



Residual Copper Effects on Resistance Spot Welded Low Carbon Steel

Increasing residual copper leads to a higher instance of expulsion and higher strength but lower ductility in resistance spot welds

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Abstract

The use of scrap for steel making has increased worldwide and is expected to continue as steelmakers and users pursue sustainability efforts. Advances in steelmaking practices have enabled greater scrap recyclability and energy savings, but have come at the cost of reduced control over residual elements such as copper. This work studies the effect of increased copper content, up to 0.26 wt-%, on the base-metal microstructure and resistance spot-welding behavior of a low-carbon automotive sheet steel. Alloys were subcritically annealed prior to spot welding, tensile-shear testing, electrical resistivity measurements, and microstructural analysis. The higher-copper alloys showed increased base-metal strength, likely due to copper solid-solution strengthening. The higher-copper content alloys also exhibited higher electrical resistivity, resulting in a greater incidence of expulsion during resistance spot welding. Despite increased expulsion at high welding currents, resistance spot welds of the higher copper content alloys showed higher strength and lower ductility in tensile-shear testing. This work shows that elevated residual copper content can be accommodated in welded automotive steel sheets, provided base metal processing and welding parameters are adjusted to account for its influence.

Keywords

- Weldability
- Resistance Spot Welding (RSW)
- Scrap Steelmaking
- Steel
- Residual Copper

Introduction

Resistance spot welding (RSW) is a highly utilized joining technique in auto body fabrication, with over three million spot welds performed every day (Ref. 1). In RSW, two electrodes induce a simultaneous clamping force and electrical current through two overlapping metal sheets. This creates a series of contact “resistors” between the electrodes, with the highest resistivity occurring between the two workpieces (or “faying surfaces”), generating enough heat to melt and form a weld nugget (Ref. 2). However, at high enough electrode current, expulsion can occur, which is the ejection of molten metal from the faying surfaces. Welding parameters are often taken to just below, and sometimes in excess of, this “expulsion limit,” to ensure proper spot weld strength and size requirements (Ref. 3). The propensity of an expulsion to occur is directly related to the heat generated during a weld, which is why increasing either weld current or weld time can induce expulsion (Ref. 4). With such parameters fixed, however, heat generation also varies by virtue of the base metal’s electrical resistivity. Namely, a more resistive material will generate more heat at a given weld current. It has been observed that the addition of common alloying elements increases the overall resistivity of steels, including copper (Refs. 5–7). In light of increased residual elements in scrap-based steels, it is important to quantify how the expulsion limit may shift with base-metal resistivity.

Secondary steelmaking in the electric arc furnace (EAF) boasts scrap recovery rates of up to 90% while emitting approximately one-third the greenhouse emissions of steelmaking from ore (Ref. 8). However, due to increased electrical components in the scrap cycle, the concentration of residual elements such as copper is increasing (Ref. 9). Left unmitigated, copper is known to cause metallurgical problems during thermomechanical processing, most notably hot-shortness (Ref. 10). For steels that do not exhibit this phenomenon, residual copper may still affect downstream processing. At high temperatures, copper is known to hamper grain growth in both austenite and ferrite due to solute drag (Refs. 11, 12). While these mechanisms often

Table 1 — Chemical Compositions for Each of the Base Metals

Alloy	C	Mn	Si	Cr	Mo	Cu	Sn	Fe
0 Cu	0.09	2.19	0.17	0.59	0.087	0.003	0.003	Bal.
14 Cu	0.09	2.25	0.18	0.62	0.087	0.14	0.003	Bal.
26 Cu	0.09	2.27	0.2	0.58	0.084	0.26	0.003	Bal.

impart increased base-metal strength, the effects on subsequent spot weldability remain an open question (Ref. 13).

The goal of this work is to investigate the effect of copper content on the resistance spot weldability of low-carbon sheet steels. Welding performance was characterized by expulsion rate, base metal resistivity, weld microstructure, and tensile-shear strength. Mechanical behavior was compared with that of the unwelded base metal. The results of this work are expected to shed light on the influence of increasing residual copper on the spot weldability and weld performance of automotive sheet steels.

Experimental Procedures

Base Metal Composition and Production

A low-carbon sheet steel composition was used for this study, with controlled amounts of copper content up to 0.26 wt-%, an amount approaching/exceeding typical tolerance, depending on product form and application (Refs. 14, 15). All compositions were laboratory-melted and cast by Cleveland-Cliffs, Inc., hot-rolled to 16 mm thick, pickled, and cold-rolled to a final thickness of 1.5 mm.

Annealing

To select an appropriate heat treatment temperature to produce recrystallized ferrite, single-axis equilibrium simulations of Ae1 (equilibrium critical transformation temperature, above which austenite begins to form) were performed in Thermo-Calc 2024a software using the TCFE13 database. A temperature range of 550–850°C was used for all simulations. Further details are described in the results section. An annealing temperature of 600°C was selected for all alloy compositions to prevent austenite formation while still achieving ferrite recrystallization in the cold-rolled material. Samples from each composition were annealed at 600°C for 3, 5, 6.5, 8, 10, and 18 hours, then cooled under forced air. Ultimately, a 5-hour anneal at 600°C was selected for further welding experiments.

Resistance Spot Welding

Coupons of the alloys shown in Table 1 were sheared into 25 mm × 76 mm rectangles oriented along the sheet's rolling direction. Coupons were then annealed at 600°C for 5 hours

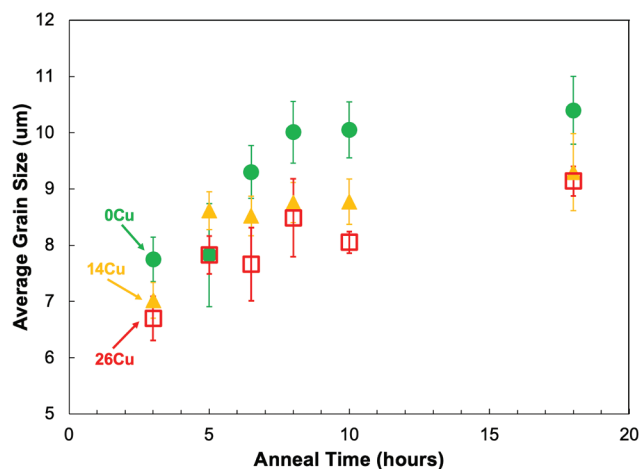


Fig. 1 — Average ferrite grain size as a function of annealing time at 600°C for each of the three alloy compositions. Error bars represent 95% confidence intervals.

and sanded to remove oxide. Coupon pairs were spot-welded together with a 25 mm overlap on a pneumatically operated mid-frequency direct current (MFDC) resistance spot welder with a WTC weld controller. Dome-shaped Cu-Cr-Zr electrode caps with a face diameter of 6 mm were used to apply a 4 kN load for 500 ms during each weld. Separate samples were welded using two different electrical currents, 7 kA and 8 kA. Expulsion events were recorded as a function of alloy composition and welding current.

Mechanical Testing

Vickers Hardness

Spot weld samples performed at 8 kA were sectioned, mounted, and polished to 1 μm prior to Vickers microhardness testing. Hardness traverses were made in 4 rows centered about the fusion zone, using an indent spacing of 275 μm, a load of 500 g, and a dwell time of 10 seconds. Hardness profiles were generated using the average column value and plotted with 95% confidence intervals.

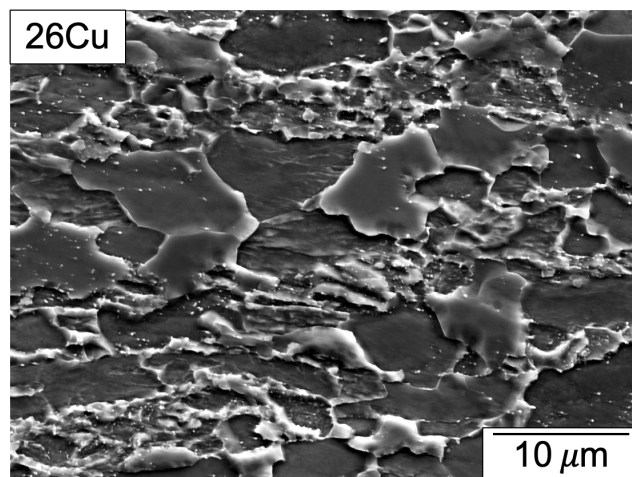
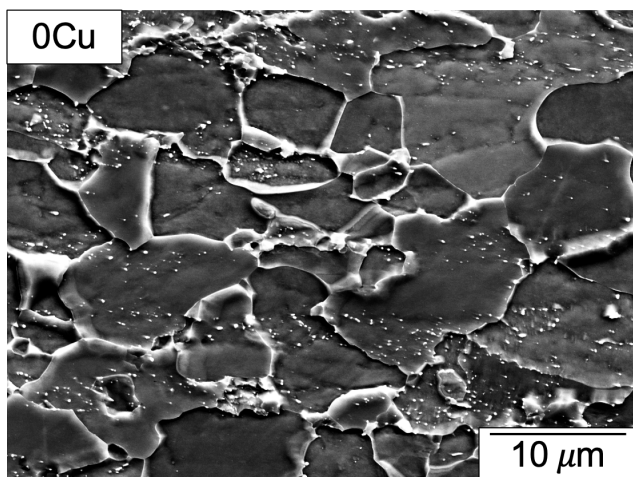


Fig. 2 — SEM SE micrographs of the low- and high-copper base metals after annealing at 600°C for 5 hours. Samples etched with 1% nital prior to imaging.

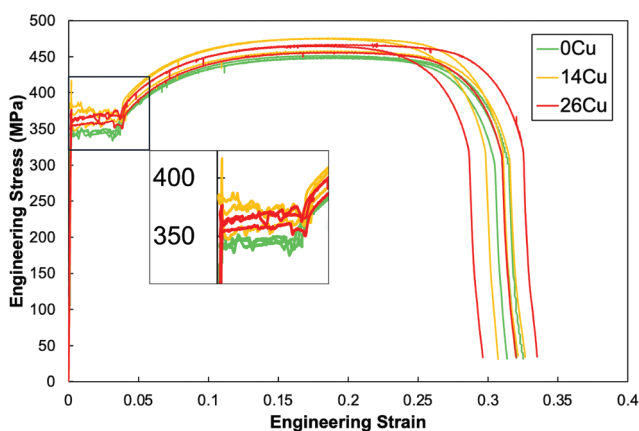


Fig. 3 — Engineering stress-strain curves for each of the annealed base metals. The lower yield point region is shown in the close-up window.

Base Metal Tensile Testing

Subsize ASTM E8 specimens were machined from each of the annealed base metals for tensile testing, having a 6 mm gauge width, 32 mm parallel length, and 1.5 mm thickness. Three specimens of each alloy composition were tested to failure on an MTS Alliance RT/100 electromechanical load frame at an engineering strain rate of $6 \times 10^{-4} \text{ s}^{-1}$ using an extensometer with a 25 mm gauge length. Averages and standard deviations for each condition were pooled to calculate a 95% confidence interval for strength and elongation metrics.

Tensile-Shear Testing

Tensile-shear tests were performed on each of the spot-weld coupons, with 25 mm $\times$ 25 mm steel tabs spot-welded onto each end for gripping. For each composition, three samples welded at 8 kA and two samples welded at 7 kA were tested. A starting grip-grip distance of 75 mm was used for all tensile-shear tests, and samples were tested to failure at

a crosshead velocity of 0.01 mm/s. Cross sections of the failure site were sectioned, mounted, and polished for imaging using light optical microscopy. Averages and 95% confidence intervals of peak load, elongation, and work to fracture, were calculated in a similar fashion as for base metal tensile tests.

Electrical Resistance Testing

Four-probe measurements were done using a Zurich Instruments 500 kHz/5 MHz Impedance Analyzer on sections (160 mm long and 26 mm wide) of the base metal using copper probes. The measurement was done between 1 Hz–1 MHz with an amplitude of 30 mV. The impedance values were recorded and averaged over a 10-minute period, yielding 250,000 measurements per base metal. The measured resistance showed no frequency dependence, validating that it is an electronic conductor and that the measured values (normalized to sample geometry) are the resistivity. Due to the large number of measurements, standard deviations are shown in the plot because 95% confidence intervals would be too small to be appropriately represented graphically.

Microstructure Characterization

Sections of annealed base metal were mounted and polished to 1 μm for grain size measurements using electron backscatter diffraction (EBSD). Grain sizes were averaged over five separate scans for each alloy-anneal combination. Spot welds were prepared similarly and then etched with 1% nitric acid in ethanol (1% nital). Microstructural analysis of the base metal, weld nugget, and heat-affected zones (HAZ) was performed using a Tescan S8252G SEM with a 20 kV accelerating voltage and 10 nA beam current using secondary electron (SE) imaging.

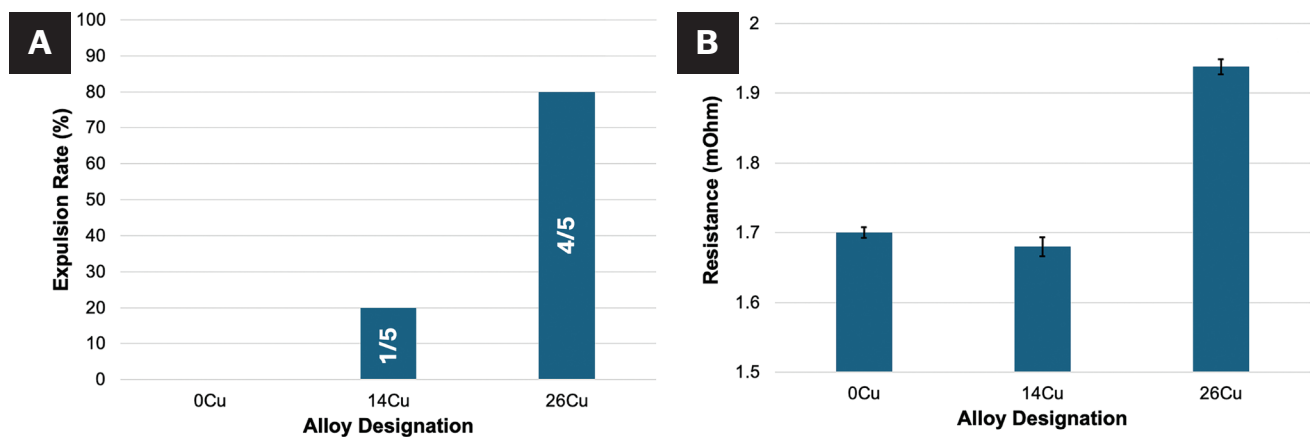


Fig. 4 – A – Expulsion rates (out of 5 samples) for each composition welded at 8 kA electrode current; B – average electrical resistivity of each base metal composition.

Table 2 – Equilibrium Austenite Start (Ae1) Temperatures Calculated in ThermoCalc Software

Alloy	0 Cu	14 Cu	26 Cu
Ae1 Temperature (°C)	660	645.5	627.3

Results

Simulations and Annealing Treatments

Equilibrium critical (Ae1) temperatures were predicted for each alloy composition and are listed in Table 2. As copper content increases, a steady decrease in Ae1 is observed, reflecting increased stabilization of the austenite phase. As a result, 600°C was chosen for subcritical annealing to prevent austenite formation in the higher-copper alloys.

At a subcritical annealing temperature of 600°C (followed by forced air cooling), average ferrite grain sizes were measured by EBSD for each alloy at varying heat treatment times. These average grain sizes, along with 95% confidence intervals, are shown in Fig. 1. Among all heat treatment times, the 5-hour anneal yielded the most comparable average grain size among all compositions. Beyond this time, the grain size of the copper-free composition grew much faster than that of the higher-copper counterparts, demonstrating the copper solute drag effect. Annealing for less than 5 hours yielded microstructures that were not yet fully recrystallized in the higher-copper alloys.

Base Metal Microstructure and Tensile Properties

Scanning electron micrographs of the low- and high-copper (0 Cu and 26 Cu, respectively) base metals annealed at 600°C for 5 hours are shown in Fig. 2. Both base metals show recrystallized ferrite with bands of fine particles that are likely cementite. The higher copper alloy (26 Cu) shows regions of finer ferrite grains, although there is no statisti-

cally significant difference in the average ferrite grain size between the various alloys annealed for 5 hours.

Sections of annealed base metal machined to ASTM E8 subsize geometry were tested to failure. Engineering stress-strain curves for each of the alloy compositions are shown in Fig. 3, with a close-up of the yield point region. Averages with 95% confidence intervals of ultimate tensile strength, lower yield point, uniform elongation, and total elongation (among the triplicates) for each composition are shown in Table 3. Elongation to failure decreases slightly as copper content increases. Yield point and ultimate tensile strength are lowest for the 0 Cu composition, but do not subsequently correlate with copper content. Unintended variations in other alloying elements, such as chromium or manganese, might also influence base metal tensile properties.

Expulsion Rate and Electrical Properties

Spot welds were performed at two separate welding currents, 7 kA and 8 kA. While no expulsion events were observed at 7 kA, several samples exhibited expulsion at 8 kA. The expulsion rates for each composition are shown in Fig. 4A. The tendency for expulsion increases with increasing copper content in the base metal alloys, although the 0 Cu and 14 Cu alloys show more similar behavior, and 26 Cu shows a much higher rate of expulsion. To determine whether the increased expulsion rates of the higher-copper base metals were related to base metal electrical properties, the resistivity of each alloy was measured, and the results are shown in Fig. 4B. Figure 4B shows that the highest copper-containing alloy (which showed the greatest amount of expulsion) has higher electrical resistance than the lower copper alloys.

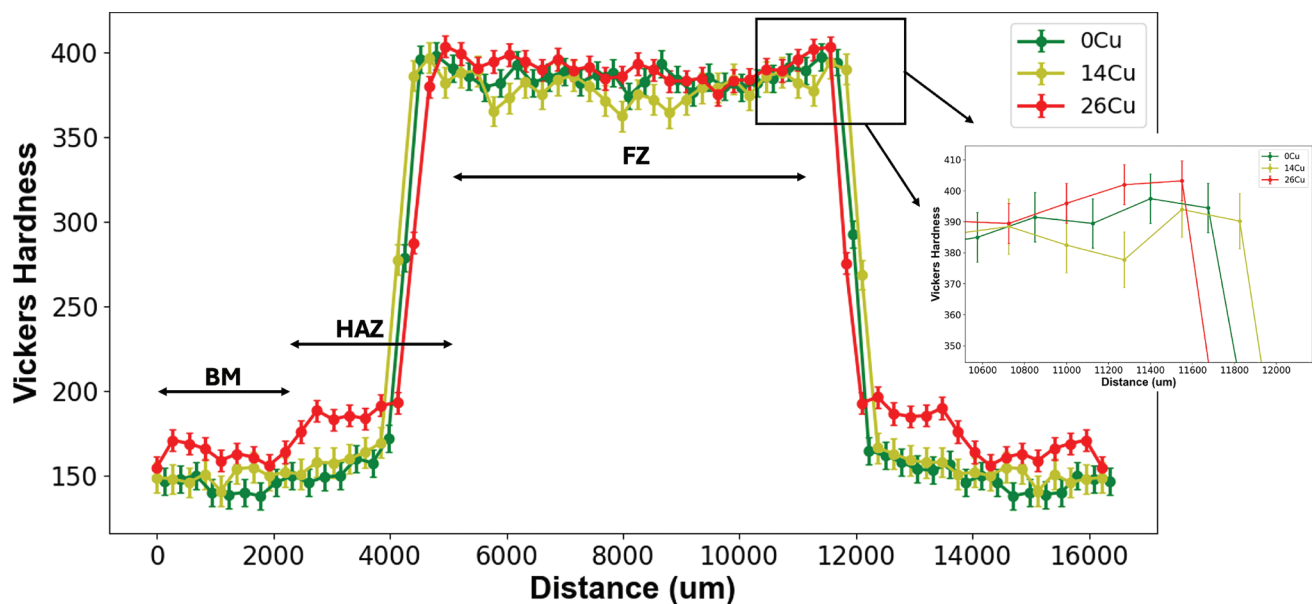


Fig. 5 — Vickers hardness profiles for the spot welds performed at 8 kA, with approximate base metal (BM), heat-affected zone (HAZ), and fusion zone (FZ) regions labeled.

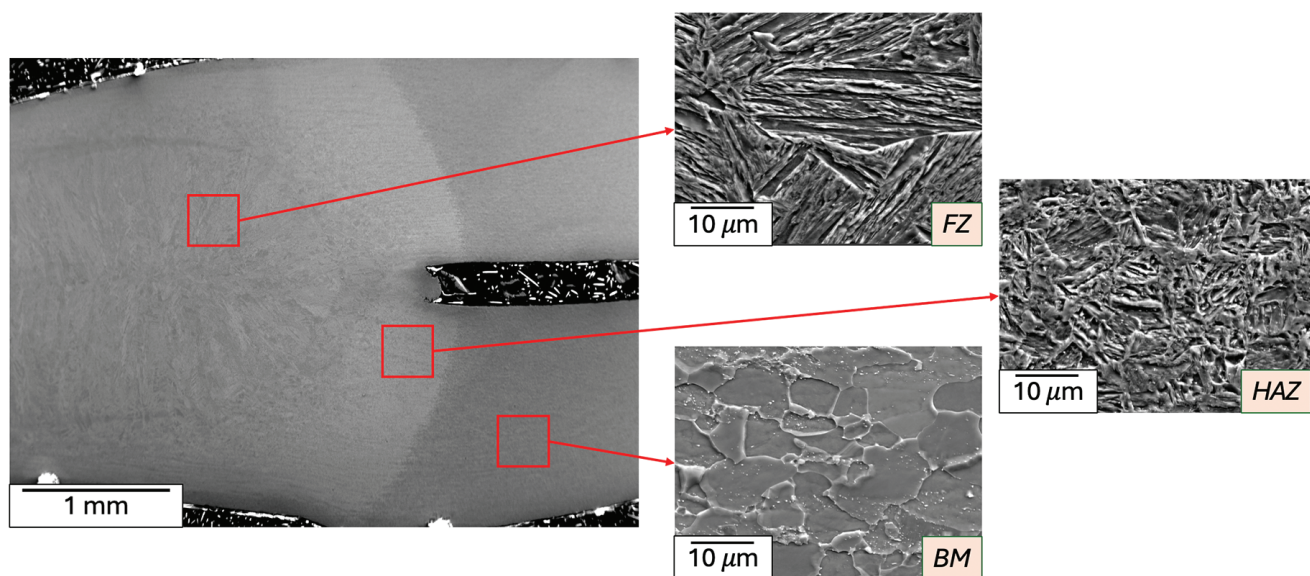


Fig. 6 — SEM SE micrographs of a representative spot weld cross section and various subsections of the weld: fusion zone (FZ), heat-affected zone (HAZ), base metal (BM). Samples etched with 1% nital.

The two lower Cu alloys show similar resistivity that correlates with their more similar tendencies for expulsion.

Resistance Spot Weld Hardness and Microstructure

Vickers microhardness profiles were measured on resistance spot welds of each alloy and are shown in Fig. 5 for the samples welded at 8 kA. In general, the hardness values in the fusion zone do not vary significantly with copper content. Similarly, the highest hardness region of the HAZ also does not vary considerably with copper content. The 14 Cu alloy

shows a slightly larger heat-affected zone compared to the 0 Cu alloy, which may be related to the increased hardenability with Cu content. The highest Cu alloy (26 Cu) shows the smallest HAZ, which may be a result of expulsion slightly modifying the weld size and thermal conditions around the weld. Finally, at the interface with the high-hardness regions of the HAZ, the hardness of the base metals increases with higher Cu content, especially in the 26Cu composition.

Microstructures of the various regions of the spot welds were evaluated. An SEM SE micrograph of the fusion zone, HAZ, and base metal is shown in Fig. 6. The fusion zone and heat-affected zones show microstructures that appear to be

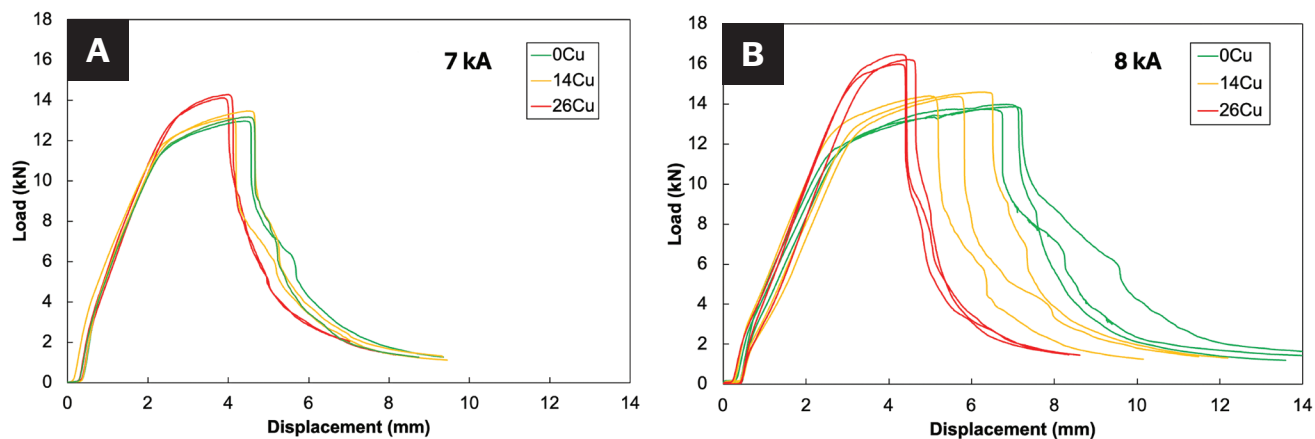


Fig. 7 – Load-displacement curves for the tensile-shear testing of all samples at: A – 7 kA; B – 8 kA welding currents.

Table 3 – Summary of Ultimate Tensile Strength, Yield Point, and Elongation Results for Each Alloy Composition, Presented as Average $\pm$ 95% Confidence Interval

Alloy	0 Cu	14 Cu	26 Cu
UTS (MPa)	450 $\pm$ 3.27	470 $\pm$ 3.27	463 $\pm$ 3.27
Lower Yield Point (MPa)	337 $\pm$ 3.72	358 $\pm$ 3.72	357 $\pm$ 3.72
Uniform Elongation	0.186 $\pm$ 0.002	0.187 $\pm$ 0.002	0.182 $\pm$ 0.002
Total Elongation	0.320 $\pm$ 0.007	0.318 $\pm$ 0.007	0.317 $\pm$ 0.007

martensitic, while the base metal region adjacent to the HAZ closely resembles that of the base metal having equiaxed recrystallized grains. No significant difference was observed in the microstructures of the various regions of the weld as a function of copper content.

Mechanical Performance of Spot Welds

Tensile-shear tests were performed on the spot weld coupons for each alloy at both welding currents. Load-displacement curves for representative tests of each alloy and welding current are shown in Fig. 7 and summarized in Table 4. For both welding currents, the higher copper alloy shows higher peak loads, but smaller displacements to failure (lower ductility). Additionally, the work to fracture (area under the load curve) was lowest for the high-copper composition. Both trends were more pronounced at higher weld current, which may be related to expulsion. In all conditions, full button pullout failure was observed.

Tensile-shear samples were sectioned across the weld nugget and mounted for light optical microscopy of the failure site. For all samples and welding currents tested, failure initiated in the base metal adjacent to the HAZ interface, as shown in Fig. 8. Because failure initiated in the base metal for each condition, higher peak loads were observed with higher copper content, which correlates with higher hardness, as shown in Fig. 5.

Discussion

Influence of Residual Copper on Base Metal Microstructure Evolution and Properties

Solute copper's effect on ferrite grain growth during subcritical annealing is quantified in Fig. 1. For anneals longer than 5 hours, it was observed that compositions with elevated copper (14 Cu or 26 Cu) generally showed slower ferrite grain growth. Similar solute drag behavior has been observed in both ferritic and austenitic microstructures by Takaki and Meng, respectively (Refs. 11, 16). Further, while not observed or studied in this work, copper precipitates are also known to impede grain boundary migration (Ref. 17). It is clear that residual copper has a significant influence on the microstructure developed during processing of the base metal.

Base metal tensile properties between the different compositions exhibited similar ultimate tensile strength as seen in Fig. 3 and Table 3. Total elongation only slightly decreased as a function of copper content, and ultimate tensile strength was highest in the 14 Cu composition. This could be due to unintended variations in manganese, chromium, and copper. Regardless, yield-point elongation remained consistent across all compositions. Any addition of copper was shown to increase the lower yield point, as shown in the inset of Fig. 3. With copper and manganese

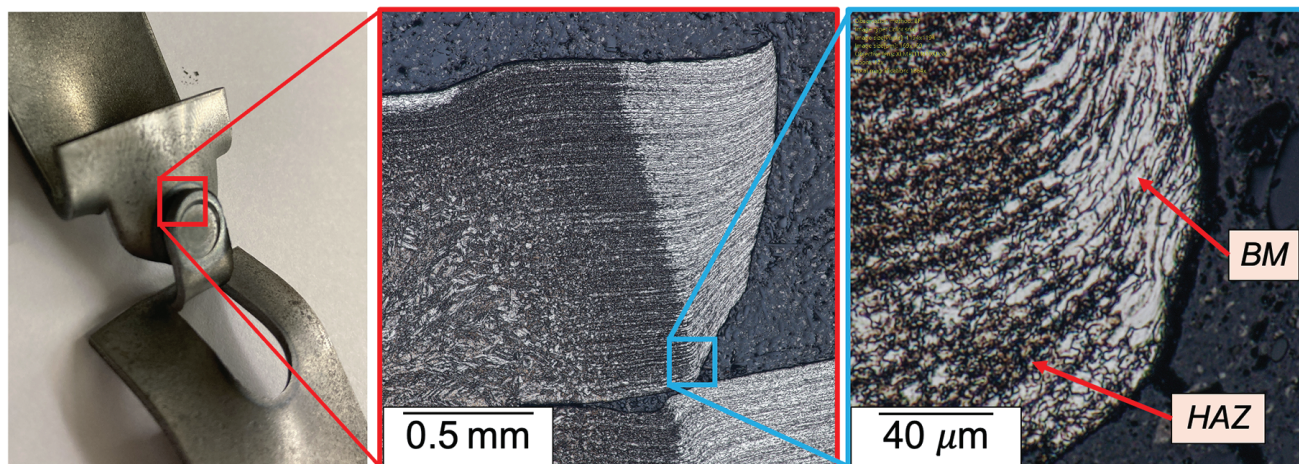


Fig. 8 — Cross section of failure site in a tensile-shear specimen obtained by light optical microscopy. Shown above, Cu alloy welded at 8 kA, etched with 1% nital.

Table 4 — Statistical Summary of Tensile-Shear Properties at Both 7 and 8 kA Weld Currents, Presented as Average $\pm$ 95% Confidence Interval

Alloy	0 Cu	14 Cu	26 Cu
7 kA			
Peak Load (kN)	13.1 $\pm$ 0.11	13.3 $\pm$ 0.11	14.2 $\pm$ 0.11
Total Elongation (mm)	9.1 $\pm$ 0.33	9.4 $\pm$ 0.33	7.6 $\pm$ 0.33
Work to Fracture (N·m)	57.5 $\pm$ 4.2	57.5 $\pm$ 4.2	51.5 $\pm$ 4.2
8 kA			
Peak Load (kN)	13.9 $\pm$ 0.09	14.5 $\pm$ 0.09	16.2 $\pm$ 0.09
Total Elongation (mm)	13.8 $\pm$ 0.27	11.3 $\pm$ 0.27	8.5 $\pm$ 0.27
Work to Fracture (N·m)	106.4 $\pm$ 3.43	76.1 $\pm$ 3.43	58.0 $\pm$ 3.43

lending solid solution strengthening contributions of 52 and 44 MPa/wt-%, respectively, strengthening of up to 13–14 MPa could be expected for the copper range explored in this work (Ref. 18). Measured shifts in lower yield strength lie well within that range, indicating that the main contributor to differences in strengthening observed in this work is likely due to solid solution strengthening. It should be noted, however, that base metal annealing times were selected to minimize differences in ferrite grain size between the various alloys. If longer annealing times had been used to process the base metal, additional differences in base metal strength would likely have been observed due to varying grain-size strengthening.

Influence of Residual Copper on Resistance Spot Weldability and Performance

In all the copper contents explored, the microstructure in the fusion zone consisted of larger martensite laths, while the highest hardness portion of the HAZ adjacent to the fusion zone contained fine martensite laths, as shown in Fig. 6. Hardness profiles shown in Fig. 5 show comparable fusion zone hardness, which is essentially controlled by the hardness of fresh martensite. The higher copper composition (26 Cu) exhibited a slightly narrower FZ/HAZ. This could be due to expulsion in higher-copper alloys, resulting in a loss of heat-generating material. All compositions displayed a slight hardness increase at the edge of the fusion zone and heat-affected zone interface, which has the finer martensitic structure shown in Fig. 6. It is likely that less austenite grain growth occurred at the edge of the heat-affected zone rela-

tive to the center of the fusion zone, leading to subsequently finer martensitic laths and higher hardness.

In the intercritical HAZ nearest the fusion zone, the 26 Cu alloy exhibited significantly higher hardness than the others, likely due to a higher fraction of non-ferritic constituents following intercritical heating. This is a latent effect of copper's stability of austenite and has been observed in intercritical annealing studies of similar material (Ref. 19). It could also be a consequence of softening resistance afforded by higher copper content, which would require more in-depth investigation. Time-temperature studies during spot welding (i.e., using thermocouples) could help explain the mechanism for this distinction in BM/HAZ hardness.

At a lower welding current (7 kA), the tensile-shear strength of the 0 Cu and 14 Cu samples showed similar maximum load and total elongation, as seen in Fig. 7. The high-copper composition, 26 Cu, exhibited a significantly higher maximum load, with reduced total elongation. Spot welds performed at the higher weld current (8 kA) showed a greater spread in total elongation with increasing copper content. The higher copper composition, even with expulsion, exhibited the highest strength and lowest elongation. The 0 Cu and 14 Cu heats showed comparable strength but reduced total elongation as copper content increased. As shown in Fig. 8, all welds failed by "full button pull-out" — the preferred mode of weld failure — with failure initiation in the base metal just outside of the HAZ (Ref. 20). This region shows the highest disparity in strength/hardness and alludes to a mechanical failure controlled by the softer base metal. Weld nugget sizes were also comparable amongst the compositions at each weld current tested. The observed trends in the performance of the spot-welded samples agree with those in base-metal strength and hardness as a function of copper content: higher copper content leads to higher strength (mostly solid-solution strengthening) and lower ductility.

None of the compositions exhibited expulsion at the lower welding current (7 kA). At 8 kA current, expulsion was most prevalent in the high copper composition, 26 Cu, as quantified in Fig. 4B. While bulk copper has substantially lower electrical resistivity than steel, the presence of copper in solid solution increases overall resistivity by acting as a scattering site (Ref. 7). While expulsion technically reduces the amount of fusing material during the weld, no discernable difference in weld nugget size was measured. Further, weld strength did not decrease with increasing expulsion. In fact, strength increased as a function of copper content despite expulsion, likely a consequence of the solid solution strength imparted to the base metal.

Outlook for Resistance Spot Welding of Steels with Increasing Residual Copper Contents

Increasing copper content in the steel scrap stream is inevitable, so it is necessary to understand how base metal processing and subsequent welding processes must be adjusted. The results of this work show that the influences

of residual copper, up to 0.26 wt-%, are somewhat subtle and can be accounted for. Copper's slowing of ferrite grain growth during subcritical annealing can be accommodated by extended anneal times. Increases in base metal electrical resistivity due to copper can be accommodated by lower welding currents. However, further investigation exploring larger ranges in weld current and duration could help develop a more comprehensive weld lobe that accounts for residual copper content. Overall, this work shows that resistance spot-welded low-carbon steel sheets can accommodate elevated copper content, suggesting a bright future for automotive steels containing high levels of recycled content.

Conclusion

The goal of this work was to investigate copper's effect on the resistance spot weldability and performance of a low-carbon automotive steel sheet. The expulsion rate, electrical resistivity, hardness, base metal strength, and tensile-shear properties of resistance spot welds with copper contents ranging from 0–0.26 wt-% were evaluated. The conclusions of this work are as follows:

- During subcritical annealing of the base metal at 600°C, higher copper content impeded ferrite grain growth, leading to finer grain sizes in the higher copper materials.
- Higher copper content generally resulted in higher yield strength but lower ductility in the subcritically annealed base metal, likely from copper solid solution strengthening.
- Expulsion at higher weld currents was observed to increase with copper content. The increase in the expulsion rate correlated with the base metal's electrical resistivity as a function of copper content.
- Tensile-shear strength of the spot welds increased with copper content, while elongation decreased. Work-to-fracture generally decreased with increasing copper content, particularly at higher welding current.
- The primary failure mode in tensile-shear testing was full button pull-out, where fracture initiated in the base metal nearest the heat-affected zone, which is why trends in tensile-shear testing of the spot welds match those of base metal tensile properties.
- The results of this work show that residual copper does affect microstructure and mechanical performance of resistance spot-welded automotive sheet steels, but the effects can be accommodated with modifications to base metal processing and welding parameters.

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