Heat Transfer in the Hot Rolling of Metals

C.O. HLADY, J.K. BRIMACOMBE, I.V. SAMARASEKERA, and E.B. HAWBOLT

The heat-transfer coefficient (HTC) in the roll gap during the hot rolling of AA5XXX-series (aluminum-magnesium) alloys has been measured in a laboratory mill with the aid of thermocouples attached to the surface and embedded in the interior of test samples. The heat-transfer coefficient was calculated from the sample temperature response using an implicit finite-difference model over a range of temperatures, strain rates, and pressures. Values of 200 to 450 kW/m^2 °C were obtained by backcalculation. A comparison of the results from this study with those measured in a previous investigation on two steel alloys has led to the development of an equation which characterizes the HTC as a function of the ratio of the rolling pressure to the flow stress at the surface of the workpiece. This relationship has been employed to explain the apparent differences in the heat-transfer behavior of different metals at similar rolling pressures.

I. INTRODUCTION

MODERN steel and aluminum hot-rolling practices call for the achievement of high productivity coupled with the precise control of strip shape and mechanical properties. Accurate knowledge of the heat-transfer coefficient (HTC) in the roll gap is essential to achieving these goals, because the HTC determines the temperature distribution in the rolls and the rolled strip which, in turn, influences the microstructural evolution and ultimately the mechanical properties of the strip, as well as the shape of the rolls and rolled strip.

To date, only a few studies have been conducted to measure the HTC between the rolls and workpiece for aluminum rolling. Pietrzyk and Lenard[1] reported an HTC between 18.5 and 21.5 kW/m^2 °C in the warm rolling (155 °C to 210 °C) of commercial-pure aluminum, whereas B.K. Chen *et al.*[2] reported values of 10 to 50 kW/m^2 °C for the hot rolling of Al + 5 pct Mg alloy. In order to study the temperature distribution in the laboratory rolling of AA5083, Timothy *et al.*[3] employed subsurface thermocouples to obtain a HTC of 15 kW/m^2 °C. Smelser and Thompson[4] reported a single value of 30 kW/m^2 °C. However, only B.K. Chen *et al.*[2] have presented, for aluminum rolling, the dependence of the HTC in the roll bite on the variation of roll pressure along the arc of contact, in a similar manner to that reported by W.C. Chen *et al.*[5] for various grades of steel.

Hlady *et al.*[6] reported an HTC in the roll gap between 100 and 350 kW/m^2 °C for the hot rolling of the aluminum alloys AA5052 and AA5182. The HTC was calculated from the temperature response of the aluminum samples in the roll gap, which was measured by double-intrinsic thermocouples fastened to the surface of the samples. Furthermore, Hlady *et al.*[6] observed a slight increase in the HTC with increasing roll pressure. They also noted that at similar rolling pressures, aluminum exhibited an HTC approximately 4 times higher than that of steel. They attributed this difference to the higher flow stress of steel at the roll-workpiece interface, as compared to aluminum. Thus, they concluded that at similar rolling pressures, aluminum asperities deform to a greater extent than steel asperities, thereby enhancing direct metal-metal contact between the roll and workpiece and, therefore, the HTC.

Semiatin *et al.*,[7] in a series of ring-upsetting tests on AA2024-O, observed increasing heat transfer between the ring and die with increasing applied pressure. They attributed this to an increased smoothening of asperities at the ring surface, thereby bringing the workpiece into better thermal contact with the dies. This concept was developed in greater detail by Samarasekera,[8] who suggested that during rolling, the roll and workpiece surfaces come into metal-metal contact only at the tips of asperities, as shown schematically in Figure 1. Since the bulk of heat flow occurs through these contact points, the HTC at the roll-workpiece interface is dependent on the fractional area of the two surfaces that are in direct contact with each other. This has helped to explain the observed dependence of the HTC in the roll gap on such parameters as rolling speed, severity of reduction, gage, and lubrication.[8] Experimental verification of the relationship between the HTC and real area

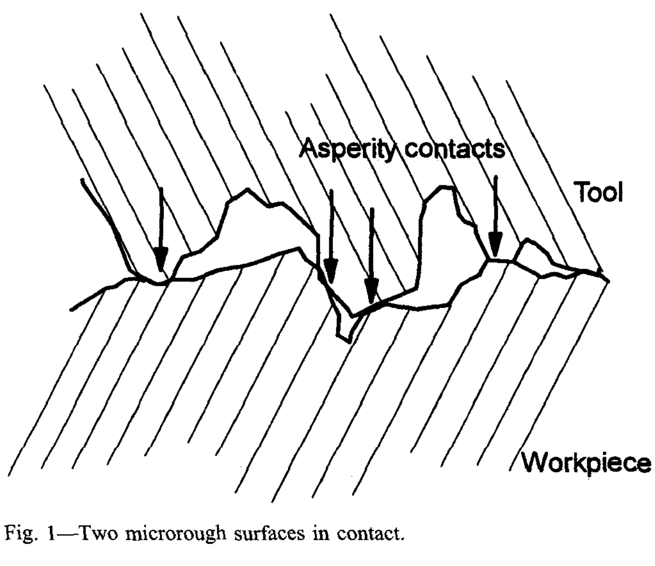

Fig. 1—Two microrough surfaces in contact.

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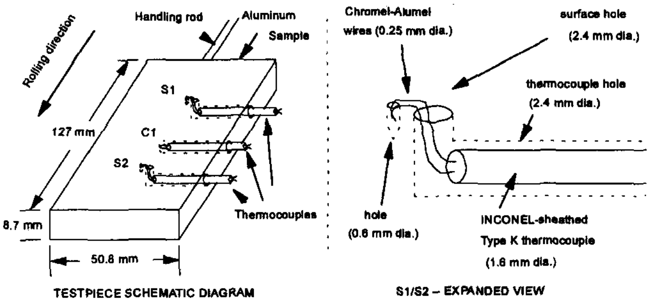

Fig. 2—Schematic diagram of thermocouple installation in aluminum workpiece.

of contact in the hot rolling of steel was provided by Devadas *et al.*[9] and by W.C. Chen *et al.*,[5] who established a linear relationship between the HTC at the roll-workpiece interface and roll pressure.

In order to determine the relationship between the fractional contact area of two surfaces and the interfacial pressure, Pullen and Williamson[10] conducted experiments in which aluminum samples with artificially roughened surfaces were pressed by a flat, hardened-steel ram. Before being pressed, the cylindrical aluminum samples were forced into tight-fitting holes in hardened-steel dies. The confinement of the aluminum samples by the steel dies prevented any bulk deformation of the samples as they were pressed by the ram. Thus, interfacial pressures of up to 15 times the yield stress of aluminum were attained in the study. From the results of their experiments, Pullen and Williamson[10] characterized the fractional area of contact, a_c (the ratio of the real area of contact, A_r, to the apparent or bulk area of contact, A_a), as follows:

$$a_c = \frac{P_a}{H + P_a} \qquad [1]$$

where P_a is the nominal pressure (the applied force divided by the apparent area) and H is the surface hardness of the material (approximately 3 times the bulk hardness, or yield stress, of the bulk material). Since for an unsupported material the ratio P_a/H can never be greater than unity (the applied pressure cannot exceed the surface hardness of the material), the maximum fractional contact area that can be obtained between two microrough surfaces is 0.5, as indicated in Eq. [1]. Experimental verification of this calculated result has been provided by Williamson and Hunt.[11]

A small body of research has been published on the HTC between two nominally flat, but microscopically rough, surfaces and its relationship to contact pressure and surface roughness.[12–16] Cooper *et al.*[12] developed an equation that described heat transfer as a function of the rolling pressure–surface hardness ratio, as well as of the harmonic conductivity and surface roughness parameters of the tool and workpiece. This equation was experimentally verified by a small set of tests conducted with rolling pressure–surface hardness ratios of less than 0.1. Fenech *et al.*[13] developed a so-called "button model" of two surfaces in contact to characterize the HTC as a function of the number of metal-metal contacts per unit area, total fractional area of contact, and average asperity heights. A difficulty with applying the model of Fenech *et al.* is the impracticality of obtaining a reliable estimate of the number of metal-metal contacts per unit area. Mikic[14] presented variations of the equation developed by Cooper *et al.*[12] to take into account different assumptions concerning the mode of deformation at the surface, ranging from pure plastic deformation to pure elastic deformation. Song and Yovanovich[15] developed an explicit equation relating the HTC to the bulk hardness of the material, rather than to the surface microhardness. This equation was shown to have good agreement with experimental data in the range $10^{-6} \leq P_a/H \leq 2.3\ (10^{-2})$. W.C. Chen[16] applied the work of Fenech *et al.*[13] to the case of hot rolling of stainless and high-strength low-alloy (HSLA) steels and employed suitable approximations and modifications to establish a theoretical linear relationship between the HTC and the apparent roll pressure.

II. SCOPE AND OBJECTIVES

The experimental component of this study concentrated on two aluminum alloys, AA5052 and AA5182, containing 2 and 4.5 pct Mg, respectively. The AA5XXX group of alloys is primarily used in beverage container and automotive sheet production. The continuing demand for improved mechanical properties in both of these applications has increased the need for refined rolling practices.

Heat transfer from the strip to the work rolls is one of the major sources of strip cooling during the hot rolling of both steel and aluminum; thus, accurate knowledge of the HTC in the roll gap is essential for exact control of the strip temperature and shape. Previous investigators[1,3,4,7] have reported values for the HTC in the roll gap for various alloys under laboratory rolling conditions. Other investigators have attempted to determine the HTC as a function of the rolling pressure (B.K. Chen *et al.*[2] for aluminum and W.C. Chen *et al.*[5]) for steel. The present study attempts to establish a more fundamental basis for the observed behavior of the HTC in the roll gap than has been previously established, by determining HTCs for the commercially important AA5XXX-series aluminum alloys and relating the results to those reported by W.C. Chen *et al.* for two steel alloys.[5] Copper hot-rolling tests were also performed to provide an additional material for comparison.

III. EXPERIMENTAL

A. *Preparation of Test Samples*

Aluminum samples (8.7 × 50.8 × 127 mm) were machined and then homogenized: AA5052 samples were held at 560 °C for 2 hours and then air cooled, while AA5182 samples were held at 530 °C for 1 hour and then air cooled. Subsequently, the samples were instrumented with three thermocouples (1.6-mm diameter INCONEL*-sheathed type-K thermocouples having CHROMEL-ALUMEL** wires 0.25-mm in diameter). As shown in Figure 2, two of the thermocouples, S1 and S2, were located on the sample surface and a third, C1, at the center of the sample. Thermocouples S1 and S2 were inserted into holes extending

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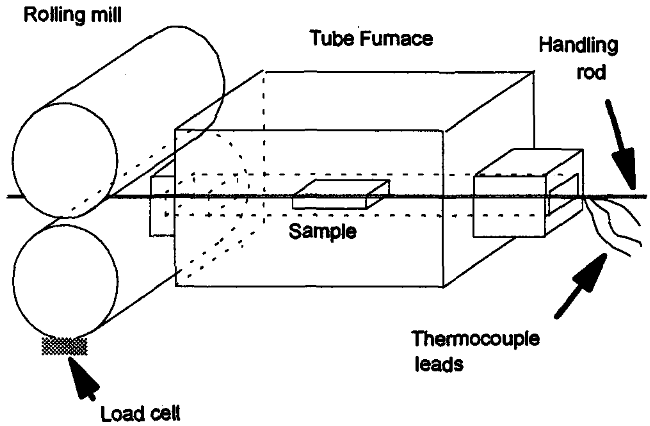

Fig. 3—Schematic diagram of laboratory rolling mill and furnace.

horizontally halfway into the sample; and the exposed CHROMEL-ALUMEL wires were brought to the surface through vertical holes which intercepted their horizontal counterparts. The CHROMEL-ALUMEL wires were placed on the sample surface approximately one-half millimeter apart to establish a double-intrinsic junction and were subsequently fastened to the sample by insertion into a shallow 0.6-mm diameter hole drilled into the surface, which was then punched shut. The thermocouple holes were drilled oversize so that deformation of the sample would not crush the thermocouple sheathing; uncertainties involving the effect of thermocouple sheath deformation on temperature measurement thus were avoided. For thermocouple C1, the thermocouple wires were spot welded together to form an extrinsic junction. Electrical resistance checks ensured that the extrinsic junction made physical contact with the sample. The copper samples were prepared in a manner similar to that of the aluminum samples.

B. *Measurement of the Thermal Response of Instrumented Samples during Rolling*

The instrumented samples were placed in a square tube furnace which was located in front of the laboratory rolling mill, as shown in Figure 3. The rolling mill was a four-speed, two-high mill with 100-mm-diameter rolls. The rolls were manufactured from a tool steel with a composition of 1.0 pct C, 1.0 pct Cr, and 0.2 pct V. The furnace was designed to butt against the rolls of the mill, so that the heated samples had little time to cool during transfer from the furnace to the rolls. The rolling mill was instrumented with a load cell to record the total separating force during rolling. The load cell and thermocouples were connected to a portable microcomputer equipped with a data acquisition board. During the rolling tests, the data acquisition rate was 1500 Hz.

The samples were rolled initially without bulk plastic deformation. This first pass served to flatten the thermocouple wires into the sample, thereby further assuring good electrical contact with the sample and establishing the double-intrinsic junction at the sample surface. In addition, this pass served as a final check to ensure that the thermocouples were responding properly. The samples were then returned to the furnace and reheated, prior to being rolled approximately 20 pct in a second pass. The sample was then rolled a third time, after reheating, to a further 10 pct

Table I. Conditions Employed in Aluminum Rolling Tests

Test	Alloy	Initial Thickness (mm)	Initial Temperature (°C)	Reduction (Pct)	Strain Rate (s^{-1})	Mean Pressure (kg/mm^2)	Lubricant
AL12	5052	8.70	513	19.8	9.83	10.41	A
AL13	5052	7.01	505	11.2	3.93	10.09	A
AL15	5052	8.70	516	20.1	9.92	10.35	B
AL16	5052	6.99	510	10.9	7.74	8.81	A
AL18	5182	8.70	505	19.8	9.83	13.80	A
AL19	5182	7.01	497	10.1	3.70	12.45	A
AL21	5052	8.70	415	18.9	9.56	13.50	A
AL22	5052	7.09	505	11.8	8.03	9.49	A
AL24	5182	8.70	377	20.1	9.92	19.89	A
AL27	5182	8.70	321	19.2	9.65	21.51	A
AL28	5182	7.06	327	9.3	7.05	22.7	A
AL30	5052	8.70	329	20.3	9.99	16.46	A
AL31	5052	6.96	323	10.9	7.76	17.27	A
AL33	5052	8.70	371	20.1	9.92	14.75	A
AL34	5052	6.99	321	10.5	7.58	16.59	B
AL37	5182	6.99	321	10.2	7.46	20.79	B

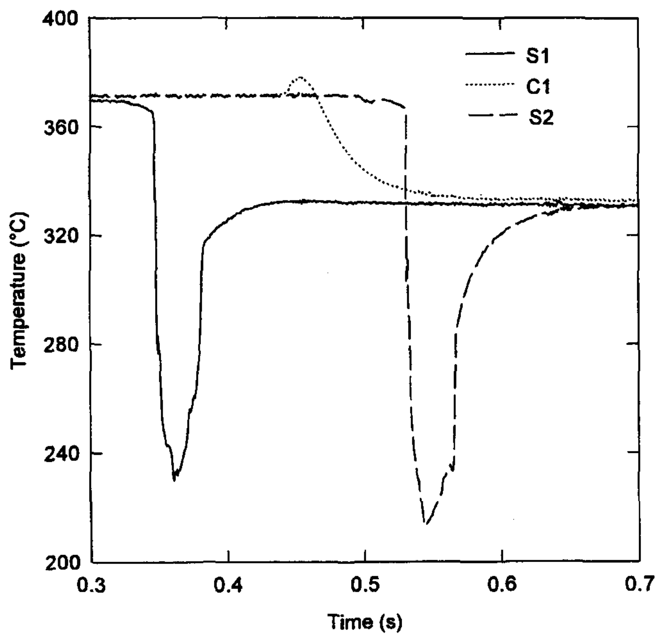

Fig. 4—Typical temperature response during the hot rolling of an instrumented aluminum sample (test AL33).

deformation. During these tests, the rolls were continuously lubricated by one of two oil (5 pct)-water emulsions. Lubricant A was a viscous, low-friction lubricant, and lubricant B was comparatively less viscous. Table I presents the conditions of the tests that were performed.

Typical temperature responses obtained during a laboratory rolling operation are presented in Figure 4. Individually, the two surface thermocouples exhibited a sudden drop in temperature due to contact with the rolls, followed by reheating upon exit from the roll gap. The centerline temperature, on the other hand, initially increased slightly due to the heat of bulk deformation and then gradually declined. The test sample achieved a uniform bulk temperature within about 200 ms of exiting the roll bite.

The series of copper rolling tests was also conducted on

Table II. Conditions Employed in Copper Rolling Tests

Test	Initial Thickness (mm)	Initial Temperature (°C)	Reduction (Pct)	Strain Rate (s^{-1})	Mean Pressure (kg/mm²)	Lubricant
CU4	11.64	574	13.2	9.05	11.20	none
CU5	5.51	578	12.4	9.38	10.45	none
CU7	6.35	602	13.6	9.21	11.10	B
CU8	5.49	523	11.6	9.04	11.64	B

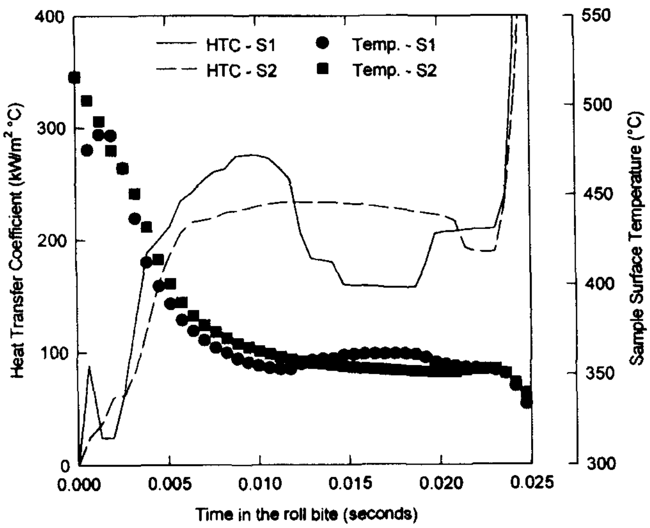

Fig. 5—Surface temperature and calculated instantaneous HTC in the roll bite (test AL15).

the University of British Columbia (UBC) pilot rolling mill. The conditions of the copper tests are shown in Table II.

IV. RESULTS AND DISCUSSION

A. *The HTC at the Roll-Workpiece Interface*

A one-dimensional finite-difference model was developed to backcalculate the HTC from the temperature response of the sample thermocouples. The formulation of the model has been discussed previously[5,9] and so will not be repeated here.

Several methods of calculating the HTC from the thermocouple responses were attempted. First, the local HTC through the roll bite was computed from the response of the surface thermocouples using the finite-difference model. Figure 5 shows the surface temperature of an aluminum sample while in the roll bite and the resulting calculated local HTC. At larger values, the HTC is increasingly sensitive to changes in surface temperature, as can be seen in Figure 5. Average roll-bite HTCs were calculated by dividing the area under the instantaneous HTC time plot by the contact time. In general, the roll-bite HTC calculated in this manner exhibited considerable scatter because of its sensitivity to small fluctuations in the measured surface temperature of the workpiece.

A second method, involving the calculation of the local heat flux at the sample surface from the center thermocouple response (a form of the so-called "inverse heat conduction problem"), was also attempted. The method employed the technique developed by Beck *et al.*[17] However, the centerline thermocouple proved to be too remote from the surface to use its temperature response to calculate the surface heat flux. Small variations in the recorded temperature exacerbated the problem, resulting in severe fluctuations of the calculated surface heat flux. Thus, this method was not adopted.

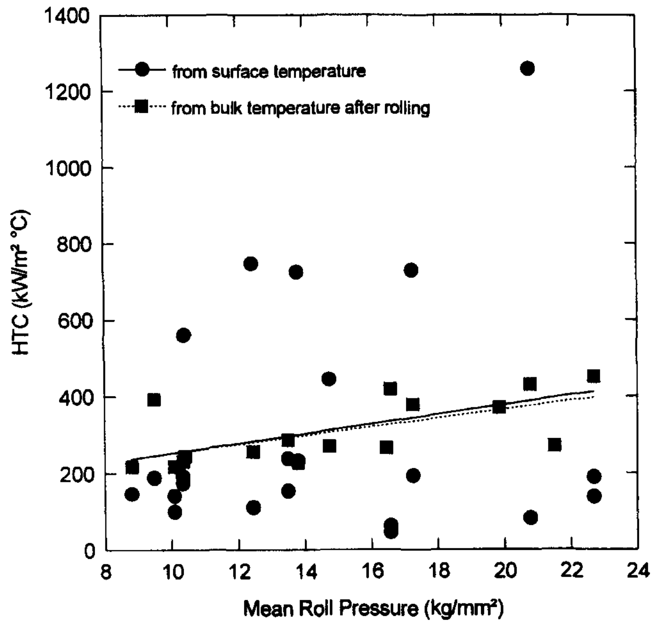

Fig. 6—Comparison of roll-gap HTCs calculated from the workpiece surface and bulk temperatures.

Finally, the technique that produced the best results was to calculate an average HTC in the roll bite based on the temperature measurement of the centerline thermocouple, C1 (Figure 2). As mentioned earlier, within 200 ms of exiting the roll bite, the aluminum samples attained a homogeneous temperature, which was typically 30 °C to 60 °C cooler than the initial bulk temperature (Figure 4). The finite-difference model was modified to estimate an initial roll-gap HTC, then to predict a bulk temperature of the sample 200 ms after rolling from this initial estimate, and to adjust to the HTC iteratively until the predicted and measured final bulk temperatures of the sample agreed to within 1 °C.

Figure 6 shows a comparison between the HTCs calculated from the surface thermocouple response and from the comparison of the bulk temperature of the workpiece before and after rolling. The linear regressions of the two sets of data agree with each other closely, which provides evidence that the surface thermocouples measured the true surface temperature of the aluminum in the roll bite and not an average temperature of the roll and sample surfaces. However, the HTC calculated from the bulk temperature of the workpiece exhibited much less scatter, making this method more reliable than calculating the HTC from the surface temperature measurements for aluminum rolling. This method is not feasible for calculating the HTC in steel rolling, unfortunately, because the lower thermal diffusivity of steel prevents it from attaining a uniform temperature after rolling within a reasonable period of time. However, because the thermal diffusivity of copper is even higher than

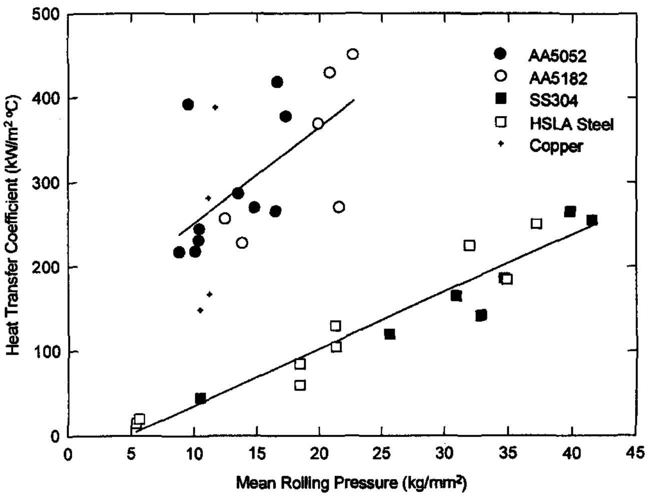

Fig. 7—Influence of mean rolling pressure on the HTC in the roll gap.

that of aluminum, this method is also suitable to calculate the roll-gap HTC during copper hot rolling.

B. *Dependence of the HTC on Rolling Pressure*

Figure 7 shows the calculated HTC for the aluminum rolling tests presented in Table I, grouped by alloy type. The four copper rolling experiments, shown in Table II, and a series of stainless steel (AISI type 304) and HSLA-steel tests, performed by W.C. Chen[16] in a previous study, are also shown in Figure 7. The steel tests were conducted at two different locations; HSLA-steel rolling experiments were performed on the UBC laboratory rolling mill, and stainless-steel rolling trials were made on a two-high pilot rolling mill at CANMET (Ottawa, ON, Canada) with 460-mm-diameter rolls manufactured from high-nickel iron. The stainless-steel samples were subjected to one pass, and the HSLA samples were subjected to two passes. The HTC in the roll gap for the steel tests was calculated from surface temperature responses of double-intrinsic thermocouples, which were spot welded onto the surface of the steel samples. Since the magnitude of the HTC was lower for the steel tests than for the aluminum tests, the resulting scatter in the data was less than that calculated from the surface thermocouples on the aluminum samples. Also shown in Figure 7 are regression lines calculated from the respective aluminum and steel results. Difficulties in attaching the thermocouples to the copper samples led to somewhat erratic temperature responses in the roll bite. This resulted in a large variation in the calculated HTC, limiting the value of the copper data.

At similar rolling pressures, the HTC for the two aluminum alloys is approximately 4 times greater than that of the steel alloys. As the HTC increases, its measurement becomes increasingly sensitive to small errors in the measurement of the bulk temperature of the sample 200 ms after rolling, for the same reason as the HTC becomes increasingly sensitive to surface temperature fluctuations. Therefore, the same absolute error in temperature measurement causes greater uncertainty in calculating high values of the HTC. For example, at the level of HTC measured in the aluminum rolling trials in this study (200 to 450 kW/m² °C), a cumulative error of 2 °C in the bulk sample temperature measurement (which includes the error in measuring the bulk heat of deformation) results in a 20 to 40 pct error in the HTC determination.[18] This is thought to be the source of the scatter observed in the aluminum HTC data calculated from the bulk temperature of the aluminum samples.

A comparison of the two aluminum alloys revealed no statistically significant difference in the magnitude of the HTC. The two alloys are similar enough in thermal and physical properties that this is a reasonable finding. The choice of lubricant also did not have an effect on the HTC, which corroborates the findings of B.K. Chen *et al.*[2]

C. *Dependence of the HTC on the Roll Pressure–Surface Hardness Ratio and Thermal Conductivity*

When the surfaces of the roll and workpiece bear on one another, true metal-metal contact occurs only at discrete locations where the asperities of each surface meet. Based on the approach adopted by Cooper *et al.*,[12] where all heat is assumed to flow only through the contact points of the two surfaces, the roll-gap HTC is formulated as a function of the real (actual metal-metal) contact area, as well as the combined conductivity and surface roughness of the roll and workpiece, expressed (in dimensionless form) as

$$\frac{hC}{k} = \left(\frac{a_c}{1 - a_c}\right)^m \qquad [2]$$

where C is a general roughness term. The term k is the combined conductivity of the roll, k_r, and workpiece, k_{wp}, defined as

$$k = \frac{k_r k_{wp}}{k_r + k_{wp}} \qquad [3]$$

Finally, the term $[a_c/(1 - a_c)]^m$ represents a family of equations that approaches 0 as a_c (the fractional contact area = A_r/A_a) tends to 0 and approaches infinity as a_c approaches unity.

Employing the relation between contact area and normal load proposed by Pullen and Williamson,[10] (Eq. [1]) and substituting it into Eq. [2] yields

$$\frac{hC}{k} = \left(\frac{P_a}{H}\right)^m \qquad [4]$$

The roll-gap HTC in the form of Eq. [4] is then characterized as a function of the applied pressure and the surface hardness of the material being deformed. Equation [4] is, in effect, a generalized version of the equation proposed by Cooper *et al.*[12]

A limitation of the previous heat transfer–pressure equations is their treatment of the surface hardness of the workpiece as a single value. In order for an equation in the form of Eq. [4] to be capable of describing the HTC in the roll gap, the surface hardness of the workpiece, H, must be replaced by a temperature and strain-rate dependent yield stress to obtain

$$\frac{hC}{k} = \left(\frac{P_r}{\sigma(T_s, \bar{\dot{\varepsilon}})}\right)^m \qquad [5]$$

where P_r is the mean rolling pressure; σ is the bulk flow

Table III. Constants for Constitutive Stress Equation

Parameter	AA5182	AA5052	Copper
Q (kJ/mol)	185	189	173
α (MPa^{-1})	0.0450	0.0317	0.0729
n	1.818	3.536	1.257
ln (A)	24.48	26.13	18.02

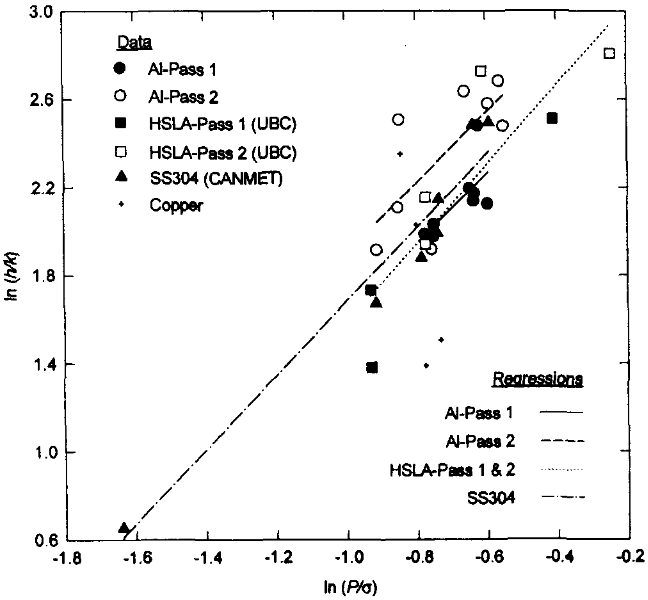

Fig. 8—HTC-combined conductivity ratio as a function of the rolling pressure surface flow stress ratio.

Table IV. Slopes and Surface Roughness Parameters of Steel and Aluminum Data

Alloy	Slope (m)	Surface Roughness Parameter C (μm)	Coefficient of Determination (r^2)
SS304—CANMET	1.67	35.0	0.967
HSLA—UBC	1.80	34.0	0.784
AA5XXX—pass 1	1.59	40.1	0.482
AA5XXX—pass 2	1.59	30.4	0.515

stress of the workpiece surface, T_s is the surface temperature of the workpiece, and $\bar{\dot{\varepsilon}}$ is the mean strain rate. The bulk flow stress at the workpiece surface, σ, and the surface hardness, H, are not identical; the surface hardness is generally assumed to be approximately 3 times the bulk flow stress.[11] In this derivation, the numerical difference between the two variables is absorbed into the surface roughness parameter, C.

Equation [5] is an implicit equation, because the HTC in the roll gap is characterized as a function of the surface temperature of the workpiece, which in turn is dependent on the HTC. To handle this situation, the workpiece surface temperature may be calculated by assuming perfect thermal contact between the roll and workpiece, for the purpose of computing the flow stress of the material at the roll-workpiece interface. This is accomplished by distributing the heat of the roll and workpiece according to their respective volumetric heat capacities to calculate a weighted average temperature, as follows:

$$T_s = T_{wp} + (T_r - T_{wp}) \frac{\rho_r C_{pr}}{\rho_r C_{pr} + \rho_{wp} C_{pwp}} \qquad [6]$$

where T_{wp} and T_r are the homogenous temperatures of the workpiece and roll, respectively, just prior to the workpiece entering the roll gap. The flow stress, σ, may consequently be calculated using a hyperbolic-sine equation:

$$Z = \dot{\xi} \exp\left(\frac{Q}{RT_s}\right) = A \sinh (\alpha\sigma)^n \qquad [7]$$

where Z, the Zener–Holloman parameter, is the temperature-compensated strain rate, R is the gas constant, Q is the activation energy for deformation, and A, α, and n are constants. The parameters Q, α, n, and A in Eq. [7] were determined for each material from the stress-strain behavior measured at varying temperatures and strain rates, using a method developed by Davies *et al.*,[19] which allowed each parameter to have an unconstrained value. The resulting parameters of the constitutive equation for the two aluminum alloys and the copper are shown in Table III. In this manner, the HTC may be formulated explicitly from Eq. [5].

In order to determine whether an equation of the form of Eq. [5] is appropriate to describe the experimental data, the logarithm of the HTC-combined conductivity ratio was plotted against the logarithm of the rolling pressure–surface flow stress ratio for the aluminum, steel, and copper tests, as shown in Figure 8. A regression analysis was performed on each of the aluminum and steel data sets to determine m, the slope of the regression line, and C, the roughness parameter. Table IV shows the values of m, C, and the coefficient of determination, r^2 (which gives a measure of the fit of the data to the regression), obtained from the regression analysis for each set of data plotted in Figure 8. From Figure 8 and Table IV, the similarity of the value m for each set of data is clearly apparent, which suggests that it is roughly independent of material type. This value is somewhat larger than has been reported by other researchers, who assigned m a value slightly less than unity.[12,14] The reason for the discrepancy between the present and previous values of m is not known. However, the previous heat-transfer analyses were based on experiments which were conducted at low pressure-to-surface hardness ratios compared to the present study: $0.01 < P_a/H < 0.1$ investigated in Reference 12,[12] and $10^{-6} < P_a/H < 0.02$ studied in Reference 15,[15] *vs* $0.07 < P_a/H < 0.27$ in the present study (assuming H to be 3 times the bulk flow stress at the surface). Conceivably, m is not constant over the full range of pressure-to-surface hardness ratios but increases with contact area. However, there is no evidence available at present to support this speculation.

The data from the first pass on aluminum, as well as from the stainless-steel tests conducted on the CANMET rolling mill and the HSLA-steel tests performed on the UBC laboratory mill, have similar values of C. Given that the data were collected from two different rolling mills and three different sets of materials, it may be that the surface roughnesses of the roll and workpiece are of secondary importance when compared to the ratios of HTC to the combined thermal conductivity and rolling pressure to surface flow stress. This suggests that for the first rolling pass, a single

Table V. Surface Roughness Characteristics of Aluminum Samples

Sample	R_a (μm)	Δa (Deg)
Al—heat treated	0.856	4.05
Al—rolled once	0.371	1.00
Al—rolled twice	0.665	0.92
SS304—rolled once	1.184	4.00

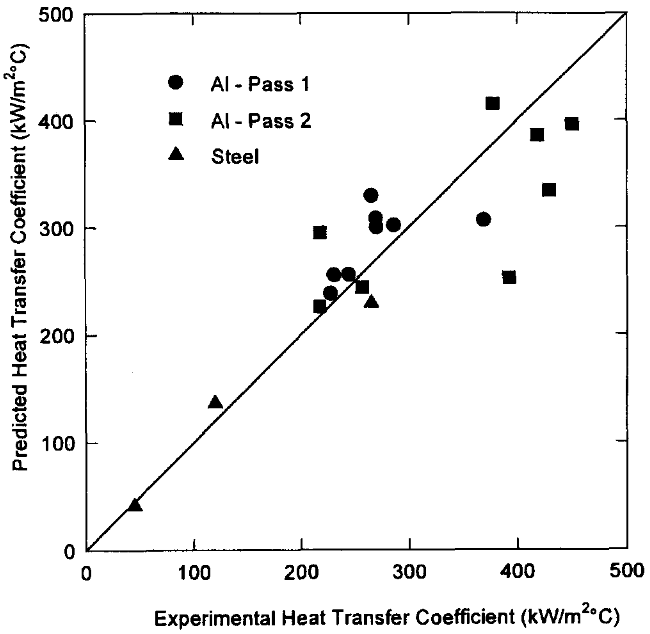

Fig. 9—Experimental and predicted HTCs.

value of m (1.7) and C (35 μm) in Eq. [5] can satisfactorily describe the heat-transfer behavior of any metal in the roll gap. Although it is not clear whether Eq. [5] is applicable to copper rolling, due to the scatter present in the copper HTC data, the average of the four copper data points lies on the regression line described by the first-pass data.

A statistical analysis of the HSLA-steel results revealed no difference in the HTC obtained from the first and second rolling passes. Therefore, the HSLA data were treated as a single group for the regression analysis shown in Figure 8. The data pertaining to the second rolling pass of the aluminum samples, however, in spite of the scatter, revealed a statistically significant enhancement of the HTC as compared to the first pass. This may be attributed to the smoothening of the aluminum sample surface as a result of being rolled, leading to a greater real contact area between the roll and workpiece during the second rolling pass.

The surface roughness characteristics of a heat-treated, unrolled aluminum sample were measured with a surface profilometer and compared to the surface characteristics of rolled samples. Table V shows the arithmetic mean of the surface profile from the mean line (R_a) and the average slope of the surface profile (Δa) for the unrolled sample; for a sample which was rolled once at 370 °C; and for a separate sample which was rolled twice, with both passes at 370 °C. The two rolled samples, compared to the unrolled sample, exhibited a smaller value of R_a, as well as a considerably smaller value of Δa. However, the average slopes (Δa) of each rolled sample were similar, indicating that after the first rolling operation, further smoothening of asperities was negligible. The sample rolled twice, in fact, exhibited a higher value of R_a than the sample rolled once. This may indicate that R_a can vary considerably even among specimens rolled under similar conditions; therefore, only large changes in R_a should be considered to be significant. A comparison of the surface roughness parameter (C) values of the aluminum samples, shown in Table IV, reveals a statistically significant decrease as a result of rolling, which reinforces the conclusions obtained from the surface profilometer measurements. Consequently, for aluminum rolling, a value of C somewhat lower than for the first rolling pass, 30 μm rather than 35 μm, provides a better estimate of the HTC in the roll bite during subsequent passes.

By comparison, the surface of the rolled stainless-steel sample exhibited more pronounced and steeper asperities than the rolled aluminum samples (Table V); this corresponds to the observed lower HTCs measured from the steel tests compared to those obtained from the aluminum tests (Figure 7). This indicates that the steel surface asperities were not deformed by the rolling procedure to the same extent as the aluminum asperities; therefore, no heat-transfer enhancement effect due to rolling, such as was observed for the aluminum samples in Figure 8, would be expected. The data for the HSLA-steel tests, shown in Figure 8, support this conclusion. For steel, then, the values of m and C mentioned earlier are equally applicable for subsequent rolling passes, as well as for the first pass. Therefore, the following equation characterizes the heat-transfer behavior for all rolling passes for steel:

$$\frac{35(10^{-6})h}{k} = \left(\frac{P_r}{\sigma(T_s, \dot{\varepsilon})}\right)^{1.7} \qquad [8]$$

Since the probability is high that the aluminum data can be described by the coefficients obtained for steel, Eq. [8] may be used for the first rolling pass of aluminum as well. However, since the flattening of asperities due to the initial rolling pass reduces the surface roughness parameter, a slightly reduced value of C, $30(10^{-6})m$, must be used to determine the HTC for subsequent aluminum rolling passes. The slight difference between the value of m calculated from the stainless-steel and aluminum data is not significant; therefore, the exponent m is taken from the stainless-steel data due to the higher coefficient of determination.

In Figure 9, a comparison of experimental and predicted HTCs using Eq. [8] is presented with the steel data treated as one group and the aluminum data divided into the first and second rolling passes. Generally good agreement is obtained between the predicted and experimental values for both the steel and aluminum data.

The observed flattening of the asperities on aluminum samples due to rolling makes characterization of the HTC as a function of initial surface roughness difficult for two reasons. First, the extent of flattening is a complex function of initial surface geometry, local workpiece temperature, flow stresses, and roll pressure. Second, theories such as that proposed by Cooper *et al.*[12] depend on the workpiece surface profile following a Gaussian distribution, which is less likely after the asperity tips of the workpiece have been flattened due to rolling. Thus, in this study, the linking of

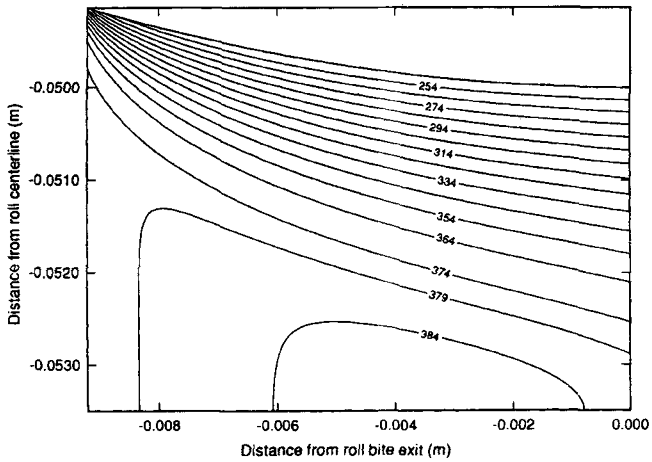

Fig. 10—Isotherms in the workpiece predicted with an HTC of 380 kW/m² °C.

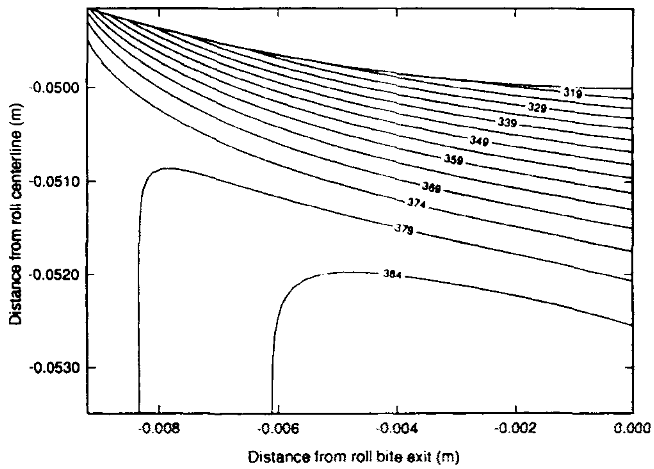

Fig. 11 Isotherms in the workpiece predicted with an HTC of 38 kW/m² °C.

C to physical surface parameters such as R_a and Δa was not attempted beyond observing that a small decrease of the surface roughness coefficient, C, from the second-pass aluminum data corresponded to an observed decrease in surface roughness of aluminum samples due to the first rolling pass.

D. *Effect of the HTC on Workpiece Temperature in the Roll Gap*

Figures 10 and 11 show the effect of the HTC on the temperature distribution in a rolled aluminum sample. Figure 10 presents the calculated temperature profile for a sample, initially at a temperature of 377 °C, rolled to 20 pct deformation with the HTC held constant at 380 kW/m² °C throughout the roll gap. It shows that the sample surface cools from the initial temperature to less than 254 °C within the first 10 pct of the roll bite and then remains at almost a constant temperature through to the roll exit. In the interior of the sample, the temperature initially increases slightly due to the heat of deformation and then cools again farther along the roll bite as heat flows to the sample surface.

Figure 11, on the other hand, shows the calculated temperature profile for a sample with an assumed HTC of 38 kW/m² °C, an order of magnitude less than the HTC assumed in Figure 10. As expected, the surface temperature cools more gradually through the length of the roll bite. Also, the interior of the sample that is heated to above the initial rolling temperature due to the heat of deformation is enlarged because of the reduced temperature gradient.

The HTC measured for aluminum rolling in this study is about 10 times greater than values reported in the literature.[1-4] This result is surprising and begs further analysis. The behavior of the surface temperature of the workpiece at a high HTC, such as illustrated in Figure 10, demonstrates the need for temperature measurement techniques capable of extremely fast response times if the HTC is calculated from the surface temperature of the workpiece. Clearly, if response times are too slow, the rapid initial temperature decrease of the workpiece will be missed and, consequently, a more gradual cooling of the workpiece surface will be measured, giving rise to an artificially low HTC. The use of extrinsic thermocouples on the surface of samples in previous investigations, with inherently slower response times as compared with the intrinsic thermocouples employed in this study, may explain the previously reported low values for the roll-gap HTC. An exception is the value reported by Smelser and Thompson[4] (30 kW/m² °C), who determined the HTC in the roll gap using a similar technique to that employed in this study. This value is most likely valid, but their experiment was performed with a rolling speed almost 10 times slower than that used in the present investigation. Therefore, the applicability of this value for industrial rolling conditions is doubtful.

V. SUMMARY

The HTC in the roll gap for two aluminum-magnesium alloys was compared to that of HSLA steel and stainless steel. The HTC for aluminum was found to be approximately 5 times larger than that for steel at comparable rolling pressures. The type of lubricant used during aluminum rolling had no observable effect on the resulting HTC. The observed difference in the roll-gap HTC for aluminum and steel has been explained in terms of the combined thermal conductivity of the roll and workpiece, as well as the ratio of the rolling pressure to the surface flow stress of the workpiece. The physical mechanism that determines the HTC between the workpiece and roll is the real contact area, quantified in this study by the rolling pressure–surface flow stress ratio; the majority of heat flow between the roll and workpiece occurs at points of direct metal-metal contact. Aluminum exhibits a lower local flow stress at the roll-workpiece interface than steel at similar rolling pressures. This increases the flattening of asperities under pressure, thereby enhancing direct roll-workpiece contact and the HTC.

The surface roughness of the workpiece was found to have a relatively small effect on the HTC. The steel and aluminum samples were found to have similar values of the roughness parameter, C. The aluminum was found to exhibit a slight increase in the HTC upon rerolling due to the smoothening of the surface asperities during the first rolling pass; owing to the higher resistance of asperities to deformation, steel did not exhibit this behavior.

Copper experiments were conducted to determine whether an equation of the form of Eq. [5] is also applicable to other metals besides aluminum and steel. However, the copper results were inconclusive. Recommended work for the future, therefore, includes a more comprehensive series of copper rolling tests, using an improved method of sample instrumentation. Also, future rolling experiments should include surface profilometer measurements of both the rolls and workpieces in order to further quantify the influence of surface roughness on the roll-gap HTC.

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TABLE OF SYMBOLS

Δa	mean of asperity slopes (deg)
a_c	fractional contact area
A	constant used in constitutive stress-strain equation
A_a	apparent contact area (m^2)
A_r	real contact area (m^2)
C	surface roughness parameter (m)
C_{pr}	specific heat of the roll (kJ/kg °C)
C_{pwp}	specific heat of the workpiece (kJ/kg °C)
h	heat-transfer coefficient (W/m^2 °C)
H	surface hardness of the sample (kg/mm^2)
k	combined conductivity, Eq. [3] (W/m °C)
k_r	conductivity of the roll (W/m °C)
k_{wp}	conductivity of the workpiece (W/m °C)
m	exponent used in heat-transfer equation
n	exponent used in constitutive stress-strain equation
P_a	apparent pressure (kg/mm^2)
P_r	mean roll pressure (kg/mm^2)
Q	activation energy used in constitutive stress-strain equation (kJ/mol)
R_a	arithmetic mean of the surface profile from the mean line (μm)
T_r	temperature of the roll (°C)
T_s	surface temperature of the workpiece (°C)
T_{wp}	temperature of the workpiece (°C)
Z	Zener-Holloman parameter
α	constant used in constitutive stress-strain equation (MPa^{-1})
$\dot{\varepsilon}$	strain rate (s^{-1})
$\bar{\dot{\varepsilon}}$	mean strain rate (s^{-1})
ρ_r	density of the roll (kg/m^3)
ρ_{wp}	density of the workpiece (kg/m^3)
σ	steady-state flow stress (MPa)

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