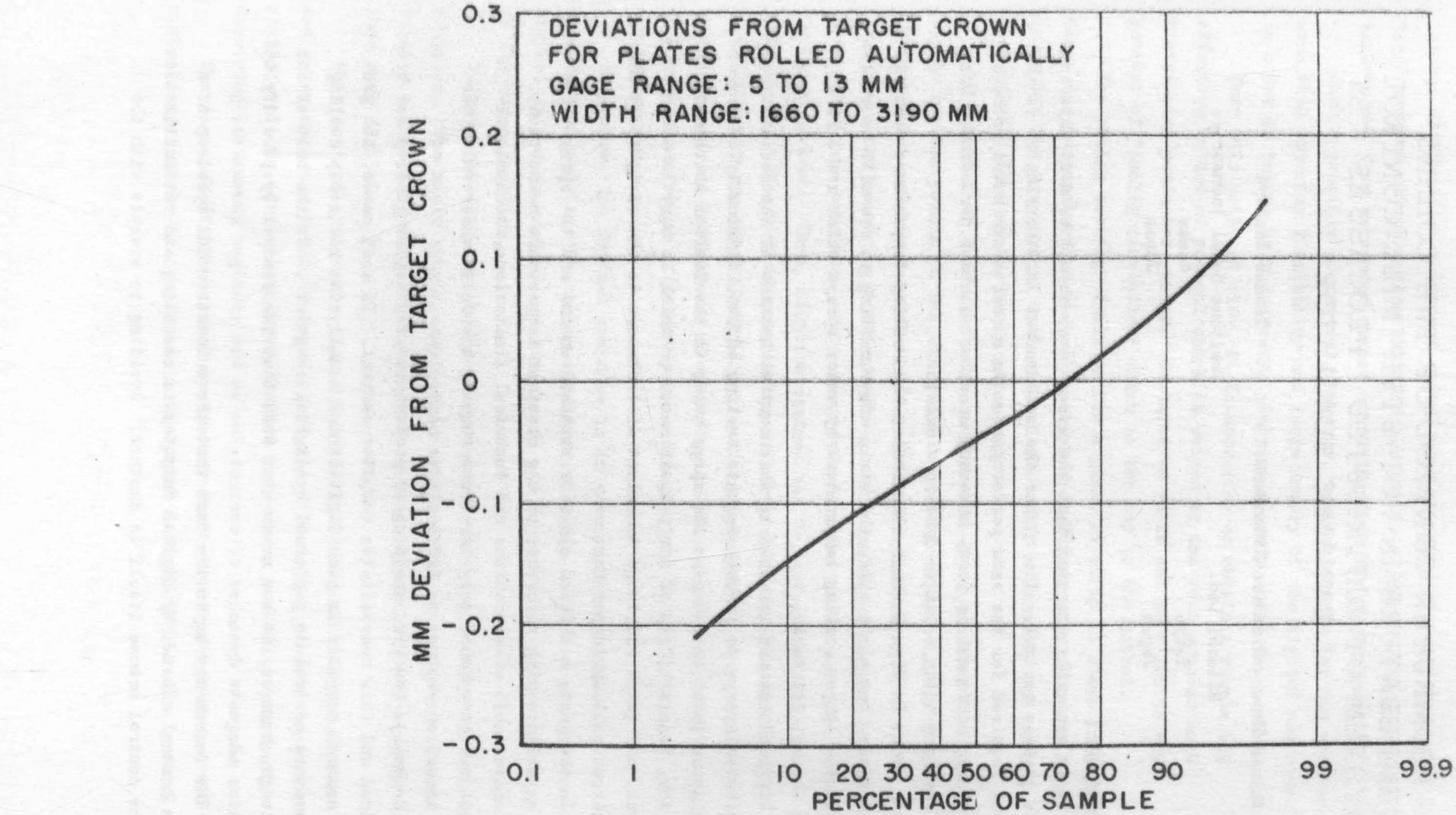


Figure 12 "Deviations from target crown are plotted here for automatic operation".

COMPUTER CONTROL OF THE COILING TEMPERATURE IN HOT STRIP MILL-CONTROL SYSTEM OF DISTRIBUTED PROCESSES BY DYNAMIC SIMULATOR

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Introduction

It is generally accepted that the measurement should be most important in the process control. The richer the measurement is, the simpler is the control required for the same performance. On a real distributed process where the measurement is poor, however, excellent control performance has been realized using a unique dynamic simulator.

As shown in Fig. 1 which illustrates the coiling temperature control of a 6-tandem hot strip mill, the strip after rolling in the mill is cooled down to the target coiling temperature by water sprays which are laid up along the hot run table.

Difficulties are involved in this control because of the necessity of distributed sprays to insure adequate cooling effect, difficulty of temperature measurement in and near the spray owing to the limited thermometer's accuracy, impossibility of strip speed maneuver which is busy in mill control, and quick and large transient distrubances to the strip speed and the target coiling temperature.

In the past, a skilled operator switched on and off the spray valve from experience with reference to the chart of temperature measurement. With unavoidable misoperations and technical limitations, such manual control was acceptable only for those running schedules under which the mill operation was not so difficult to control.

Recently, however, speed-up of production with higher quality has been required and this necessitates computer control. In most cases, the process control computer is pure digital, and usually the hot strip coiling temperature control is performed by digital computer[1]. To the best of our knowledge, however, it has never been seen that the control by pure digital provides adequate dynamics of control.

The reason may be in the fact that the automation and speed-up of a given control scheme by digital computer is one thing and rationalization of the control scheme itself is another. Avoiding to wrestle with the control difficulties mentioned above, the past pure digital first applied rough control on assumption that the process is a concentrated parameter system, and then corrected errors resulting from the approximation.

Such a practice of control, however, was not enough for the purpose even with superior flexibility and large memory of the digital computer. In order to insure high accuracy, programmed strip speed was needed.

From this point of view, it is necessary to obtain a simple but effective method of control which is suited to the real process as a distributed parameter system. We dared to do it and were led to the concept of "analog simulation" which is the key to the method.

The analog cooling simulator for a piece of strip is shown in Fig. 2. Given the temperature at the mill outlet as initial value, the simulator indicates the temperature variation of the strip accurately and continuously with time as the strip moves on.

If a number of such simulators are installed in parallel corresponding to various points on the strip and driven in real time, the temperature at each point can be measured with no use of thermometers.

Since the measuring difficulties are eliminated, excellent feedforward control becomes possible. This means reduction in burden and dead time of feedback control. Thus, adaptive control can be performed simply and effectively. The need of programming of strip speed is eliminated, and even with such expanded flexibility, control dynamics is better. This method is not an improvement of measuring hardwares and their environments, but is software which effectively uses all the past measured values concentratively.

Of course, the digital computer is in a sense allmighty and can operate similarly to the analog simulator, but its exclusive use for such control is not economical and its shared use for mill set-up is difficult by its computing time.

We have embodied the method of dynamic simulator by a mixed hybrid computer. The mixed hybrid computer is suitable for this method and can realize a control system of higher performance, reliability and economy than pure digital.

This control system has been completed by close coordination of user and maker and is a fruit of overall efforts of manager, process researcher, system engineer, device engineer, device inspector, production engineer, measuring instrument engineer and so on.

The research of the control system was started in April 1965 and the control experiment was completed in the plant in March 1966. The control system has been in practical operation since October 1967.

Layout of the plant

Fig. 1 shows the layout of the plant. Rolled in a 6-tandem finishing mill consisting of 6 stands, F1, F2... F6, a strip is cooled by water spray devices which are laid up along the hot run table and divided into six banks of equal intervals, and is wound by the downcoiler. Measurements include; winding speed V m/s by a tachometer of the last rolling stand (F6 in most cases), thickness of strip h mm by an Xray gage at the outlet of F6, and strip temperature Tf ^{o}C at the outlet of mill and winding temperature Tc ^{o}C before the downcoiler by radiation pyrometers.

Each bank of water sprays is composed of many spray nozzles and their pipings, and each group of spray nozzles is manipulated by a valve.

Because of reliability, response, and linearity of water quantity to valve opening, the on-off valve was applied in stead of the continuous control valve.

The water spray pressure is controlled constant so as to hold the spray cooling ability of each valve constant.

To maintain favorable environments for each thermometer, devices to eliminate water splash and vapor are provided. It is difficult to set thermometers in the water spray or in the section between the water spray and just before the downcoiler.

Operation of the plant, and the target of control

Hot strips are supplied intermittently from the finishing mill and after winding of each strip's head, the winding speed is raised either quickly or slowly. The former is for preventing rolling temperature drop and increasing production speed: the latter is for holding the rolling temperature constant.

In order that the wound strip may have homogenious quality for different carbon contents from the head to the tail end, the target coiling temperature Tco is changed as the strip moves on.

The quantity of cooling spray is decided mainly by Tco, h, Tf and V. h is held nearly constant by automatic gage control. It is difficult to obtain proper distribution of cooling spray at every instant of changing V, Tf and Tco. Rapid change of Tf is due to change of V.

It would be convenient if V could be manipulated to control Tc, but this is impossible because V must be manipulated for rolling temperature control, etc.

The target of control is an error of the order less than 1σ, 10°C over the total length of strip under the conditions as mentioned above.

Cooling process equation and macro model control

There is a fairly long distance between sensor (Tc thermometer) and actuator (water spray device). It is, therefore, impossible to reduce the control error below the required value if it is attempted only by such feedback control as PID when rate of change of V, Tf or Tc is large.

In such a case, it is effective to apply feedforward control by a model, if possible[2]. To build the model, it is necessary at first to express the strip cooling process in a numerical form.

The cooling process equation for a point on the strip is shown by Eq. (1).

$$\frac{dT}{dt} = -\frac{1}{h}\left\{\frac{dK}{dL}\cdot T + \frac{K'}{3}(T+273)^4\right\} \tag{1}$$

where T: temperature of a point on the strip (°C)

t: time (sec)

K: cooling ability of the spray ($mm \cdot m \cdot sec^{-1}$)

L: distance from inlet of No. 1 bank toward downcoiler (m)

K': cooling coefficient of radiation ($mm \cdot sec^{-1} \cdot {}^{o}C^{-3}$)

Eqs. (2) and (3) of the model for feedforward control are derived by limited integral of Eq. (1). These equations apply to the macro-point-models which neglect the distribution of sprays, temperature distribution in the thickness direction of the strip, heat transfer in the horizontal direction, impossibility of superposition of spray cooling and radiation cooling, and other nonlinearities.

$$\sum_{ij} \delta ij \cdot Kij \doteqdot h \cdot V \cdot \log_e \frac{T_f}{T_f'} \tag{2}$$

$$\frac{1}{(T_f'+273)^3} = \frac{1}{(T_{co}+273)^3} - \frac{K' \cdot L_o}{h \cdot V} \tag{3}$$

where i: No. of the spray bank

j: No. of the valve in the same spray bank

ij: quantity to show on or off of No. j valve in No. i bank, 1 for on, 0 for off

Kij: spray cooling ability when No. j valve in No. i bank is on

($mm \cdot m \cdot sec^{-1}$)

Lo: distance between inlet of No. 1 bank and Tc thermometer (m)

Since spray density across the width of the strip is nearly the same for each valve, magnitude of Kij is independent of the width of the strip and is nearly proportional to the quantity of spray water if the water pressure is constant.

Eqs. (2) and (3) suppose that all sprays are concentrated at the inlet of No. 1 bank and from there up to Tc thermometer, there is only radiation cooling.

If, however, valves of No. 6 bank are manipulated when V and Tf rise rapidly, there yields a large negative transient error of Tc as shown in Fig. 3.

To eliminate this error, manipulation of each valve should be given a proper delay. However, the value of the delay should be varied with the position of valve and changes of V and Tf.

Though a digital computer is suitable for such compensation because of its flexibility in programming, if it still difficult to obtain strict compensation in all cases. In practice, programmed V is needed and this diminishes the controlling flexibility.

Control by dynamic simulator as a kind of micro model

To eliminate troubles of the macro model control, we have applied a dynamic simulator, a kind of micro model. The dynamic simulator consists of many unit simulators shown in Fig. 2 and expressed by Eq. (1).

The dynamic simulator is expressed by Eq. (4)

$$\frac{\partial T}{\partial t} + V \cdot \frac{\partial T}{\partial L} = -\frac{1}{h} \cdot \left\{ \frac{\partial K}{\partial L}(L) \cdot T + \frac{K'}{3} \cdot (T+273)^4 \right\} \quad (4)$$

where L = 0 ~ (Lo-L2), T = Tf when L = 0, T = Tm when L = Lo-L2

L: distance of a point on the strip from No. 1 bank inlet toward downcoiler (m)

L2: distance from No. 6 bank inlet to Tc thermometer (m)

Tm: strip temperature at No. 5 bank outlet and No. 6 bank inlet (°C)

$\frac{K}{L}$ (L): density of spray cooling in the winding direction ($mm \cdot sec^{-1}$)

The block diagram of the control system using the real time dynamic simulator is shown in Fig. 4. This dynamic simulator simulates strip temperatures in 5 spray banks and indicates strip temperature Tm at the outlet of No. 5 bank where thermometer can not be set.

Using Tm as Tf, feedforward control is possible by Eqs. (5) and (6) similar to Eqs. (2) and (3) for macro models.

$$K_6 = h \cdot V \cdot \log_e \frac{T_m}{T_m'} \tag{5}$$

$$\frac{1}{(T_m' + 273)^3} = \frac{1}{(T_{co} + 273)^3} - \frac{K' \cdot L_2}{h \cdot V} \tag{6}$$

where K6: cooling ability required for No. 6 bank ($mm \cdot m \cdot sec^{-1}$)

Because No. 6 bank is close to Tm, macroscopic assumptions of Eqs. (5) and (6) similar to Eqs. (2) and (3) approach the reality. Because L2 is slightly smaller than a half of Lo, transient error due to variation of V is smaller than in Eqs. (5) and (6). Error due to quick disturbances is thus eliminated, and such transient error as in Fig. 3 is diminished significantly.

Feedback control and model modification (adaptive control) eliminate the error remaining after the feedforward control. The feedback control is expressed by Eq. (7) and the model modification is expressed by Eq. (8). Eqs. (7) and (8) are derived by partial differentiation of Eqs. (5) and (6).

$$\Delta K_c = -\alpha \cdot h \int_0^t \frac{V^2 \cdot (T_m' + 273)^4}{(T_{co} + 273)^4 \cdot T_m'} \cdot (T_c - T_{co}) \cdot dt \tag{7}$$

$$\Delta K_a = -\frac{h}{\Delta t} \int_0^{\Delta t} \frac{V \cdot (T_m' + 273)^4}{(T_c + 273)^4 \cdot T_m'} \cdot (T_c - T_{co}) \cdot dt + \Delta K_{ao} \tag{8}$$

where α: constant

Kc: cooling quantity by feedback ($mm \cdot m \cdot sec^{-1}$)

Ka: cooling quantity by model modification ($mm \cdot m \cdot sec^{-1}$)

t: elapsed time from winding of strip head (sec)

Kao: integrated value of Ka up to previous strip ($mm \cdot m \cdot sec^{-1}$)

Manipulation of No. 6 bank's valves is expressed by Eq. (9) which distributes the sum of feedforward cooling, feedback cooling and model modification cooling to spray cooling of each valve.

$$\sum_j \delta_{6j} \cdot K_{6j} \doteqdot K_6 + \Delta K_c + \Delta K_a \tag{9}$$

The feedback is expressed in an integral form according to Mr. A. Haalmann. It holds next suitable dynamics at some constant ratio of the open loop integral time constant to its dead time. α is selected according to the same opinion.

The block diagram of a feedback control loop is shown in Fig. 5. The response characteristic, non-dimensionalized for step disturbance and winding speed, is shown in Fig. 6.

The model modification reduces average error at the head of the strip. In the operational schedule where hs, Tfs, Tcos and Vs are nearly same, equation's errors are also nearly equal. So the cooling quantity which just eliminates the error of the strip head can be used as the initial compensation cooling quantity for the next strip head.

Error of the strip head becomes a step disturbance and is detrimental to the feedback control with a long dead time. By the above mentioned model modification, except for the first strip in the schedule, the strip head error can be decreased significantly and the following feedback control made smooth.

In this way, in the real time dynamic simulator, each control function, feedforward, feedback or model modification, deals with the disturbance manageable by itself most effectively.

If the disturbances dealt with are arranged in the order of rate of change, the arrangement corresponds to that of control functions just listed above.

All the control actuation except for the preset mentioned next, feedforward, feedback or model modification, is gathered to No. 6 bank as shown in Eq. (9). The purpose is not only for simplifying actuating devices but for diminishing the feedback loop dead time.

Each valve of No. 6 bank has smaller size and deals with less spray quantity than other banks. The intention is to reduce quantizing error of Tc and to shorten the response time to match the feedforward control.

It is necessary to hold the prescribed cooling quantity of No. 6 bank below its capacity in order to insure normal control. For this purpose, Nos. 1 through 5 banks are manipulated properly by preset technique. The mathematical model of the preset is expressed by Eq. (1) similar to Eqs. (2) and (5).

In addition to the actual valves, the preset is performed on the bank model in the dynamic simulator mentioned later.

$$\sum_{ij} \delta_{ij} \cdot K_{ij} = h \cdot V \cdot \log_e \frac{T_f}{T_f'} - \Delta K_{a0} - K_{60} \tag{10}$$

where K60: a half of No. 6 bank capacity ($mm \cdot m \cdot sec^{-1}$)
Eqs. (2) and (5) are used also for multiple regression analysis to identify the cooling ability of each valve.

As mentioned above, the real time dynamic simulator control supported by the micro model is free from many troubles involved in the macro model. There is a bright prospect for a control system with high flexibility and excellent dynamics.

Quantitative evaluation of control methods by simulation

The dynamic simulator control was compared by analog simulation with manual control and macro model control. The comparison in terms of typical values of h and V is shown in Table 1.

From this table, it is seen that the transient error of manual control and macro model control is over $\pm 10^{\circ}C$ with 20% and 50% rise of V in 10 sec, while the dynamic simulator control shows the maximum error within $+6^{\circ}$ and $-5^{\circ}C$ under the same conditions which well meets the control target mentioned above.

Computing controller of mixed hybrid form

Nowadays, the process computer control is the summary control by single digital computer in most cases. It is not necessarily proper, however, to treat all the content of control by pure digital alone. For the realization of control by dynamic simulator already mentioned, we have applied a mixed hybrid controller of single purpose, called "Spray controller", because of higher performance-to-cost ratio and reliability, as well as ease of handling like industrial measuring instruments.

If the control of such a purpose were accomplished by pure digital alone, the computing time would be critical as both the mill set-up and the spray control should be taken care for by a single computer. The performance-to-cost ratio is high in the case of the spray control alone.

The mixed hybrid is not a common hybrid system which is a parallel combination of analog computer and digital computer connected together by AD converter, DA converter and linkage device. But, it expands the operational control of analog computer to such an extent that some analog circuits are switched by logic and some logics are determined depending on whether an analog signal is higher than another analog value or not.

By the mixed hybrid, functions difficult to be realized by analog only, digital only or both paralleled can often be realized easily.

Examples are pace circuit, dynamic simulator circuit and valve selecting circuit in "Spray Controller", and will be explained in the following.

In the pace circuit shown in Fig. 7, input is the strip speed and output is the clock signal generated by a unit progress of the strip equal to the bank interval. The output of the pace circuit controls the dynamic simulator circuit shown in Fig. 8 and is the basis for each timing signal of feedforward, feedback and model modification. The variable interval of the clock signal is in contrast to the constant interval with digital computer. The variable interval makes the control intimate with the process behavior, simple and effective.

The dynamic simulator shown in Fig. 8 consists of a strip model, a bank model and a switch matrix. The strip model consists of 7 integrators and simulates temperatures of sampled points on the strip for each bank interval. The bank model consists of 5 nonlinear circuits and simulates superposition of spray cooling and radiation cooling in each of 5 banks. The switch matrix is switched by logical outputs of a ring counter in the pace circuit and simulates the relative position of distributed spray and strip by shifting the connections of integrators and nonlinear circuits. Such a clear construction is given because all-points on the strip are at the same speed at any time. An integrator and a nonlinear circuit are connected as shown in Fig. 2 and their combined operation is expressed by Eqs. (1) and (12) in integral form.

$$T = T_{fo} - \frac{1}{h}\int_0^t \left\{ \frac{\partial K}{\partial L}(L)\cdot T + \frac{K'}{3}(T+273)^4 \right\} dt \qquad (11)$$

$$L = \int_0^t V\cdot dt \qquad (12)$$

where Tfo: simulated temperature of a sampled point at outlet of mill (°C)

t: elapsed time from the instant when the sampled point enters into No. 1 bank (sec)

At an instant, each of 5 out of 7 integrators simulates the sampled point in computing mode under each of 5 banks, another one tracks Tf in resetting mode and remainding one holds Tm in holding mode.

Fig. 9 shows the valve selecting circuit. It distributes required cooling quantity on the right side of Eq. (9) or (10) to quantized cooling ability on the left side of the same equation. Selection of valves is the result of this distribution. It may be called "device of distributing continuous quantity and selecting quantized quantities" or "general AD converter" in which the order of selection and each quantized value can be set arbitrarily. The valve selection order is prescribed from the metallurgical view point.

Experimental results of the plant

An experimental "spray controller" was manufactured and operated in Wakayama Steel Plant. Problems noted in completing of the practical system are; superposition of spray cooling ability of each valve, measurement of winding speed after rolling, environment and response of each thermometer, magnitude and deviation of valve response time, working frequency and life of valve, saturation of control bank (No. 6 bank), residual heat of hot run table in down time, equation's error on strip thickness and so on.

None of these problems, however, was not so serious as to deny the dynamic simulator control.

Completed practical system and its expanding

After studying the problems encountered in the plant experiment, function and reliability were improved, and the practical system was completed by adding such a new feature as varying the target winding temperature with time (taper cooling).

With this system, control accuracy over the total length of strip except for thick strips over 7 mm was 20°C, 95%, as contrasted to the past skilled manual control which attained only 10~, 20°C under easier schedules.

By further improvement and expansion of the system completed in Wakayama, a plan for Kashima Steel Plant is now in preparation. The Kashima system is generally larger and more complex than Wakayama. It will have such features as 4 downcoilers, 2 blocks of spray device, faster winding, wider range of schedules, but essentially it may be based on the same control principle as Wakayama. Participation of digital computer is under consideration for long and high accuracy memory and complex arithmetic required by improved preset and model modification.

Conclusion

A control system which is effective even with poor measurement information has been completed using a real time dynamic simulator. The dynamic simulator permits exact grasping of process dynamics, and each control function can treat the disturbance manageable by itself most effectively.

The mixed hybrid computing control device is most suited for this

system and provides excellent dynamics, high reliability, low cost and ease of handling.

Though the dynamic simulator control is just suitable for such processes where simulated objects are rigid, it is also expected that the same concept may also be applicable to other processes with distributed character.

Not mentioned in detail above, identification of cooling ability of each spray valve and radiation, and statistical on-line model modification as contrast to the determinative dynamic simulator, are interesting as themes of modern control theories. We are continuing studies on them.

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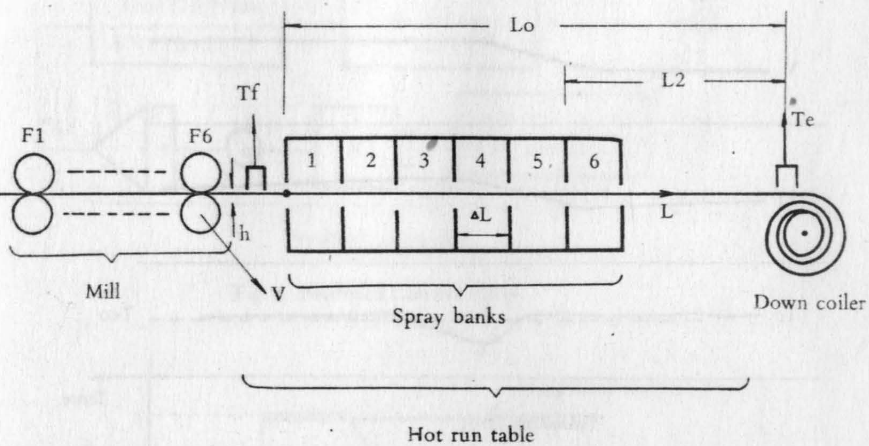

Fig. 1 Layout of Plant

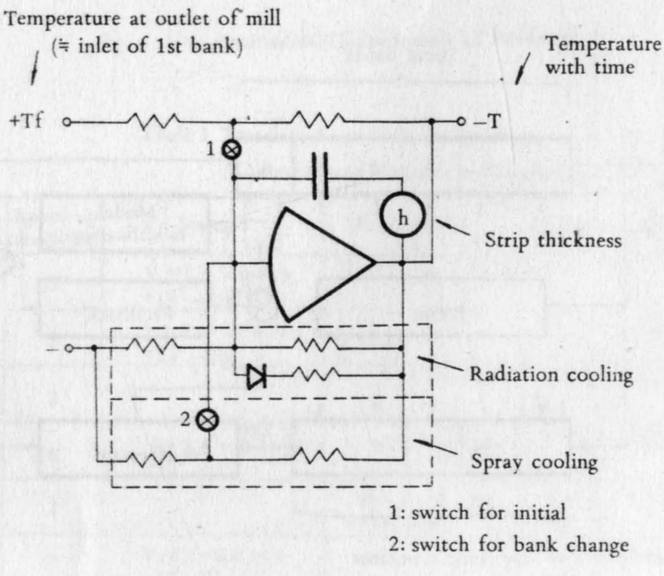

Fig. 2 Analog cooling Simulator for a Strip Fraction

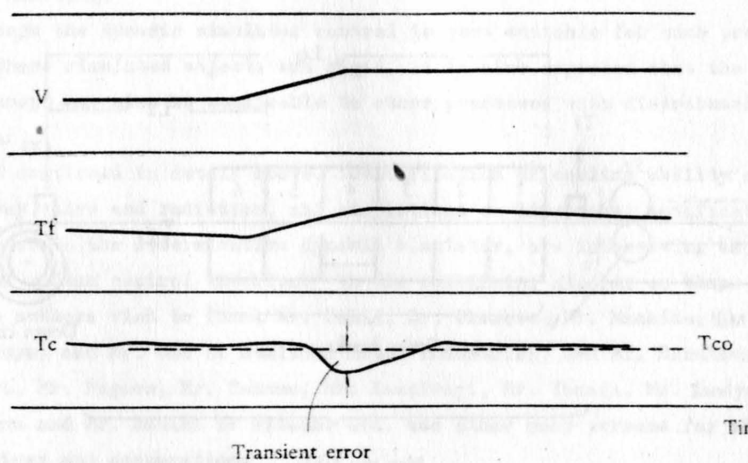

Fig. 3 Characteristic of Macro Model Control

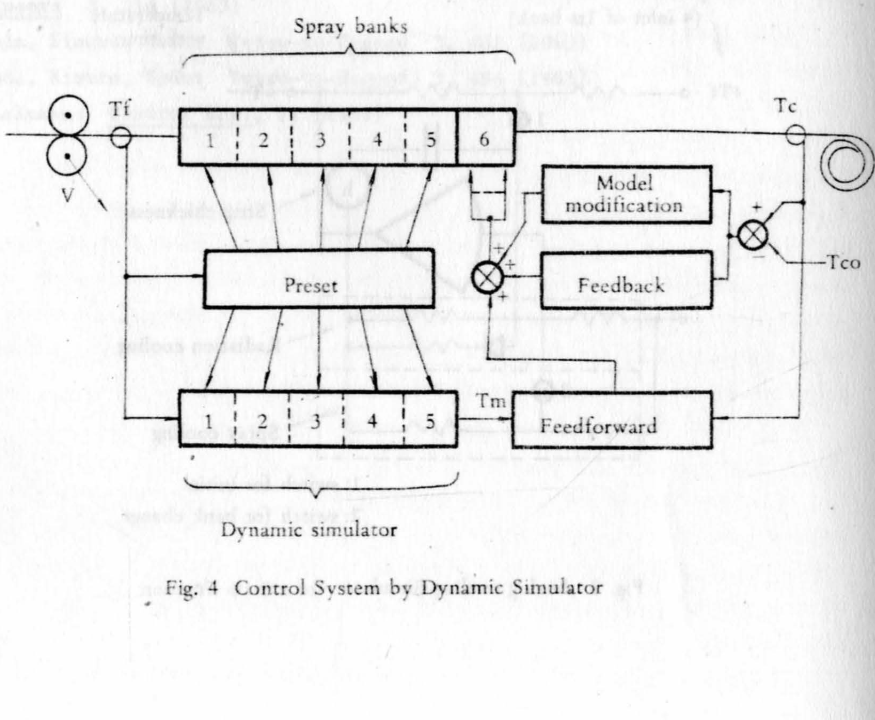

Fig. 4 Control System by Dynamic Simulator

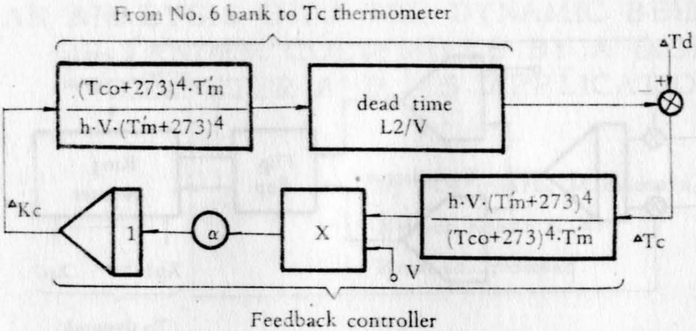

Fig. 5 Feedback Control Loop

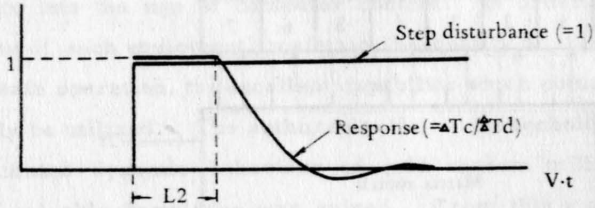

Fig. 6 Non-dimensional Characteristic of Feedback

Table 1 Transient Error of Tc by Speed up
(Comparison of Methods by Simulation)

h mm	Speed-up rate %/sec	Manual	Macro model	Dynamic simulator
1.2	2	V = 7 → 8.4 m/s +10°, −10°		
	5	V = 7 → 10.4 m/s +33°, −20°		V = 7 → 10.4 m/s +5°, 0°
2.0	2			V = 8.4 → 10.1 m/s +2°, −2°
	5	V = 8.4 → 12.6 m/s +30°, −15°	V=8.4→12.6 m/s +30°, −12°	V= 8.4 → 12.6 m/s +6°, −2°
5	2		V=4.2 → 5.1 m/s +18°, −10°	V=4.4 → 5.3 m/s +3°, 0°
	5	V=4.4→6.6 m/s +37°, 0°		V=4.4→6.6 m/s +2°, −2°
6.3	2	V=4.4→5.3 m/s +12°, −10°	V=4.4→5.3 m/s +30°, −0°	V=4.4→5.3 m/s 0°, −5°
	5	V=4.4→6.6 m/s +4°, −22°		

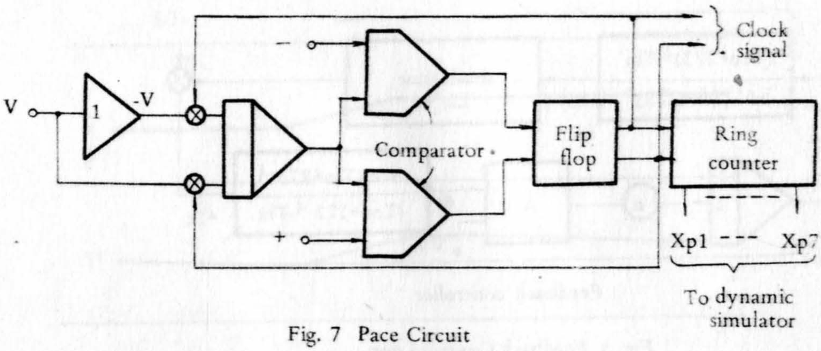

Fig. 7 Pace Circuit

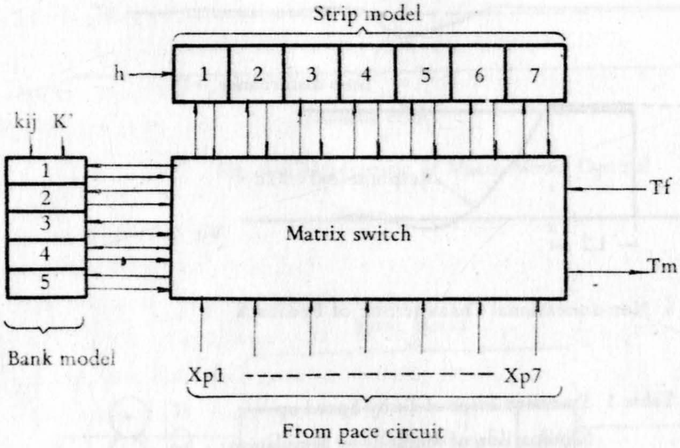

Fig. 8 Dynamic Simulator

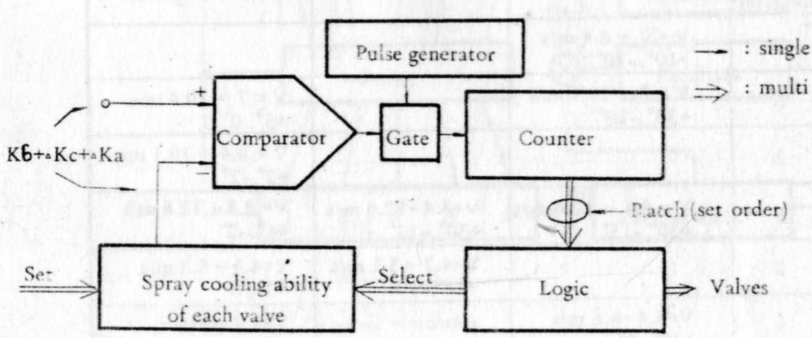

Fig. 9 Valve Selecting Circuit

AN ANALYSIS INTO THE DYNAMIC BEHAVIOUR OF TANDEM COLD MILLS BY A DIGITAL COMPUTER AND ITS APPLICATION

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Introduction

In recent years the automation of tandem cold mills has been making a big stride into the age of computer control. In order to promote the productivity of such equipment, maintain the quality of the products, and carry out safe operation, the excellent capability which computers possess should fully be utilized. The authors developed the technique to simulate the complicated dynamic behaviour of cold tandem mills, by which a variety of valuable knowledge was gained. From this a guidance to develop a new computer directed control system out of the conventional local feed back system was obtained.

Nomenclature

- H ; Thickness of ingoing strip.
- h ; Thickness of outgoing strip, or gauge.
- S_r ; Roll opening, or screw setting.
- K ; Rigidity of mill stand.
- P ; Roll force per unit width.
- G ; Roll torque per unit width.
- $\mathfrak{G}$; Torque generating function.
- t_f ; Forward tension per unit area.
- t_b ; Backward tension per unit area.
- f ; Forward slip.
- ϵ ; Backward slip.
- V_{out} ; Speed of outgoing strip.
- V_{in} ; Speed of ingoing strip.
- $V_{i,i+1}$; Speed of strip btw. i th and i + 1 th stands.
- V ; Peripheral speed of roll, or speed of stand.
- L ; Distance btw. stands.
- L_x ; Distance btw. a stand and an X-ray gauge meter.
- E ; Young's modulus of steel.
- D ; Torque characteristic of main motor.
- i ; Suffix for number of stand.
- Δ ; Symbol which denotes the small deviation.

Description of the mill system

1. Mathematical Expression of the System

Concerning the transient state of rolling by tandem mills, analyses were made by R.A. Phillips,[1] Sekulic and Alexander[2] and В.М Щитова, И А Кувщинов, and Е. И. Слепушкин [3]. In this paper, these analyses were developed further and using a digital computer the dynamic behaviour of a 5 stand tandem mill was investigated in details. In general the thickness of outgoing strip is determined by the roll opening and the elastic elongation of the mill as follows.

$$h = Sr + P/K. \tag{1}$$

Taking the thicknesses of ingoing and outgoing strip, forward and backward tensions, and roll opening as variables in rolling, equation (1) is linerarized for the small deviation of the variables as

$$\Delta h = \Delta Sr \cdot K/(K - \frac{\partial P}{\partial h}) + \Delta H \cdot (\frac{\partial P}{\partial H})/(K - \frac{\partial P}{\partial h}) + \Delta t_f \cdot (\frac{\partial P}{\partial t_f})/(K - \frac{\partial P}{\partial h}) + \Delta t_b \cdot (\frac{\partial P}{\partial t_b})/(K - \frac{\partial P}{\partial h}). \tag{2}$$

The speed of ingoing strip is slower and that of outgoing strip is faster than the peripheral speed of roll. This relationship is expressed as

$$V_{out} = (1+f)\,\mathrm{V}. \tag{3}$$

$$V_{in} = (1+\epsilon)\,\mathrm{V}. \tag{4}$$

Taking the thicknesses of the ingoing and outgoing strip, and the forward and backward tensions as the variables which influence the forward and the backward slips, equations (3) and (4) can be linearized as

$$\Delta V_{out} = \mathrm{V}\left\{(\frac{\partial f}{\partial H})\Delta H + (\frac{\partial f}{\partial h})\Delta h + (\frac{\partial f}{\partial t_b})\Delta t_b + (\frac{\partial f}{\partial t_f})\Delta t_f\right\} + (1+f)\,\Delta \mathrm{V}, \tag{5}$$

$$\Delta V_{in} = \mathrm{V}\left\{(\frac{\partial \epsilon}{\partial H})\Delta H + (\frac{\partial \epsilon}{\partial h})\Delta h + (\frac{\partial \epsilon}{\partial t_b})\Delta t_b + (\frac{\partial \epsilon}{\partial t_f})\Delta t_f\right\} + (1+\epsilon)\,\Delta \mathrm{V}. \tag{6}$$

Also, the rotational speed of the roll varies with the torque. This characteristic of the motor can be expressed as

$$\Delta \mathrm{V} = D\Delta G. \tag{7}$$

The variation of the torque is caused by the variations of the thicknesses of the ingoing and outgoing strip, and the forward and backward tensions. Therefore the deviation of the torque is expressed as

$$\Delta G = \mathbb{G}(\Delta H, \Delta h, \Delta t_f, \Delta t_b) = (\frac{\partial G}{\partial H})\Delta H + (\frac{\partial G}{\partial h})\Delta h + (\frac{\partial G}{\partial t_f})\Delta t_f + (\frac{\partial G}{\partial t_b})\Delta t_b. \tag{8}$$

Tension is applied on the strip between stands, and deforms it elastically. The deviation of the inter-stand tension is determined by the speed of the outgoing strip at one stand and that of the ingoing strip at the next stand as follows.

$$\Delta t_{fi} = \frac{E}{L}\int_0^t (\Delta V_{in,\, i+1} - \Delta V_{out,\, i})\,dt \, . \tag{9}$$

The relationship between the thicknesses of the outgoing strip and the ingoing strip is expressed by using the Laplacian operator as

$$H_{i+1} = h_i \cdot e^{-s(L/v_{i,\, i+1})} \, . \tag{10}$$

The partial derivatives were calculated from rolling theories[4,5]. Figure 1 shows the block diagram of the mill system which includes the torque generating function (block G i), and the Automatic Speed Regulation system (block Di). The system contains more than one hundred elements which makes the simulation by an analogue computer impractical. In view of the multiplied capacity and calculating speed of digital computers, the simulation technique of the continuous system by such a computer was developed[6].

System dynamics of the mill

To analyse the dynamic behaviour of the cold tandem mills the step change of the hot band gauge, the peripheral speed of the rolls, and the roll openings were put into the mill system, and the response of the system was investigated. The rolling schedule used in the calculation is shown in Table 1. The results of the simulation are shown in Figure 2 ~ Figure 7 for the cases of the small deviation of hot band gauge of roll openings at the first and the fifth stands, and of the peripheral speed of the rolls at the first, the third, and the fifth stands. The results from the analyses are summarized as follows.

(1) The abrupt increase of the hot band gauge decreases the interstand tensions. When the gauge deviation arrives at one stand, the forward tension decreases, and it decreases further when the deviation arrives at the next one.

(2) The outgoing strip gauge increases the most by the increase of the ingoing strip gauge. However it is further increased by the decrease of the tension between the stand and the next stand caused by the arrival of the thickness increase at the next stand.

(3) By the decrease of the roll opening of the first stand, the gauge at

all stands and all the interstand tensions decrease.

(4) By the decrease of the roll opening of the fifth stand, the finished gauge decreases. But at the same time the tension between the fourth and the fifth stands decreases to a large extent, causing the increase in the gauge at the fourth stand. And after certain moment only small deviation is observed as for the finished gauge.

(5) By the increase in the speed of the first stand, all the interstand tensions decrease by which all the gauges decrease.

(6) As for the stands between the first and the final one, the increase of the speed causes the decrease of the forward tension and the increase of the backward one. The finished gauge deviates to a small extent after a transient change.

(7) The increase of the speed at the fifth stand increases the tension between the fourth and the fifth stands, decreases the gauge at the fourth stand and finally the finished gauge.

(8) The backward effect of the rolling conditions of one stand through interstand tensions is limited to the preceding stand and affects the stand before the preceding one to negligibly small extent.

(9) Accordingly the factors which influence the finished gauge are the change in the speed of the first and the fifth stand, the roll opening of the first stand, and the hot band gauge. The other factors change the finished gauge temporarily, but have small effect on it finally.

The Analysis of the AGC System and its Application

1. Improvement of the conventional AGC system

To analyse the complicated dynamic behaviour of the AGC (Automatic Gauge Control) system, the simulation was applied to a tandem cold mill which is equipped with the conventional AGC system. The block diagram of No.1 STD. AGC, and the No.5 STD. AGC are shown in Figure 8 and 9 respectively. The gauge deviation at the first stand will be fed back to the screw down motor at the stand when it is over the range of a dead zone. The motor continues running during an ON-TIME which is supposed to be the time to cancel the gauge deviation, and pauses during an OFF-TIME which is the time required for strip to travel from the first stand to an X-ray gauge meter.

The present value of the gain of the system is too small to settle the deviation in a short while. So the simulation was made for the formerly used and the increased (×3) motor speeds, as shown in Figure 10, accompanied by the experiments with the motor speed 1.44 times as fast as the formerly used one, as shown in Figure 11. In both cases the response to the step change of the hot band gauge was observed with the distinct reduction in settling time. Figure 12 shows the comparison of the effects of the difference in screw down motor speed on the skid marks of hot band on the daily run. As shown in the figure the increased motor speed diminishes the deviation of gauge without hunting.

Concerning the No.5 STD. AGC, the finished gauge control is done by the tension between the fourth and the fifth stands. The change in tension is generated by the control of the speed of the fifth stand actuated by the gauge deviation signal resulted from the comparison of the set value and the signal from an X-ray gauge meter. The results of the simulation for the various control modes are summarized in Figure 13. It was clarified that the present control system is based on the proportional control principle and hence the offset in the finished gauge is inevitable, but that by using the P + I control this offset can be cleared out.

2. A new AGC system

In view of the speed-up of the response of the AGC system, the authors developed a new system in which the signal from an X-ray gauge meter located at the entry side of the first stand is fed forward to the screw down of the stand. To evade the gauge variation caused by the change of the tension btw. the first and the second stand, the change in the forward slip of the first stand is also predictively adjusted with the X-ray signal to maintain the constant speed and the tensions. The control equations for the adjustment of the screw settings and the peripheral speed of the roll is obtained from above equations by nullifying Δh_1 and compensating the speed deviation caused by the variation of the forward slip (see Figure 1) as follows.

$$\Delta S_{r1} = \frac{K}{\left(\frac{\partial P}{\partial H}\right)_1} \cdot \Delta H_x \cdot e^{-\frac{L_x}{v_{01}} \cdot s}, \tag{11}$$

$$\Delta V_1 = \frac{\left(\frac{\partial f}{\partial H}\right)_1}{1 + f_1} \cdot V_1 \cdot \Delta H_x \cdot e^{-\frac{L_x}{v_{01}} \cdot s}. \tag{12}$$

The partial derivatives and the forward slip are selected according to the pass schedules. Further, as the monitor an X-ray gauge meter is installed at the delivery side of the first stand to feed back the measured value to the No. 1 STD. AGC. As for the deviation of the finished gauge caused by the disturbances after the first stand, the conventional No. 5 STD. Tension AGC is utilized. The block diagram of the new control system is shown in Figure 14. The simulation results of the comparison between the responses of the conventional system and the new system are shown in Figure 15.

Gauge Alteration in Rolling

In order to enlarge the productivity of tandem cold mills the hot band coil should be as bulky as possible. The coil weight of the hot band is usually limited by the size of finished coils or of orders. If it is possible to alter the finished gauge freely, or to roll several kinds of finished gauges out of a hot band coil, the productivity of the mill will be considerably magnified.

1. Theory of gauge alteration in rolling

When the roll openings are changed with the purpose of altering the finished gauge, the inter-stand tensions will be varied. With the increase of the extent of the gauge alteration, the change of the inter-stand tensions is enlarged finally to the point where the smooth running of the mill becomes impossible. Therefore it is necessary to maintain the inter-stand tension constant. In order to nullify the deviation of the tensions it follows from equation 9.

$$\Delta V_{in,\,i+1} = \Delta V_{out,\,i}\,. \tag{13}$$

Therefore referring to equations 5 and 6 the following equation should be satisfied for the control of the speed of each stand.

$$\Delta V_{i+1} = \left\{ \left(\frac{\partial f}{\partial H}\right)_i \Delta H_i + \left(\frac{\partial f}{\partial h}\right)_i \Delta h_i \right\} \cdot V_i \big/ (1+\epsilon_{i+1}) + \left(\frac{1+f_i}{1+\epsilon_{i+1}}\right) \Delta V_i - \left\{ \left(\frac{\partial \epsilon}{\partial H}\right)_{i+1} \cdot \Delta H_{i+1} + \left(\frac{\partial \epsilon}{\partial h}\right)_{i+1} \cdot \Delta h_{i+1} \right\} \cdot V_{i+1} \big/ (1+\epsilon_{i+1})\,. \tag{14}$$

As is clearly shown in Equation 14 in order to maintain the constant inter-stand tensions in case of the alteration of roll openings, the speed of i + 1 th stand should be controlled in correspondence to the deviation of the gauge of i - 1 th, i th, and i + 1 th stands and that of the speed of i th stand. For this kind of control, it is proper to apply the programme control in use of a computer. First of all the patterns of the speed of each stand according to the elapsed time for the compensation of the variation of the tensions are calculated for the case of the change in screw setting of a certain stand by a unit length (0.1 mm). Figure 16 is shown for the case of the change in screw setting of the first stand. These patterns are memorized in an on-line computer. When the roll openings of the stands are required to alter in a certain mode, the speed patterns will be calculated by the linear combination of the original speed patterns as is shown in Figure 16. Figure 17 shows the speed patterns of all stands for the case of an unanimous change of the roll openings at all stands. The screw setting alteration order and the speed pattern alteration order are given to the screw down control system and the roll speed control system of each stand respectively through I/O INTERFACE as shown in Figure 18. The minor variation of the tensions will be controlled by the conventional feed back system. By such constant tension control, the G.A.I.R. (Gauge Alteration in Rolling) can be realized.

2. An experiment on the conventional tension control system

To judge how smooth the G.A.I.R. can be done by the conventional feed back system, an experiment was done on a tandem cold mill. In this system the tensions are controlled by screw settings and the speed of stands both actuated by the signal from tension meters over a range of dead zone as shown in Figure 19. In rolling, the screw settings of all the stands were lowered by 300μ in 8 seconds, with the reduction of the finished gauge by 140μ. Some of the tensions were drastically diminished, especially the one between the second and the third stands as shown in Figure 20. This seems to be due to the slow response of the control system and the main motor.

Conclusively, the present system cannot compensate the abrupt change of the tensions sufficiently and safely. And for the G.A.I.R., online computers should be used in the programme control of the speed of stands in correspondence to the change in the screw setting.

3. Possible future application of the G.A.I.R. system

In order to automatize the operation of a tandem cold mill completely, dynamic computer control system should be introduced. The following are a few examples of the future application of the G.A.I.R. system.

(1) Modification of finished gauge

Due to the complexity of cold rolling phenomena, the pre-set value of pass schedules selected by operators, or by an on-line computer may not put the finished gauge in the control range of AGC. Such adjustment can easily be done by the G.A.I.R. system.

(2) Reduction of off-gauge

Off-gauge is the increase of strip gauge caused by the speed characteristic of the bearing film thickness of back-up rolls, and the coefficient of friction in rolling in the acceleration and the deceleration of a mill. The change is too rapid to be followed by feed back control systems. A program control by the G.A.I.R. system can compensate the off-gauge without the breakage of strip or cobbles (failure of rolling by lapped strip).

Conclusion

By the simulation of 5 stand tandem cold mills the dynamic behaviour of the mill was known, which give rise to new control systems by the programming and the direction of on-line computers.

When tandem cold mills are to be fully automatized, the investment will not be justified if simply the function of human operators is replaced by computers without the cost reduction by the development of dynamic control systems.

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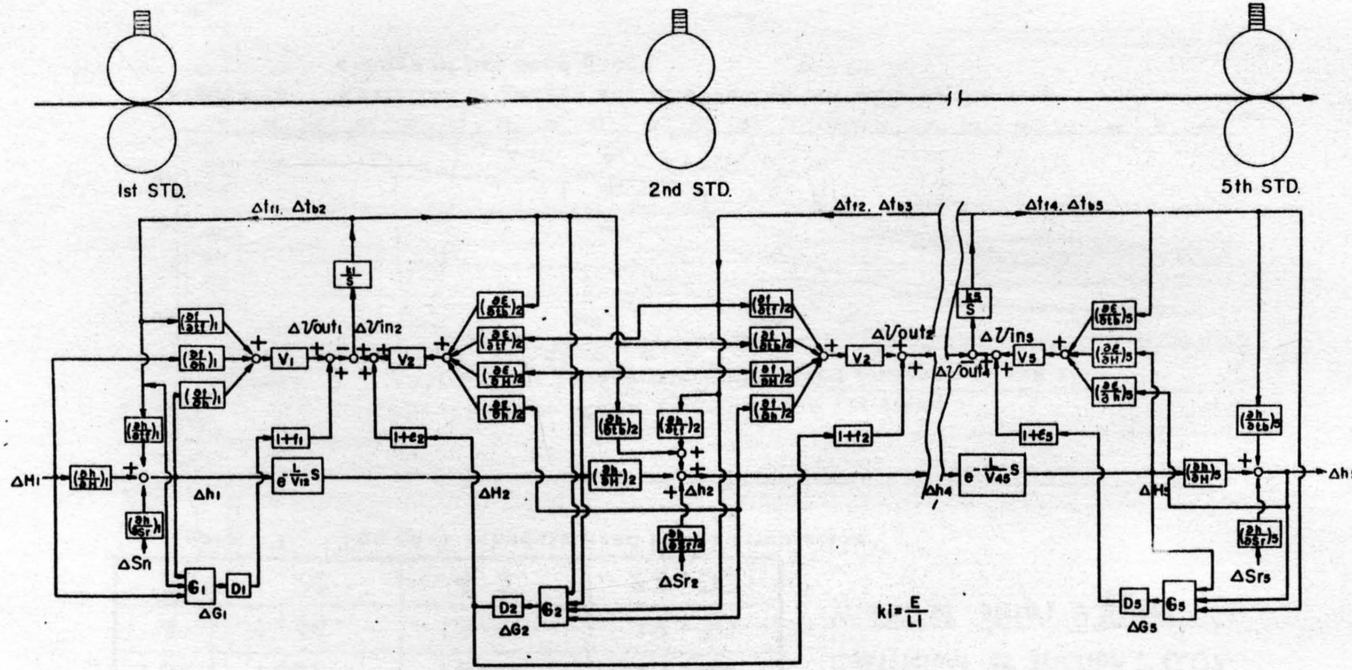


Figure 1 Block Diagram of the 5 stand Tandem Mill System

STD	STRIP GAUGE (mm)	FORWARD TENSION ($^{Kg}/_{mm^2}$)	PERIPHERAL SPEED OF ROLL ($^m/_s$)
1	2.64	10.2	9.62
2	2.10	12.8	12.35
3	1.67	16.1	15.44
4	1.34	16.1	19.30
5	1.20	4.5	22.00

Hot band gauge ; 3.2 mm

Distance btw. stands ; 4600mm

Rigidity of mill ; 470 $^{ton}/_{mm}$

Radius of work roll ; 273 mm

Coefficient of friction ; 0.07

Width of strip ; 930mm

Table 1 The pass schedule used in the simulation

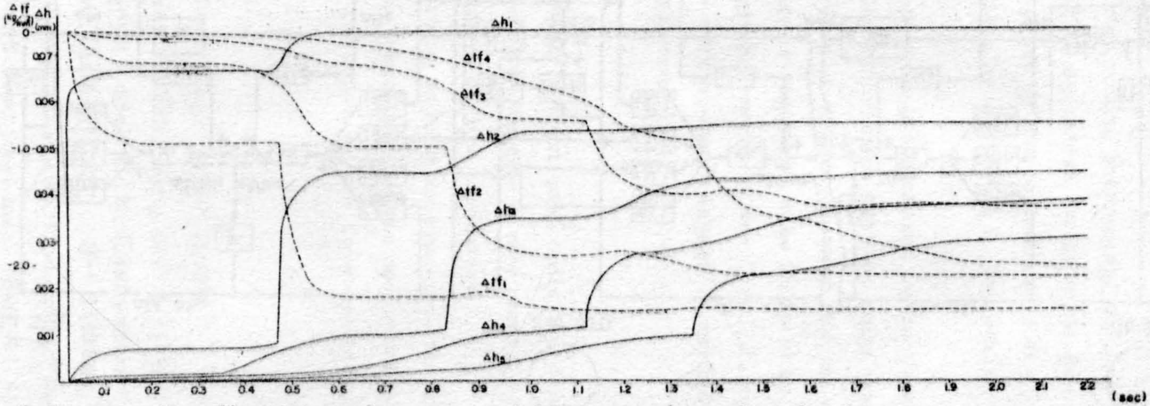


Figure 2 Variation of gauges and inter-stand tensions by the step change of hot band gauge

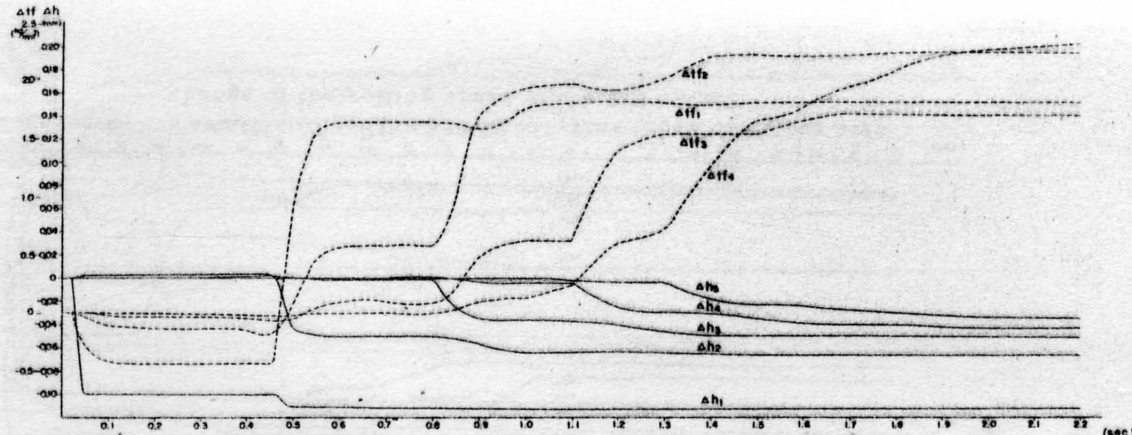


Figure 3 Variation of gauges and inter-stand tensions by the step change of the screw setting of the 1st stand

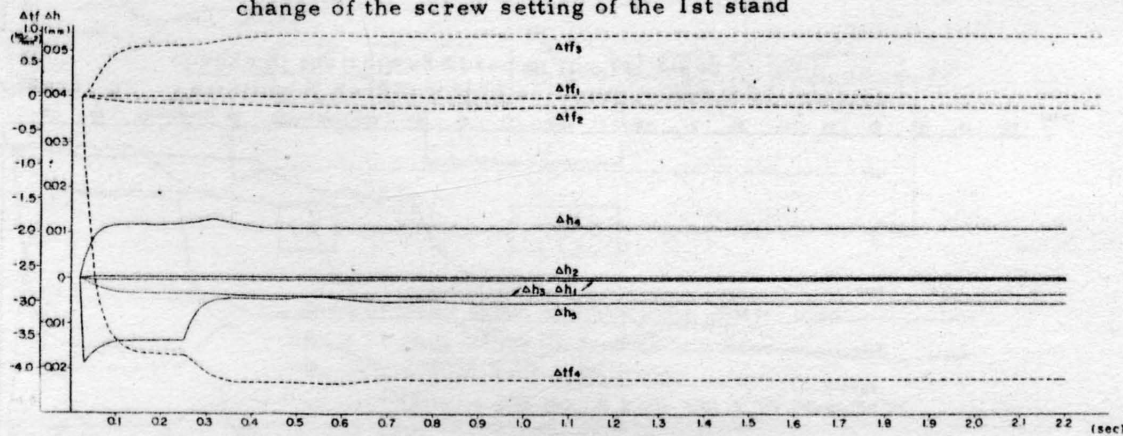


Figure 4 Variation of gauges and inter-stand tensions by the step change of the screw setting of the 5th stand

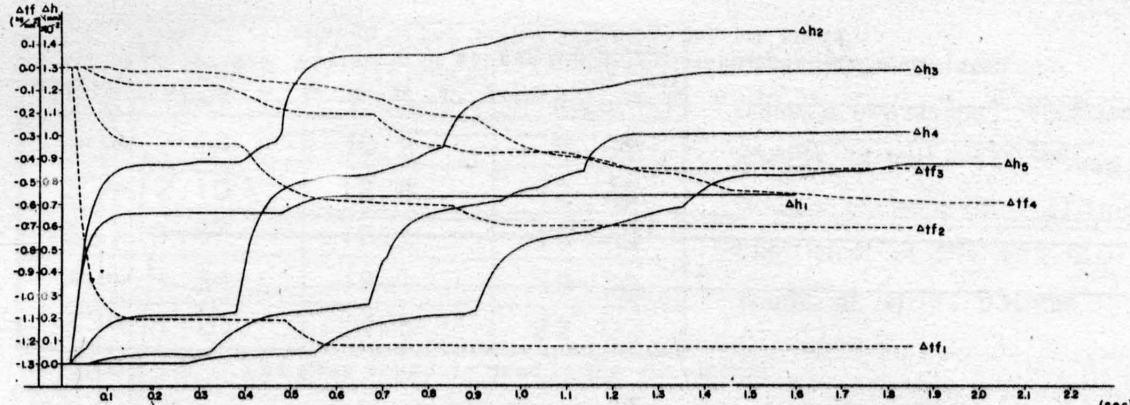


Figure 5 Variation of gauges and inter-stand tensions by the step change of the rolling speed of the 1st stand

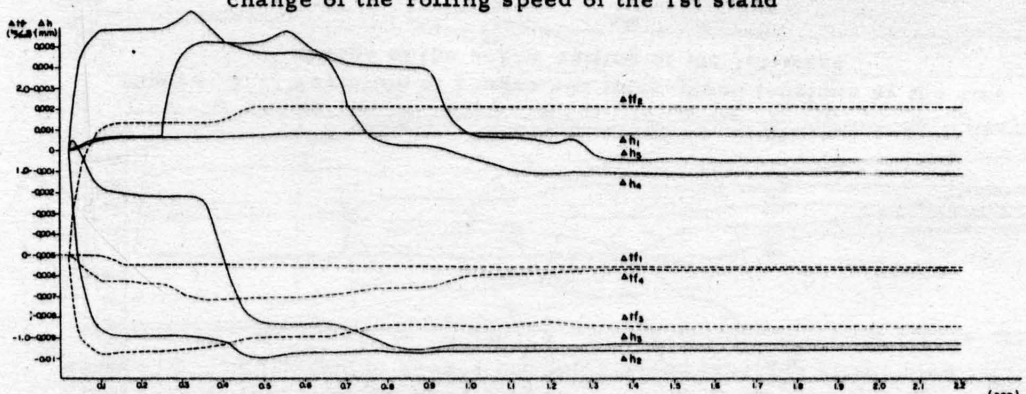


Figure 6 Variation of gauges and inter-stand tensions by the step change of the rolling speed of the 3rd stand

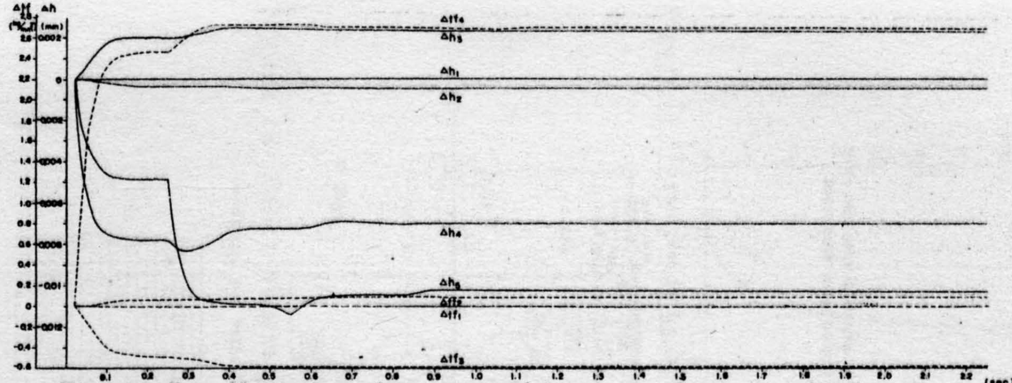
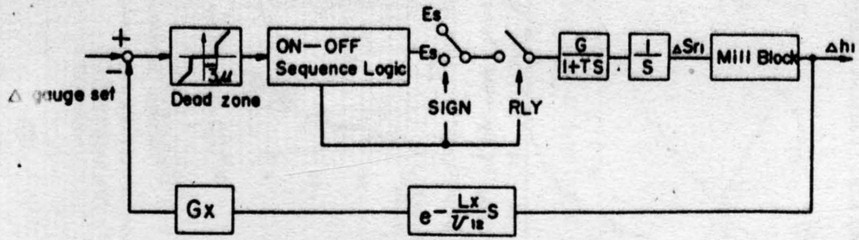


Figure 7 Variation of gauges and inter-stand tensions by the step change of the rolling speed of the 5th stand



SIGN ; Relay switch for the direction of screw down.
RLY ; Relay switch for on and off.
Gx ; Gain of X ray gauge meter.
Lx ; Distance btw. the 1st stand and X ray gauge meter.

Figure 8 No. 1 stand AGC (Screw Down Control)

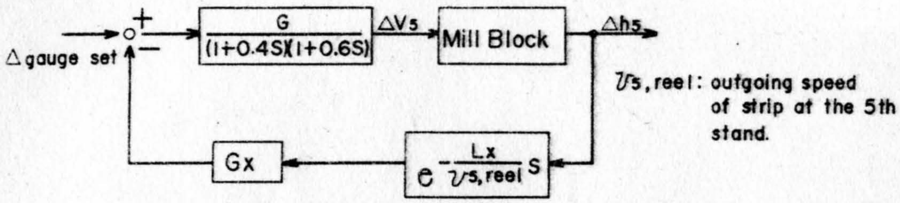


Figure 9 No. 5 stand AGC (Tension Control)

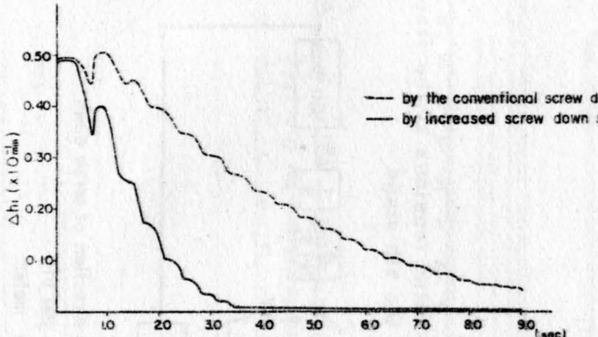


Figure 10 Variation of h_1 by the step change of hot band gauge by 0.1mm

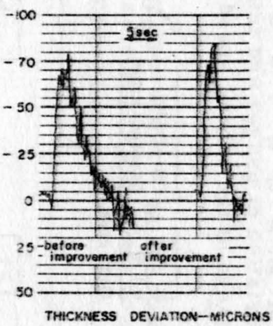


Figure 11 Comparison of settling time before and after the improvement on the No. 1 stand AGC

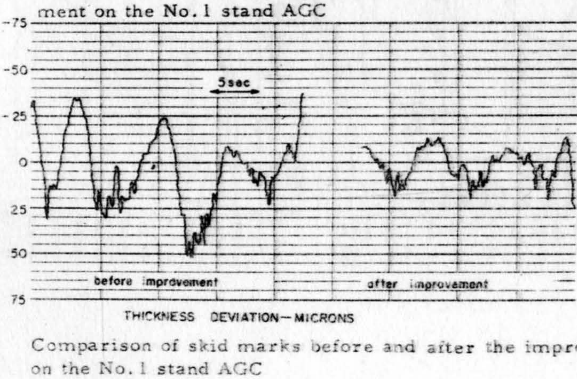


Figure 12 Comparison of skid marks before and after the improvement on the No. 1 stand AGC

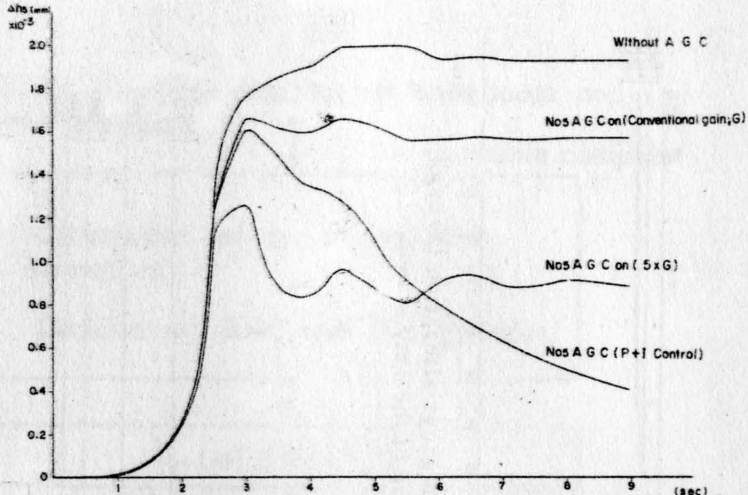


Figure 13 Variation of h_5 by the change of hot band gauge by 0.1mm

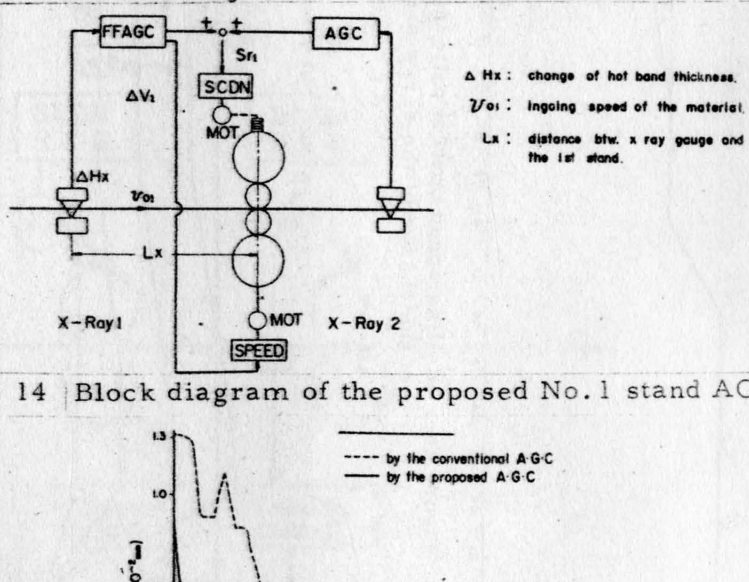


Figure 14 Block diagram of the proposed No. 1 stand AGC

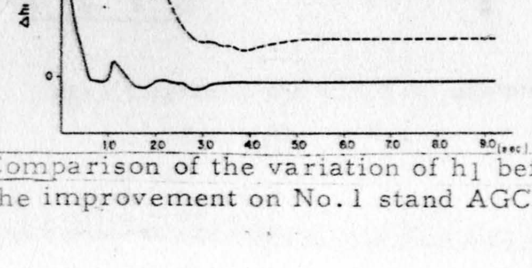


Figure 15 Comparison of the variation of h_1 before and after the improvement on No. 1 stand AGC system

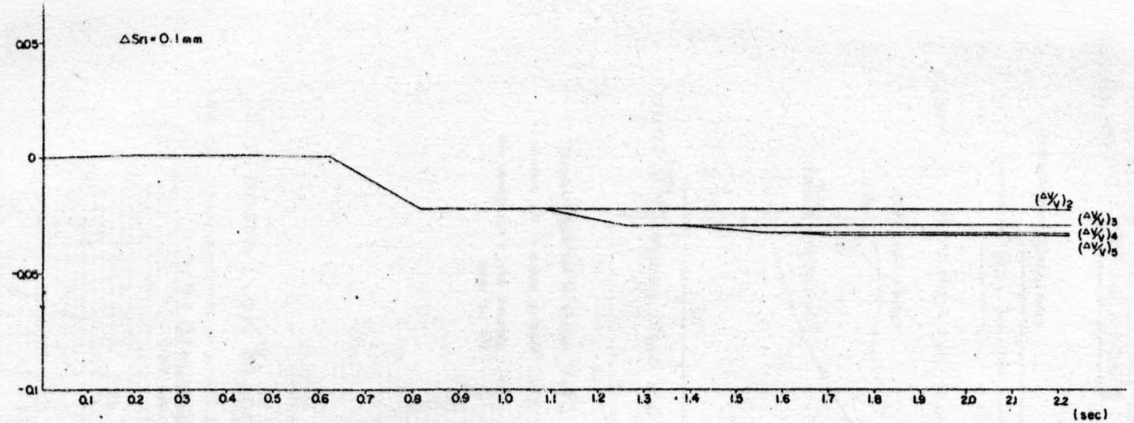


Figure 16 Rolling speed control patterns in gauge alteration (in case of the change of the screw setting of the 1st. stand)

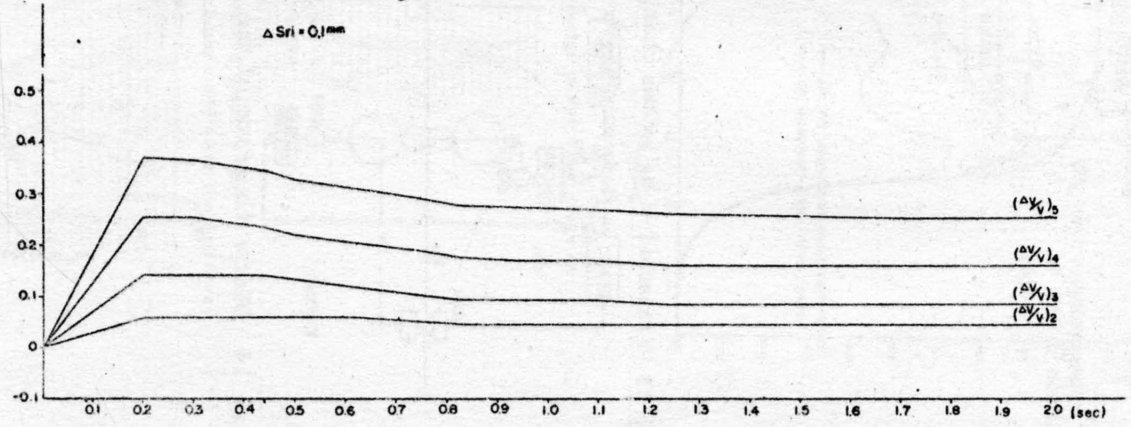


Figure 17 Rolling speed control patterns in gauge alteration (in case of the unanimous change of the screw settings of all stands)

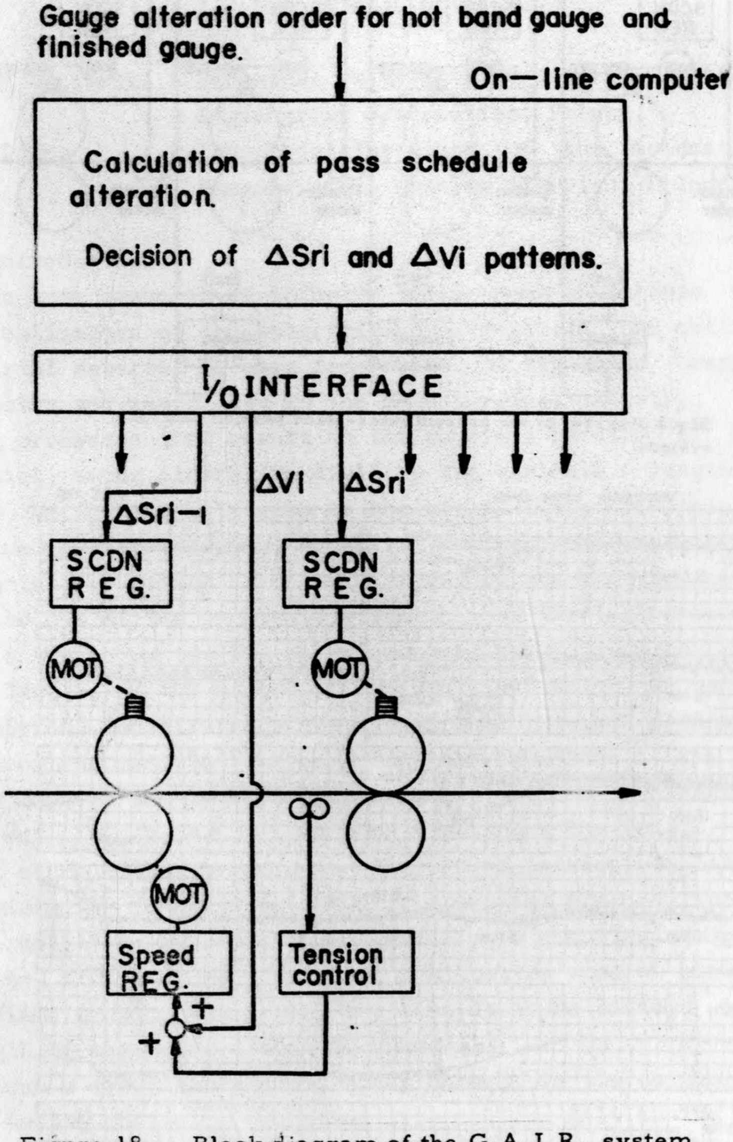


Figure 18 Block diagram of the G.A.I.R. system

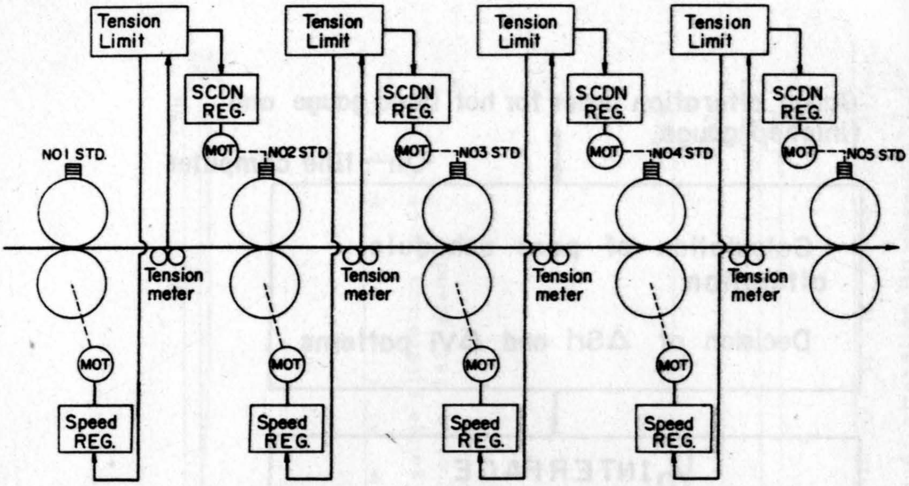


Figure 19 Block diagram of the present inter-stand tension control system

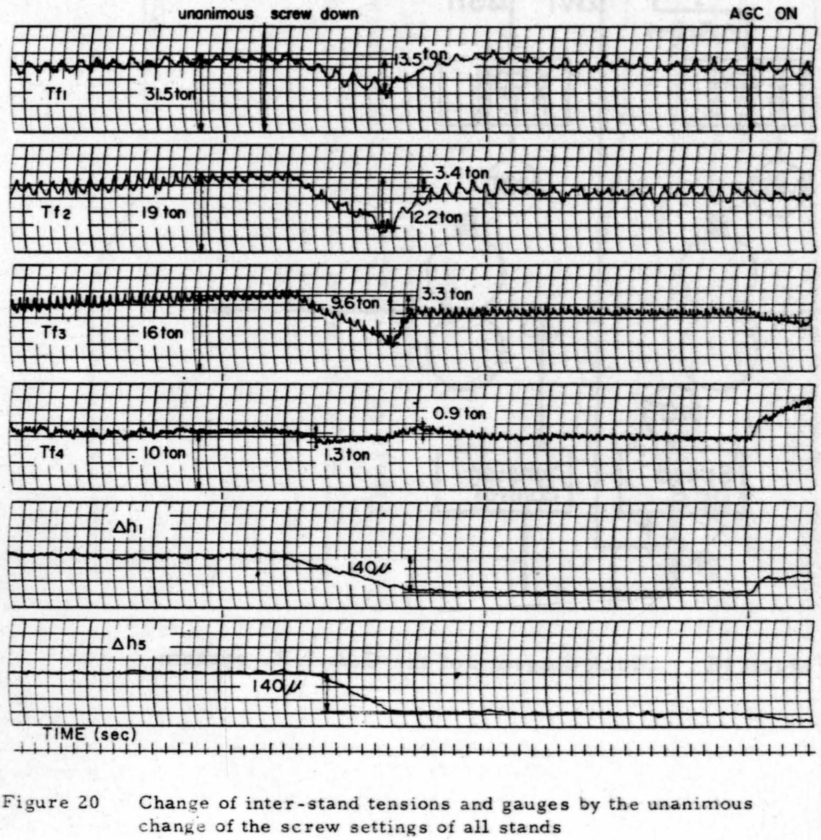


Figure 20 Change of inter-stand tensions and gauges by the unanimous change of the screw settings of all stands

THE OPTIMIZATION OF CUTTING PROCESS IN CASE OF UNCOMPLETE INFORMATION ABOUT PROCESS

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1. Introduction.

In many branches of industry there occur situations when the minimalization of the material waste resulting from cutting industrial material becomes imperative. In the basic branches of industry and especially in the metallurgical industry, the cutting processes that result in the physical parting of material consist, among others, in dividing the variable - length bands into the lengths belonging to the set of the permissible lengths defined by technological aspects. The length of the last piece of material resulting from the dividing of the band may not belong to the set of the permissible lengths and the last piece constitutes then a waste. The set of numbers expre..ing the permissible lengths of the pieces of material into which the band is to be divided constitutes often a numerical interval defined by the minimum permissible length b_o and the tolerance δ .The division of a band of the total length l into pieces of the lengths from the set $[b_o,(b_o+\delta)]$, in such a way that the length of the last piece either belongs to the set of permissible lengths or is minimum - constitutes actually a trivial problem. The technical reality is however in many cases more complicated.During the cutting processes we often meet a situation whne we know the permissible lengths into which the band is to be divided but the lehgth of the devided band is unknown.

Such a situation occurs, among others, in the cutting processes in the continous operation type rolling mill in the metallurgical industry. In the cutting process in the continous operation type rolling mills the rolled material is being cut into lengths successively i.e. every time after the piece of material having the length corresponding to the required length leaves the last roller cage. In this case the band is cut before the completion of the technological process forming the final shape of . the band and then we may say that the band does not exist physically. The diagram of the cutting process on the continuous operation type rolling mill is shown in fig.1.

The cutting process on the continuous operation type rolling mills may be considered as an illustration of the process in which the length of the band to be cut cannot be determined with an sufficient accuracy because its direct measurement is not possible.

2. Controlling of the cutting processes.

During the last years, at the same time as the digital devices and machines appeared in the automation systems of technological processes, a number of systems for thr automatic controlling of the cutting processes have been developed [1]. Their purpose was to minimize the waste. The basic operations of these systems are the following : the automatic measuring of the quantities permitting to determine the length of the band, determination of the permissible lengths of pieces minimizing the length of the waste or giving the wasteless dividing of the band and the controlling the operation of the shears that realize physically the dividing of the band.

Denoting by U a set of the controlling and measuring devices in the control system and by P - the cutting process itself, the control system structure can be represented as below - fig.2.

On the input of the control device an information regarding the length l of the band together with some disturbance Π(that we shall define in future as an estimation error) are given.

This disturbance characterizes an error when estimating the length of the band. The output of the control device determines lengths of pieces into which the band of a total length l should be divided, optimal as regards the minimum of waste. Optimal lengths of pieces are defined by a quantity b - that we shall call a controlling vector. The components of the controlling vector determine the lengths of successive pieces into which the band should be divided.

The variable $\bar{c}$ is a vector the components of which determine the actual lengths of pieces resulting from the dividing of the band. The components of the vector $\bar{c}$, except perhaps the last component, are equal to the respective components of the vector $\bar{b}$.

The cutting process control systems used in the industry are realized, generally speaking, by using the specialized digital devices, or - in some cases - by using the universal computers [2]. In the control system the lengths of the band and pieces can be they expressed as integers. It is so because these quantities are always characterized by a whole number of electrical pulses, and one unit length, invariant for a given cutting process, corresponds to each of the pulses. If we assume that $\eta = 0$ then a full information of the band length exists and the algorithm of the optimal controlling of the cutting process is the following.

Algorithm I

1. $E/\frac{1}{b_o}/ = n$ — $E/x/$ - denotes the function entier of x
2. $n/b_o + \delta/ - 1 = \alpha$

3.1 $\alpha \geqslant 0$

3.1.1 $\alpha - nE/\frac{\alpha}{n}/ = \beta$

3.1.2
$$b^i = \begin{cases} /b_o+\delta/ - E/\frac{\alpha}{n}/ + 1 & \text{for } I = 1,2,\dots\beta; \\ /b_o+\delta/ - E/\frac{\alpha}{n}/ & \text{for } i = /\beta+1/\dots n; \end{cases}$$

3.2 $\alpha < 0$

3.2.1 $b^i = b_o + \delta$ for $i=1\dots n$;

For $\alpha \geqslant 0$ the length of waste is $|\alpha|$, and in case if $\alpha < 0$, the division is wasteless. The computations according to the given algorithm are being performed in the controlling device of the control system. The above algorithm of the optimal controlling of the cutting processes makes sense only in such a case if the band length is known i.e. when there exists a full information of the cutting process.

We shall assume in further consideration that the band lengths satisfy the inequality :

$$1 \geqslant E/ - \frac{b_o}{\delta}/./ - b_o/ + /2\, b_o + \delta / \qquad /1/$$

In such a case the wasteless division of the band is always possible.

3. Control with the uncomplete information.

The controlling variables in the cutting process are the components of the control vector which may be chosen arbitrarily from the set of permissible lengths. The selection of the values of the control vector components decides, of course, of the magnitude of waste resulting from the dividing of the band. To every band of the length l satisfying the inequality /1/ corresponds a control vector constituting a sequence of natural numbers :

$$\bar{b} = / b^1, b^2 \ldots b^n/ ; b^i \in [b_o, /b_o + \delta/] ; /i = 1,2\ldots n/$$

such that the value of an expression

$$\omega_l = l - \sum_{i=1}^{n} b^i \qquad /2/$$

satisfies the inequality :

$$-b_o < \omega_l < b_o \qquad /3/$$

The value ω_l we shall call the deviation of the control vector from the band length. Of course, for every band length there exists the control vector for which the deviation ω_l satisfies the inequality /2/.

The uncomplete information regarding the process may be expressed in the form of the presenceof the prediction error when estimating the band length. The information about the band length, accessible in the control system, we shall call an anticipated band length and we shalldenote it by L. Let us assume tha t:

$$L = l + \Pi \qquad /4/$$

Besides, let us assume that the random variable Π can take on values being integers from the interval: $[-\eta, \lambda]$ where :

$$\eta > 0 \quad \text{and} \quad \lambda > 0 \quad \text{and} \quad \eta + \lambda < b_o - \delta \qquad /5/$$

In the cutting process the deviation of the control vector from the actual band length should satisfy the requirement /3/ because otherwise the cutting process would end either before the band is completely divided up, or some number of superflous "fictive" cuts would be performed in the situation when the complete division on the band has already been made.

In connection with that and on the basis of the relations /4/ and /5/, the deviation of the control vector from the anticipated band length - that we shall denote by ω_L - should satisfy the inequality :

$$-/b_o - \lambda/ < \omega_L < /b_o - \eta/ \qquad /6/$$

The length of a waste caused in result of corresponding the anticipated length to the control vector L :

$$\bar{b} = /b^1, b^2, \ldots b^n /$$

for which the deviation ω_L satisfies the inequality /6/ depends on the value of the estimation error Π as well as on the value of the deviation ω_L and on the last component b^n - of the control vector $\bar{b}$.

A function defining the length of waste for every three integers $/b^n, \omega_L, \Pi/$ where : $b^n \in [b_o, /b_o + \delta/]$; $\Pi \in [-\eta, \lambda]$ and ω_L satisfies the inequality /6/ will be called a loss function. From the analysis of the cutting process it results that the loss function has the following form :

$$\Omega[b^n, \omega_L, \Pi] = \begin{cases} /\omega_L - \Pi/ & \text{for} \quad \Pi < \omega_L \\ 0 & \text{for} \quad \omega_L < \Pi < \omega_L + /b^n - b_o/ \\ /\omega_L - \Pi/ + b^n & \text{for} \quad \Pi > \omega_L + /b^n - b_o/ \end{cases} \qquad /7/$$

The loss function can takes values being integers from the range $[0, /b_o - 1/]$.

Values ω_L and b^n are "controllable" variables and thus, for every band of a length satisfying the inequality /1/ these values can be determined a priori and the control vector $\bar{b} = /b^1, .., b^k/$ for which:

$$L - \sum_{j=1}^{k} b^j = \omega_L \qquad \text{and} \qquad b^k = b^n$$

exist in every case.

A control vextor for which $\omega_L = \omega'$ and $b^n = b'$ can be found on the basis of an algorithm I.

Thus the problem of the controlling of the cutting process can be reduced to the selection of the deviation and of the last component of the control vector, in conditions of the existance of the non-controlled disturbance in the form of the estimation error. The quality of the control, i.e. the consequence of selecting the concrete values of the pair "deviation, last component" - is defined for every value of the estimation error by the loss function. The problem of controlling of the cutting processes with the uncomplete information of the process can be considered as a discrete controlling of the object of the following form, (fig.3).

The purpose of the cutting process consists in the minimization of the waste measured by the loss function. A random variable is an independent variable of the loss function. In connection with that, the loss function for every pair of fixed values ω_L and b^n is a random variable.

If the probability distribution of the estimation error is unknown, the conception of the game against "nature" is assumed for the analysis of the problem. As the optimization criterion we choose then the minimax criterion consisting in the minimization of the value of the expected value of the loss function in the situation in which "nature" tries to maximize that value. Before attempting to define the model of the game let us note that the loss function and the values b^n, ω_L and Π take values of the finite set of integers.

Consequently the values of the loss function can be treated as elements of a matrix. We shall introduce, because of that, the following denotations that will facilitate the further analysis :

$$\omega_L = -/b_o - \lambda/ + i$$
$$\Pi = /\lambda + 1/ - k \qquad /8/$$
$$b^n = b_o + j$$

and

$$\lambda + \eta + 1 = m ; \quad b_o, \lambda, \eta = \text{const.}$$

The variable "i" characterizes the deviation of the control vector from the anticipated band length L, the variable "j" defines the difference between the value of the last component of the control vector and the value of the minimum permissible length of the pieces, while "k" is a random variable of discrete type characterizing the value of the estimation error.

From the definition of the components of the control vector and the set of values of the estimation error as well as from the inequality /6/ it becomes :

$$i \in \{1,2, \ldots ,/2b_o - m/\} \qquad /9/$$
$$j \in \{0,1, \ldots, \delta\} \qquad /10/$$
$$k \in \{1,2, \ldots , m\} \qquad /11/$$

The loss function expressed through variables /i,j,k/ has the form :

$$\Omega/b^n,\omega_L,\Pi/ = \Gamma/i,j,k/ = \begin{cases} /i+k/-/b_o+1/ & \text{for } i+k > b_o+1 \\ 0 & \text{for } /b_o+1/-j \leqslant i+k \leqslant b_o+1 \\ /j-1/+/i+k/ & \text{for } i+k < /b_o+1/-j \end{cases}$$

4. Game model.

The problem of controlling of the cutting processes in the case of uncomplete information of the process can thus be investigated as a finite matrix game with zero-sum.

It has been assumed that the control device U plays against a fiction adversary P, who charcterizes the process. The U-player can select any pair of numbers /j,i/ of elements "j" and "i" satisfying the relations /10/ and /9/. Every pair of numbers/j,i/ is a pure strategy of the U-player. The P-player can make selection between all numbers "k" satisfying the relation /11/.

The quantities "k" are pure strategy of P-player. Had the U-player selected a strategy /j,i/ and the P-player - a strategy k, the loss of the U-player or the gain of the P-player will be determined by the value Γ/j,i,k/. The selection of a strategy /j,i/ by the U-player and a strategy k by the P-player means, that in the control system the anticipatedband length L sytisfying the condition /1/ corresponds the control vector of the last component equal to /b_o+j/ and of the deviation $[-/b_o-\lambda/+i]$ in the situation when the estimation error value is $[/\lambda+1/ - k]$.

The choise of the control vector is made by the control device for which the information regarding the value of the estimation error is not accessible.

The matrix of game for the U-player contains /δ +1/./2b-m/ lines and "m" columns. Values of the loss function with a "minus " sign constitute elements of the game matrix. If we arrange the elements of the set of strategies of the U-player lexicographically and mark them with the succesive cardinal numbers and if we arrange the elements of the set of strategies of the P-player after the minority relation, then the play matrix can be written in the form :

$$C = \begin{Vmatrix} C_o \\ C_1 \\ \cdot \\ \cdot \\ \cdot \\ C_j \\ \cdot \\ \cdot \\ \cdot \\ C_\delta \end{Vmatrix} \qquad /13/$$

where C_j denotes the matrix :

$$C_j = \left\| c^j_{ik} \right\| \qquad / \; i = 1,2,\ldots,/2b-m/; \quad k = 1,2,\ldots,m \; /$$

where :

$$C^j_{ik} = - \Gamma /j,i,k/ \qquad /j = 0,1, \ldots , \delta /$$

The strategy "k" corresponds to the column with number "k" while the strategy /j,i/ which is the sth element of the arranged set of U-player strategies, corresponds to the line with number "s". Numbers expressing the gain of the U-player /length of the waste with minus sign/ for different pairs of strategies Γ/j,i/,k are the elements of a game matrix.

On the basis of the dominance principle known from the theory of games, the game matrix /13/ can be reduced to the m-dimensional Hankel's matrix of a form :

$$A = \| a_{sk} \| \qquad /s = 1,2,\ldots,m; \quad k = 1,2,\ldots,m/ ; \qquad /14/$$

where :

$$a_{sk} = - \Gamma \left[\delta ; /b_o - \delta - m + s/ ; k \right]$$

From this and from /8/ it results that the optimum value of the last component of the control vector /from the point of view of the waste minimization/ is a constant value :

$$b^n = b_o + \delta$$

and that the "advantageous" from that point of view deviations are deviations of the values from the set of integers :

$$\left\{ -/\delta + \eta /, \ldots, -1, 0, +1, \ldots , +/\lambda - \delta / \right\} \qquad /15/$$

The way of selection the deviations ω_L from the set /15/ defines the solution of the game A. If the diameter of the intervale of the changes of the estimation error is not greater than the tolerance δ , then the game A has a saddle point and the number $/\lambda - \delta/$ is an optimum value of the deviation. In such a case the division of the band is always wasteless. On the contrary, when the diameter of the interval of the change of the estimation error is greater than the tolerance, the game A is completely randomized and the optimum - in a minimax sense - decision rule is constituted by the minimax strategy :

$$X^o = /X^o_1, X^o_2, \ldots , X^o_i, \ldots , X^o_m/; \quad X^o_i = P\left[\omega_L = -/\eta + \delta + 1/ + i \right]$$

defining the optimum probability distribution in the set of the "advantageous" deviations. The average length of the waste is defined by the game value /for the P-player/ which is constant and always greater zero [3].

Because of the special form of the matrix A and the fact that the game is completely randomized, the solution of the game can be expressed explicite - without necessity of inversing the game matrix.

In the case in which the probability distribution of the estimation error is known and defined by the vector :

$Y = /Y_1, Y_2, \ldots, Y_k, \ldots, Y_m/$; $Y_k = P\left[\Pi = /\lambda + 1/ - k\right]$;

the problem of minimizing the expected value of the loss function can be formulated as the solution of the game given by the single-column matrix a form :

$$B = \left\| b_{s1} \right\| \qquad /s = 1, 2, \ldots, m/; \qquad /16/$$

where:

$$b_{s1} = \sum_{k=1}^{m} a_{sk} \cdot Y_k$$

It is evident that such a game has always a non-randomized optimum strategy, easy to be determined by comparing the elements of the matrix /16/.

Besides of the minimax principle and the criterion of the minimization of the expected value - to the selection of the deviation can also be applied other decisive criteria, e.g. Hurwic's criterion, Laplace's criterion etc.

5. Digital structures for the cutting control with uncomplete information.

On the basis of the derived strategies, the algorithms of the optimal control of the cutting processes can be formulated for such a case when the probability distribution of the estimation error is unknown as well as for a case when this distribution is a priori known. The comparison of the minimax strategy and the strategy minimizing the expected value of loss function leads to conclusion that the respective algorithms differ only by the way of selecting the value of deviation. The basic scheme of the control algorithms is identical for both cases that are being analyzed. Its form is the following :

Algorithm II

1. $L - \omega_L = t_1$
2. $t_1 - /b_o + \delta/ = t_2$
3. $E/\frac{t_2}{b_o}/ = n - 1$
4. $/n - 1//bo + \delta/ - t_2 = t_3$
5. $t_3 - /n-1/.E/\frac{t_3}{n-1}/ = t_4$

$$6.\ b^{i} = \begin{cases} /b_o + \delta/ - E\,/\frac{t_3}{n-1}/ + 1 & \text{for } i = 1,2,\ldots,t_4\ ; \\ /b_o + \delta/ - E\,/\frac{t_3}{n-1}/ & \text{for } i = /t_4+1/,\ldots,/n-1/; \\ /b_o + \delta/ & \text{for } i = n \end{cases}$$

If we use the minimax algorithm, then every time before the division of the anticipated band length L, we make the random experiment in which we divide the set of possible results into m mutually independent events the probabilities of which are $/X^o_1 \ldots X^o_m/$ and to which we allocate deviations $-/\eta+\delta/ \ldots /\lambda-\delta/$, respectively.

The result of the experiment may be only one definite value ω_L from the set of advantageous deviations. This value we subtract from the anticipated length of the band and we divide so obtained length without the remainder into the pieces of the lengths from the set of permissible lengths.

The algorithm minimizing the expected value of the loss function has the forme identical to that of the minimax algorithm with that difference that from the anticipated band length is in every case subtracted a constant value ω_L corresponding to the optimal deviation.

The digital structure realizing the minimax algorithm of the control consists of : the computation block, the generating block of random numbers and the storage block. The functional connection between the parts listed above and the remaining parts of the control system is illustrated in Fig.4.

In the computing block, operations are performed according to the minimax algorithm. The anticipated bandlength and the deviation of the control vector are determined for every band subject to be cut respectively in the bandlength prediction block and in the generation block of random numbers with a distribution corresponding to the minimax strategy. The minimax strategy components and other parameters necessary for the realization of the algorithm are stored in the storage block. Signals of the starting and ending of the cutting are generated in the real time block. Optimal components of the control vector are sent from the computation block to the shears control block. The bandlength prediction block, the real time block and the shears control block are the systems the structure of which depends on the type of the consrete cutting process. The structure of remaining parts is defined by the control minimax algorithm.

The computation block can be built on the typical logic elements. The storage block can be realized as the memory of the constants because at the process controlling there is no necessity of changing the contents of the storage cells. For the generation of random numbers, typical signal generating devices can be used on the basis of the physical phenomena of the random character such as noises in the electronic valves, decay of radioactive material etc.

These devices generats in general signals with the uniform distribution so that when using them then arises the necessity of transforming the probability distribution of the generated signals. This transformation can be performed in the digital way in the structure computation block. The digital structure that realizes the algorithm minimizing the expected value of the loss function consists only of two blocks : the computation block and the storage block. The construction of the computation block is the same as that of the computation block of the minimax structure. The storage block can also be resolved as the memory of constants the capacity of storage being however in that case much smaller.

6. Conclusions.

The minimax algorithm and the algorithm minimizing the expected value of the loss function can be used in the systems controlling the cutting processes when the information is uncomplete. The system controlling the cutting processes based on the above algorithms are namely characterized by much greater control efficiency than the deterministic systems based on the algorithm I. Assuming the uniformity of the probability distribution of the estimation error, the dependance of the average length of the waste /when cutting one single band/ on the diamater of the range of variations of the astimation error is , for the particular algorithms, the following (fig.5).

Already at relatively small estimation errore, the average length of waste occuring when applying algorithm I is several times greater than the average length of waste for the minimax algorithm. It is also worth-while to point out that the losses occuring when applying the minimax algorithm are independent of the probability distribution of the estimation error so that in the properly designed control system the losses cannot be greater then those for the minimax algorithm.

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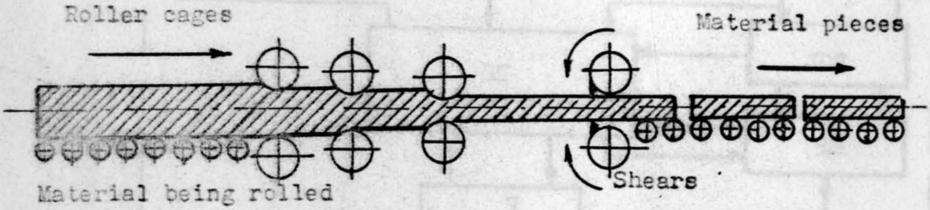

Fig.1. Diagram of the cutting process on the continuous operation rolling mill.

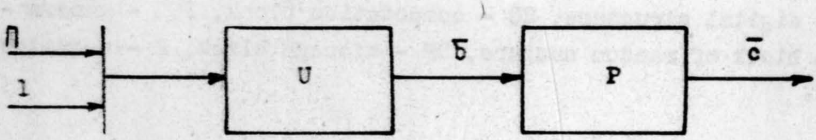

Fig.2. Cutting process control system structure.

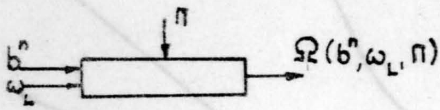

Fig.3. Control object.

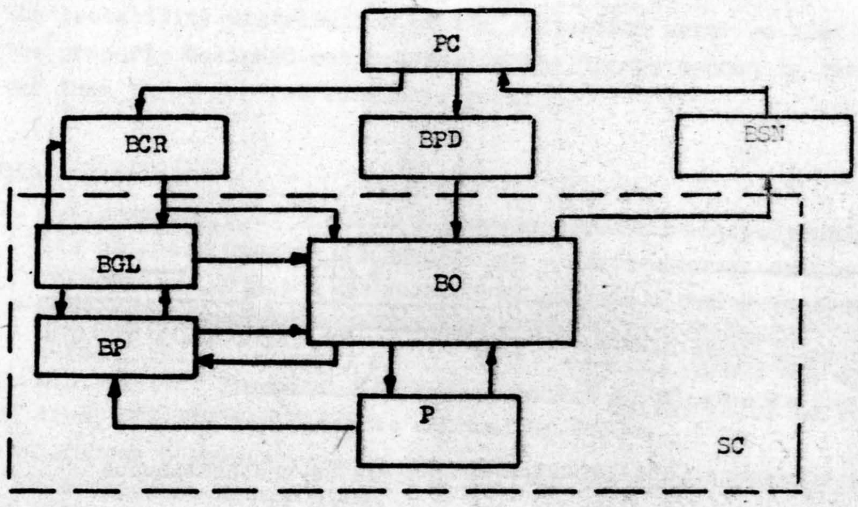

Fig.4. Control system.
Denotations : PC - cutting process, BPD - bandlength prediction block, BCR - actual time block, BSN - shears control block, SC - digital structure, BO - computation block, BGL - generation block of random numbers, BP - storage block, P - operator's desk.

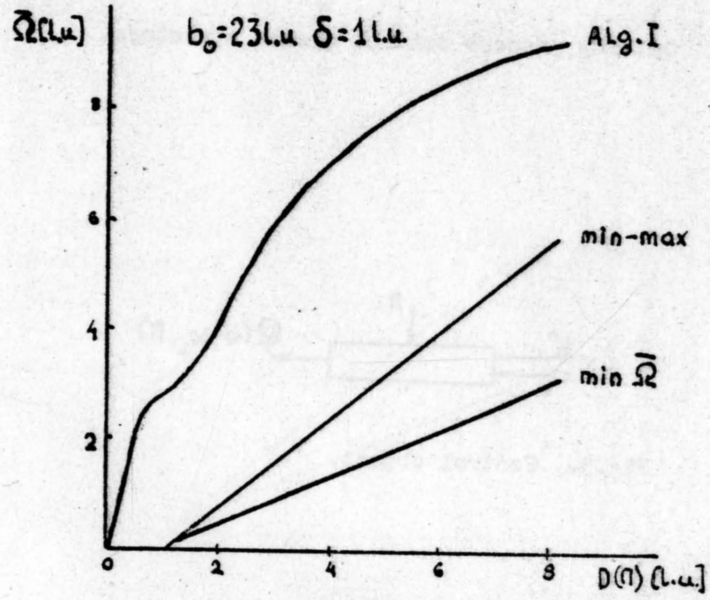

Fig.5. Losses versus estimation error.