The development of a comprehensive computerized model for cold rolling is described. Rolling forces, torques, forward slip, temperatures of rolls and strip, thermal cambers of rolls, as well as strip thickness profile and flatness, are predicted. The model is applicable to both basic and applied studies of the rolling process. Its primary purposes are to aid in optimizing performance of existing mills, in the design of new cold mills, and in devising open-loop and closed-loop automatic flatness-control systems.

This is the forty-eighth annual Campbell Memorial Lecture convened to remember and honor a man of indomitable spirit. For Professor Campbell, blinded in a laboratory accident at the age of 28, continuing life was unthinkable without the continuance of personal productivity. And produce he did, as attested by scores of pioneering investigations into the constitution and heat treatment of steel, and more importantly, by hundreds of students inspired by his enthusiastic example to take the paths of metallurgical productivity.

I am greatly honored to be among those who have been given the opportunity to toast the memory of Edward DeMille Campbell with a progress report in the field of metallurgy.

Most of the 47 previous Campbell lecturers have had an intimate association with a specific field of research, usually of decades standing. Some drifted into broader activity with a little less personal involvement at the bench of scientific inquiry. As one of those whose daily work in industrial corporate management is scarcely the yarn from which Campbell lectures are woven, I shall report to you on the progress of a major program involving a talented and dedicated group of Kaiser Aluminum and Chemical Corporation researchers, to whom...
all credit is due. The lecture will center on their development of a model, using computer solution techniques, which accurately describes the cold rolling process for aluminum—a model which we believe will make a contribution to general rolling theory for all metals.

THE COLD ROLLING PROCESS AND EQUIPMENT

Rolling is unquestionably one of the most important metal forming processes we use today. In 1973, 92 pct of the aluminum, steel and copper produced in the world was rolled, a total of 728 million tons* of metal.

During the hour of this lecture you may expect that 85 thousand tons of metal will have been rolled!

Over the past 40 years, the cold rolling process to produce sheet has progressed from two-high hand mills, taking a very large number of small reductions and producing very unflat sheet at a low yield, to highly productive multistand, or tandem, four-high mills. These commence with large hot-band coils, take large thickness reductions at high speed, and produce finished coil with comparatively good flatness and thickness tolerance.

A rolling mill weighs many tons and yet must produce cold rolled strip to tolerances measured in thousandths of an inch. In tandem mills the strip can be reduced in all stands progressively and simultaneously. Cost and quality competition in the industry have led to the adoption of new technology from the fields of mechanical engineering, hydraulics and electronics in mill design and operation as rapidly as it could be assimilated. In general, the thrust of development has been toward higher productivity and toward mechanisms for more precise control of finished strip gage.

Fig. 1 indicates the basic controls available to a mill operator. The strip is reduced between two work rolls supported by two backup rolls. The smaller diameter work rolls reduce force and energy to cause deformation, while the larger backup rolls decrease mechanical deflections. The necks of the rolls fit into bearings and bearing chocks which are supported in two mill frames. Large screws at the top of the frame raise and lower the stop position of the top backup chock which in turn determines the nominal gap between the work rolls. The work rolls are driven by dc motors through a gear reducer and pinion stand to provide instantly variable speed and torque.

In relatively recent times, mill stands have been equipped with hydraulic cylinders, usually called work roll jacks, which may be used to push the ends of the work rolls apart to aid in alleviating edge wave unflatness of the strip. Other hydraulic cylinders, called deflector jacks, are placed between the work roll and backup roll chocks so that the ends of the work rolls may be forced together. This will counteract any tendency of the strip to form center buckles. Some mills also have large diameter short-stroke hydraulic cylinders between top and bottom backup roll chocks to cause backup roll bending for still further control of buckles.

The work rolls are cooled with sprays that are distributed across the width, with individual controls to adjust local cooling rates and thermal camber. The strip payoff and takeup reels are generally of the expanding arbor type with motor brake and drive, respectively, to provide backward and forward tension to the strip.

Thus, a mill operator can control the speed, forward and backward tension, the roll gap, roll bending, and work roll cooling.

Exit thickness of strip generally has been monitored by contact micrometers, although these are being superseded by radiation gages and other thickness sensors. Many mills are being equipped with computers for the automatic control of exit gage. Signals from the sensors are used by the computer to calculate the changes in roll gap or tension and roll velocity required to control strip thickness within narrow limits. However, most of the computer systems control gage only along a single track somewhere across the width where a thickness sensor is located. Thickness variations across the width are normally ignored by present automatic gage control systems.

While the advances in production rolling over several decades have been remarkable, the major unsolved problem today is how to produce strip that is truly flat. Cold strip will tend to buckle if the percentage reduction (or elongation) varies across the width.\(^1\)\(^2\)\(^3\) This means that if flat strip is to be rolled, the roll gap dimensions must be maintained across the width during each rolling pass to match the exact profile of the incoming hot mill strip, on a relative percentage basis.

After rolling, cold mill product may be improved in flatness by roller or stretcher levelling. These operations represent additional processing costs to achieve a prime product. The problem, then, is to gain sufficient understanding of the cold rolling process to permit production of directly saleable, perfectly flat product off the mills. It is a very complex task to predict thickness variations across the width of strip, including the associated defect of buckles. Depending upon the mechanical or thermal aberrations which cause

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*English units of measure will be used throughout, since the computational program is adapted to current U.S. industry practice. Factors for conversion to S.I. units are appended.