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Design-of-Experiments Study to Examine the Effect of Polarity on Stud Welding

An investigation of the factors that influence the quality of short duration drawn arc stud welding of steels

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ABSTRACT. A study was conducted to evaluate the robustness of the arc stud welding process as applied to a range of uncoated and galvanized sheets. Within this study, a range of process, manufacturing, and materials variables were investigated including type of stud coating, level of collet wear, polarity of the stud, type of power supply used, design of the welding stud, thickness of the substrate sheet, presence of any surface oils, and coating condition of the steel.

Measures of weld quality in this study included shear, tensile, torsion, and bend testing. Some metallographic support work was also done.

Given the wide range of variables for study and ways of evaluating weld quality, a design-of-experiments (DoE) approach was used. A 32-trial design was selected that covered eight factors for study (including one three-level factor, sheet coating condition) and four destructive quality measures. Results were analyzed using statistical techniques to yield a series of process robustness plots.

Results indicated geometry effects dominated weld performance in the destructive tests. Most notably, larger studs and thicker sheets provided the best performance. This was, to some degree, contrary to the metallographic examinations, which suggested the larger studs had greater levels of internal porosity and poorer weld interface integrity. Apparently, the geometric effect outweighed the metallurgical effect. The metallographic examinations suggested that using a stud-negative configuration resulted in greater heating of the substrate sheet that, in turn, should improve weld quality. Again, with the exception of the shear tests, this was not reflected in the various mechanical tests.

Of the various mechanical tests conducted, the shear test appeared to be most sensitive to actual variations in weld quality. This test appeared sensitive to both changes in geometry, as well as changes in weld quality. It is believed that since the shear test, by design, loads the entire weld interface area, it is more representative of the range of internal weld quality concerns revealed in the metallographic examinations. The other tests, by design, preferentially load only the periphery of the joint, and tend to be dominated by geometric effects.

KEY WORDS

Arc Stud Welding
Metallography
Coated Steel
Weld Interface
Automotive

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Introduction

Drawn arc stud welding is a well-established process for attaching studs to a variety of material thicknesses and coating combinations in automotive construction. The application of arc stud welding is consistent with new automotive designs and manufacturing strategies that continually focus on ways to reduce costs. This is provided by a combination of short cycle time for stud attachment (high productivity) and adaptability to automation. Manufacturers are able to address many of the cost reduction targets by use of drawn arc stud welding, but the quality and reproducibility of such stud welds have historically been a concern. This is particularly true in safety-critical applications. Over the years, improvements have been made to increase the reliability of the stud welding process. These improvements have included the use of improved power supplies, as well as the application of more precise motion welding heads. However, the automotive market, which already has preconceived notions about the stud welding process, is not fully utilizing these technologies.

Many of the quality concerns traditionally associated with drawn arc stud welding have to do with inconsistencies in stud welding variables. These include variables inherent to the process (weld current, weld time, arc voltage, plunge depth, etc.), as well as more general manufacturing variables (sheet cleanliness, joint geometry, etc.) that directly affect weld performance. Acceptance of stud welding as a reliable, capable process is now dependent on understanding the effects of these variables. Of particular interest is the sensitivity of the process to variations in each factor.

A study was conducted specifically to address how the drawn arc stud welding process is affected by variations in a range of process and manufacturing variables. In this study, a wide range of factors was investigated. Due to the large number of variables and the need to understand interactions between them, a design-of-experiments (DoE) approach was used (Refs. 1–3). A 32-trial, fractional factorial DoE was used to examine eight process, manufacturing, and material factors. Ranges of different quality measures were also employed as dependent

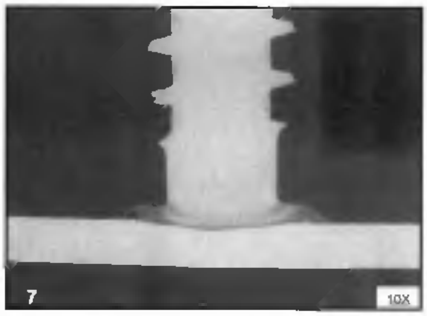

Fig. 1 — Macrograph of stud weld, Zn-coated stud, stud positive, new collet TRANSREC power, T5 stud, 1.4-mm HDG sheet with light oil coating.

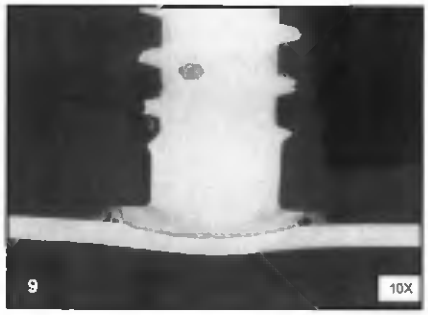

Fig. 2 — Macrograph of stud weld, Cu-coated stud, stud positive, used collet, TRANSREC power, T5 stud, 0.7-mm EG sheet with light oil coating.

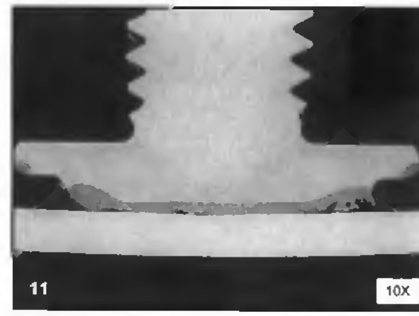

Fig. 3 — Macrograph of stud weld, Zn-coated stud, stud positive, used collet, TRANSREC power, T5 stud, 1.4-mm EG sheet with light oil coating.

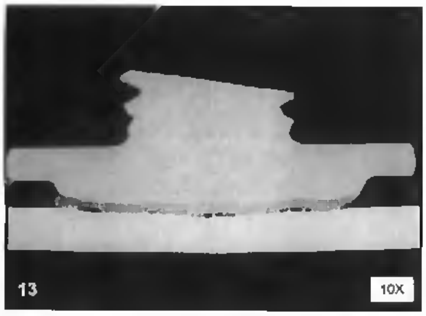

Fig. 4 — Macrograph of stud weld, Zn-coated stud, stud negative, used collet, TMP power, large flange stud, 1.4-mm EG sheet with light oil coating.

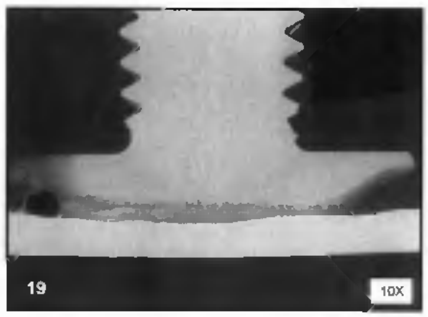

Fig. 5 — Macrograph of stud weld, Cu-coated stud, stud negative, used collet, TRANSREC power, large flange stud, 1.4-mm HDG sheet with light oil coating.

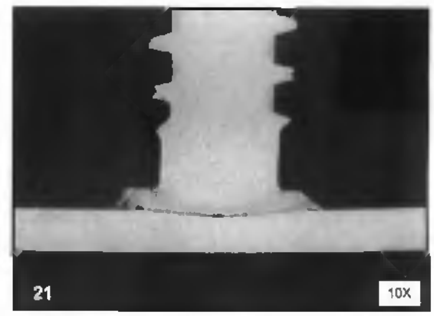

Fig. 6 — Macrograph of stud weld, Cu-coated stud, stud positive, used collet, TRANSREC power, T5 stud, 1.4-mm EG sheet with light oil coating.

factors. Results from this experiment have been analyzed and used to infer factors most critical to the process, as well as to make assessments of the utility of each different quality measure.

Experimental Procedure

Preparation of the DOE

The following variables and levels were selected for examination:

Polarity of the machine. Levels for this variable included both stud positive and stud negative configurations.

Material coating. Three material coatings were included. These covered bare, electrogalvanized (EG) 60G/60G, and hot-dipped galvanized (HDG) 70G/70G steels.

Material thickness. Two material thicknesses 0.7 mm (0.027 in.) and 1.4 mm (0.055 in.) were included.

Stud design. Levels for this variable included the small stud (T5) as well as a large flange stud (M6).

Stud coating. Two stud coatings were examined — copper (Cu) and zinc (Zn).

Collet wear. Two levels of collet wear were examined. A new collet and a collet with approximately 10,000 welds of wear were used.

Power type. Two types of power sources were investigated. Transformer rectifier (commonly referred to as TRANSREC and the multiprogrammer (commonly referred to as TMP), which is a switching mode power supply (SMPS) — also referred to an inverter-type power supply.

Surface oil. The effect of oil on the sheet was examined, comparing a relatively clean sheet with no stamping oil and a sheet with a light coating of stamping oil.

The metrics (or responsible variables) used to compare the welding processes were tensile strength, shear strength, torque to failure, and bending angle to failure. In addition, metallographic samples of a stud from each of the trials were examined to help understand the results of the trials.

A 32-trial DoE was selected. This design allowed identification of all main effects, although some two-factor interactions were confounded. To maximize the utility of this design, prior knowledge and expertise was used to first rank the preconceived significance of each interaction. Then, using the DoE software (Ref. 4), a variant of the design that confounds high-ranking interactions with low-ranking interactions was selected. The resulting high-efficiency design (Table 1) was used for the study.

Welding Trials and Mechanical Testing

Optimized welding parameters based on prior knowledge were used to make the weld samples. Fifty welds for each run of the DoE were made for subsequent testing.

Testing of the welds was conducted on the appropriate testing equipment. Ten samples were tested for each metric from each run in the DoE. Shear tests were conducted using a fixture to minimize bending and place the welds in pure shear. Tensile tests were conducted using a fixture designed to rigidly hold the sheet and place the weld in pure tension. Torque testing was conducted using a standard torque wrench. A bending test was developed to bend the sample until the weld cracked. The resulting angle of bend to failure was then measured and recorded as data.

Analysis of Results

Results of these trials were analyzed using standard statistical methodology (Ref. 3). The methodology consisted of first assessing statistical normality of the data and, where necessary, applying appropriate mathematical transformations to ensure normality of that data. This nor-

Table 1 — DOE Matrix

Trial No.	Stud Coat	Collet Wear	Stud Polarity	Type of Power Source	Stud Design (size flange)	Sheet Thick (mm)	Oil	Sheet Coating
1	Cu	New	Stud neg.	TRANSREC	Small	0.7	Light oil	EG
2	Zn	10,000	Stud neg.	TMP	Large	0.7	No oil	EG
3	Cu	10,000	Stud pos.	TMP	Large	0.7	Light oil	
Uncoated								
4	Cu	New	Stud pos.	TMP	Small	0.7	No oil	EG
5	Zn	10,000	Stud pos.	TRANSREC	Large	0.7	Light oil	EG
6	Cu	New	Stud neg.	TRANSREC	Small	1.4	No oil	EG
7	Zn	New	Stud pos.	TRANSREC	Small	1.4	Light oil	HDG
8	Cu	10,000	Stud neg.	TMP	Small	1.4	Light oil	EG
9	Cu	10,000	Stud pos.	TRANSREC	Small	0.7	Light oil	EG
10	Cu	New	Stud pos.	TMP	Small	1.4	Light oil	EG
11	Zn	10,000	Stud pos.	TRANSREC	Large	1.4	No oil	EG
12	Cu	New	Stud neg.	TMP	Large	0.7	Light oil	HDG
13	Zn	10,000	Stud neg.	TMP	Large	1.4	Light oil	EG
14	Zn	New	Stud pos.	TMP	Large	1.4	Light oil	EG
15	Cu	10,000	Stud neg.	TMP	Small	0.7	No oil	EG
16	Zn	New	Stud neg.	TRANSREC	Large	1.4	No oil	EG
17	Cu	New	Stud neg.	TMP	Large	1.4	No oil	
Uncoated								
18	Zn	New	Stud pos.	TMP	Large	0.7	No oil	EG
19	Cu	10,000	Stud neg.	TRANSREC	Large	1.4	Light oil	HDG
20	Cu	10,000	Stud pos.	TMP	Large	1.4	No oil	HDG
21	Cu	10,000	Stud pos.	TRANSREC	Small	1.4	No oil	EG
22	Zn	New	Stud pos.	TRANSREC	Small	0.7	No oil	
Uncoated								
23	Zn	10,000	Stud neg.	TRANSREC	Small	0.7	No oil	HDG
24	Zn	New	Stud neg.	TRANSREC	Large	0.7	Light oil	EG
25	Zn	New	Stud neg.	TMP	Small	0.7	Light oil	
Uncoated								
26	Cu	New	Stud pos.	TRANSREC	Large	0.7	No oil	HDG
27	Cu	10,000	Stud neg.	TRANSREC	Large	0.7	No oil	
Uncoated								
28	Cu	New	Stud pos.	TRANSREC	Large	1.4	Light oil	
Uncoated								
29	Zn	New	Stud neg.	TMP	Small	1.4	No oil	HDG
30	Zn	10,000	Stud pos.	TMP	Small	1.4	No oil	
Uncoated								
31	Zn	10,000	Stud neg.	TRANSREC	Small	1.4	Light oil	
Uncoated								
32	Zn	10,000	Stud pos.	TMP	Small	0.7	Light oil	HDG

malized data was used to produce a series of "best fit" regression equations. These, after any required back-transformation, acted as maps of the quality measures over the ranges of process, manufacturing, and material variables studied. Optimizations of these equations were done and, in an iterative process, an optimized set of conditions was found. Response plots based on these optimum conditions were then prepared showing the effects of each studied factor on each of the quality measures. These "robustness plots" provide a graphical representation of the penalties paid by varying any factor from its ideal condition. These robustness plots were also used for subsequent analysis of the process itself.

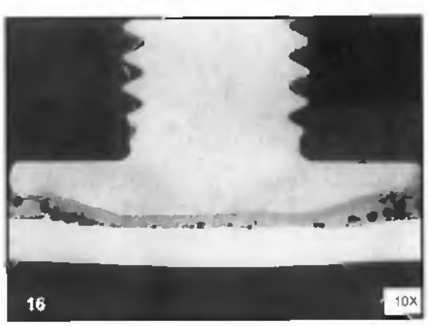

Fig. 7 — Macrograph of stud weld, Zn-coated stud, stud negative, used collet, TRANSREC power, large flange stud, 1.4-mm EG sheet with no oil coating.

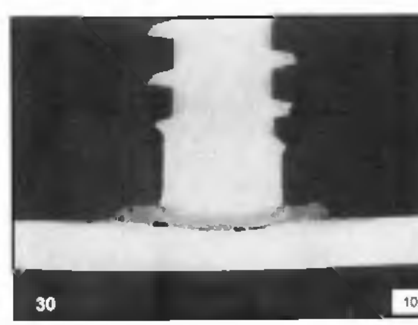

Fig. 8 — Macrograph of stud weld, Zn-coated stud, stud positive, used collet, TMP power, T5 stud, 1.4-mm bare sheet with no oil coating.

Results

Almost 1300 studs were welded and mechanically tested during this study. The representative metallographic sections for some trials of the DoE are also presented. The macrographs of the welds are shown in Figs. 1–8.

Statistical Analysis Results

Of the four quality variables included in this study, three required normality

Table 2 — Regression Analysis for the Curve Fit Relating the Measured Shear Strengths to the Factors under Study Including Designed Two-Factor Interactions (Output of the equation must be back-transformed with the appropriate function.)

Predictor	Coeff.	St. Dev	T
Constant	6.96429	0.0283	246.11
Stud design (std-Des)	0.72956	0.0283	25.78
Power supply (pwr)	–0.59331	0.0283	–20.97
Sheet coating *Polarity (shc*pol)	–0.47944	0.04002	–11.98
Sheet thickness (sht-thk)	0.22321	0.0283	7.89
Polarity (pol)	0.2163	0.0283	7.64
Polarity * Stud design (pol*sd)	0.17938	0.0283	6.34
Stud coating (std-coat)	0.17888	0.0283	6.32
Power supply * Thickness (pwr*thk)	–0.15332	0.0283	–5.42
Sheet thickness (shc*thk)	–0.19852	0.04002	–4.96
Power * Oil (pwr*oil)	0.12516	0.0283	4.42
Collet wear * Power supply (cw*pwr)	–0.10974	0.0283	–3.88
Sheet coating * Collet wear (shc*cw)	0.14626	0.04002	3.65
Power * Stud design (pwr*sd)	0.08852	0.0283	3.13
Polarity * Power supply (pol*pwr)	–0.08345	0.0283	–2.95
Stud coating * Polarity (sdc*pol)	–0.06355	0.0283	–2.25
Collet wear (coll-wr)	–0.05715	0.0283	–2.02
Collet wear * Polarity (cw*pol)	–0.05457	0.0283	–1.93

S = 0.5062 R-Sq = 84.0% R-Sq(adj) = 83.1%
The regression equation is corr-shr = 6.96 + 0.730 std-Des – 0.593 pwr – 0.479 shc*pol + 0.223 sht-thk + 0.216 pol + 0.179 pol*sd + 0.179 std-coat – 0.153 pwr*thk – 0.199 shc*thk + 0.125 pwr*oil – 0.110 cw*pwr + 0.146 shc*cw + 0.0885 pwr*sd – 0.0835 pol*pwr – 0.0636 sdc*pol – 0.0572 coll-wr – 0.0546 cw*pol

Table 3 — Regression Analysis for the Curve Fit Relating the Measured Tensile Strengths to the Factors under Study Including Designed Two-Factor Interactions (Output of the equation must be back-transformed with the appropriate function.)

Predictor	Coeff.	St. Dev	T
Constant	5.59118	0.02389	234.01
Sheet thickness (sht-thk)	0.50868	0.01689	30.11
Sheet coating * Sheet coating (shc*shc)	0.36309	0.03379	10.75
Stud design (std-Des)	0.16804	0.01689	9.95
Stud coating * Power supply (sdc*pwr)	0.15686	0.01689	9.28
Power supply * Oil (pwr*oil)	0.12904	0.01689	7.64
Stud coating (std-coat)	0.12612	0.01689	7.46
Oil (oil)	0.11332	0.01689	6.71
Polarity (polarity)	0.08617	0.01689	5.1
Polarity * Stud design (pol*sd)	0.08157	0.01689	4.83
Sheet coating * Collet wear (shc*cw)	0.09249	0.02389	3.87
Sheet coating * Sheet thickness (shc*thk)	–0.09131	0.02389	–3.82
Collet wear * Power supply (cw*pwr)	–0.06041	0.01689	–3.58
Sheet coating (sht-coat)	0.08162	0.02389	3.42
Stud design * Polarity (sdc*pol)	–0.05234	0.01689	–3.1
Polarity * Thickness (pol*thk)	0.04553	0.01689	2.7
Power supply (pwr)	0.03508	0.01689	2.08
Collet wear * Polarity (cw*pol)	0.03334	0.01689	1.97
Sheet coating * Polarity (shc*pol)	–0.04256	0.02389	–1.78

S = 0.3022 R-Sq = 83.3% R-Sq(adj) = 82.3%
The regression equation is corr-tns = 5.59 + 0.509 sht-thk + 0.363 shc*shc + 0.168 std-Des + 0.157 sdc*pwr + 0.129 pwr*oil + 0.126 std-coat + 0.113 oil + 0.0862 polarity + 0.0816 pol*sd + 0.0925 shc*cw – 0.0913 shc*thk – 0.0604 cw*pwr + 0.0816 sht-coat – 0.0523 sdc*pol + 0.0455 pol*thk + 0.0351 pwr + 0.0333 cw*pol – 0.0426 shc*pol

correction. These included shear, tensile, and torque strengths. Each was normality corrected using a power function. These power functions had exponents of 3.8, 4, and 8 for the three quality variables listed above, respectively.

The resulting regression equations from statistical analysis of corrected data are presented in Tables 2–5. In each of these tables, the reduced regression equation is supplied as well as the correlation coefficients and overall R^2 value for the fit equation. These equations generally showed each quality measure correlated with a range of the factors studied as well as interactions between these factors. In these cases, the resulting R^2 was quite high, generally over 70%. For exploratory-type DoEs, this value is quite high, indicating good predictive capability of the developed models. The exception was the fit for torque strengths. The fit in this case was hampered by two factors. First, was the dominant effect of the stud design. The larger body design had inherently higher torque strength and tended to swamp all other variables. The second was the inherently large scatter in this type of quality measure. This was evident from the raw data, and greatly reduced the fit of the regression equation.

Graphical Analysis Results

The individual corrected curve fits presented in Tables 2–5, combined with the assessed optimum set of factors as mentioned in the previous section, were used to produce a series of robustness plots. These plots allow the effect of varying individual factors from their best conditions on each of the quality measures to be observed directly. These plots are presented in Figs. 9–12. In each case, the effects of each process, manufacturing, or material factor is represented by a separate line on the graph, with separate graphs for each measure of weld quality.

These regression equations (after back transformation) were then used to predict an optimized set of input conditions. These are provided for each of the quality measures in Table 6. As might be inferred from the above discussion, shear and tensile strengths, as well as bend angles, were sensitive to the widest range of variables. Of these, shear and tensile strengths were optimized to nearly identical conditions. The only difference was regarding the type of power supply used. Shear strengths optimized with the TMP supply, while tensile strengths optimized to the TRANSREC power supply. It was noted the TRANSREC power supply adversely affected the shear strength result, while the use of the TMP unit only slightly affected the tensile strength results. Optimum conditions in this experiment, then, were selected as those predicted for the shear and tensile strength curve fits with the power supply forced to the TMP unit. These optimum conditions were used for the graphical robustness analyses described below.

The various factors that affect shear strength are shown in Fig. 9. Clearly, at least five factors can be considered detrimental to measured shear strengths. These include stud positive polarity, small stud diameters, use of the TRANSREC power supply, welding onto galvanized steels, and attachment to thinner sheets.

Each of these effects resulted in measured shear strength losses of 40–60%. Other factors (stud coating, collet wear, and the presence of surface oil) caused no more than 10% reduction in measured shear strengths. This suggests a relatively high degree of process tolerance to these factors.

Similar process robustness results for

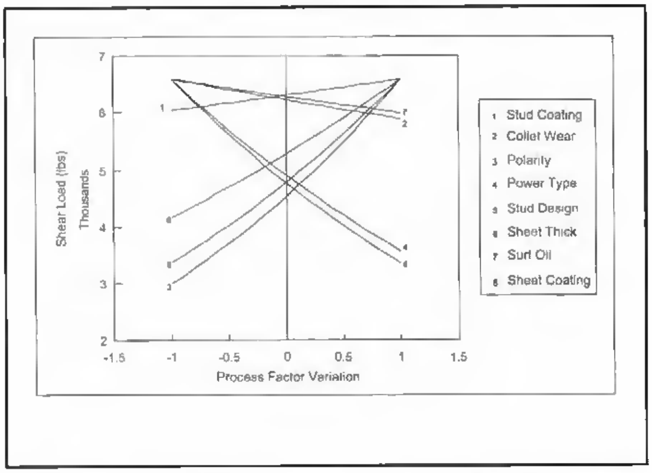

Fig. 9 — Effect of studied factors on shear strength. The values of individual factors include the following: stud coating, –1 = Zn, +1 = Cu; collet wear, –1 = new, +1 = 10,000 welds; polarity, –1 = stud positive, +1 = stud negative; power type, –1 = TMP, +1 = TRANSREC; stud design, –1 = small flange, +1 = large flange; sheet thickness, –1 = 0.7 mm, +1 = 1.4 mm; surface oil, –1 = no oil, +1 = light oil; sheet coating, –1 = bare steel, 0 = EG steel, +1 = HDG steel.

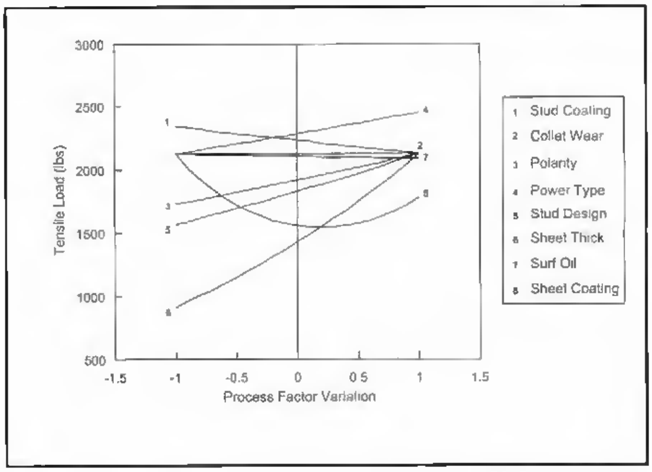

Fig. 10 — Effect of studied factors on tensile strength. The values of individual factors include the following: stud coating, –1 = Zn, +1 = Cu; collet wear, –1 = new, +1 = 10,000 welds; polarity, –1 = stud positive, +1 = stud negative; power type, –1 = TMP, +1 = TRANSREC; stud design, –1 = small flange, +1 = large flange; sheet thickness, –1 = 0.7 mm, +1 = 1.4 mm; surface oil, –1 = no oil, +1 = light oil; sheet coating, –1 = bare steel, 0 = EG steel, +1 = HDG steel.

the measured tensile strengths are presented in Fig. 10. In this case, the attached sheet thickness was found to be the dominant variable, with the thicker material demonstrating nearly double the strength compared to using the thinner material. This is not particularly surprising in that the preferred mode of failure in this test is tearing through the sheet. In such cases, thicker materials will have implied higher strengths. This, in fact, appears to be the case with tensile strengths varying nearly in proportion to the attached sheet thickness. Smaller stud diameters, stud positive polarity, and the use of coated steels all appeared to reduce tensile strengths by about 20–30%. It is of note here that the two galvanized steels actually performed quite similarly. Zinc stud coatings and the use of TRANSREC power supply actually appeared to improve tensile strength performance, although the effect was relatively small (about 10%). The level of collet wear appeared to have no effect on tensile strength performance.

Table 4 — Regression Analysis for the Curve Fit Relating the Measured Torque Strengths to the Factors under Study Including Designed Two-Factor Interactions (Output of the equation must be back-transformed with the appropriate function.)

Predictor	Coeff.	St. Dev	T
Constant	1.71465	0.00741	231.37
Stud design (std-Des)	0.123265	0.007411	16.63
Power supply * Stud design (pwr*sd)	0.022345	0.007411	3.02
Oil (oil)	–0.020466	0.007411	–2.76
Power supply * Oil (pwr*oil)	–0.019278	0.007411	–2.6
Stud coating * Polarity (sdc*pol)	–0.013574	0.007411	–1.83
Sheet thickness (sht-thk)	0.013132	0.007411	1.77

S = 0.1326 R-Sq = 49.5% R-Sq(adj) = 48.5%
The regression equation is corr-tqe = 1.71 + 0.123 std-Des + 0.0223 pwr*sd – 0.0205 oil – 0.0193 pwr*oil – 0.0136 sdc*pol + 0.0131 sht-thk

The process robustness plot for measured torque strengths is presented in Figure 11. These torque strengths were largely dominated by one variable, the diameter of the attached stud. This is not surprising because resistance to a torque load is actually proportional to the square of the radius. For this application, the difference in torque strengths between the small- and large-diameter studs was roughly a factor of two. The use of the TRANSREC power supply appeared to have a relatively strong positive effect on measured torque strengths. Reasons for this are not clear, and this effect may be an anomaly. In fact, the power supply-type term only appears in the regression equation as a two-factor interaction with the stud coating, so choice of the Zn- rather than the Cu-plated stud as the optimum value would have inferred the TMP power supply as the superior choice. Other factors (stud coating, collet wear, polarity, sheet thickness, surface oil, sheet coating type) all appeared to have either little or no effect on the measured torque strengths.

Finally, the process robustness plot for the bend angles to failure is presented in Fig. 12. Correlation between the measured angles to failure was quite high (R^2 on the order of 75%); however, only sheet thickness appeared to have a major impact on these results. This effect is not surprising since the bend test is actually a peel test (stud out of the sheet). In this case, the thicker sheet offers more resistance to tear and a stiffer base (minimizing bending distortions to the sheet) on testing. The combined effect results in bend angles on failure for the thin sheet of less than half of those for the thicker sheet. Detrimental effects were also noted when using smaller stud diameters. The smaller stud diameters yielded bend angles roughly 10% smaller than the larger stud diameters. Obviously, this effect is not great. A number of factors appear to improve bend angle performance above the selected optimum levels. These include use of the Zn coating on the stud, higher levels of collet wear, and use of the TRANSREC power supply. All of these variations have less than a 5% effect on measured bend test results and are of questionable physical significance. It is of note that most of the predicted bend test results are above the 90-deg level. This is an anomaly associated with the normality correction. In this case, the data was not a normality correction

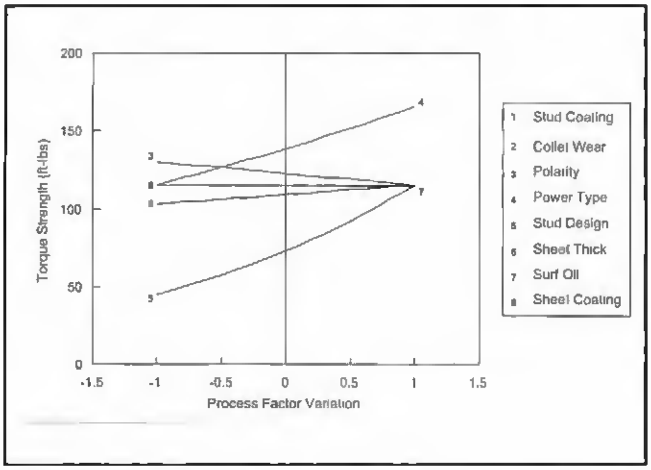

Fig. 11 — Effect of studied factors on torque strength. The values of individual factors include the following: stud coating, –1 = Zn, +1 = Cu; collet wear, –1 = new, +1 = 10,000 welds; polarity, –1 = stud positive, +1 = stud negative; power type, –1 = TMP, +1 = TRANSREC; stud design, –1 = small flange, +1 = large flange; sheet thickness, –1 = 0.7 mm, +1 = 1.4 mm; surface oil, –1 = no oil, +1 = light oil; sheet coating, –1 = bare steel, 0 = EG steel, +1 = HDG steel.

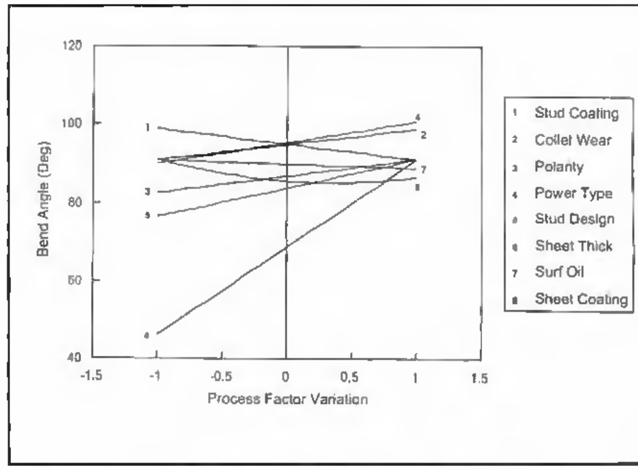

Fig. 12 — Effect of studied factors on the bend angle. The values of the individual factors include the following: stud coating, –1 = Zn, +1 = Cu; collet wear, –1 = new, +1 = 10,000 welds; polarity, –1 = stud positive, +1 = stud negative; power type, –1 = TMP, +1 = TRANSREC; stud design, –1 = small flange, +1 = large flange; sheet thickness, –1 = 0.7 mm, +1 = 1.4 mm; surface oil, –1 = no oil, +1 = light oil; sheet coating, –1 = bare steel, 0 = EG steel, +1 = HDG steel.

Table 5 — Regression Analysis for the Curve Fit Relating the Measured Angles of Bend during Bend Testing to the Factors under Study Including Designed Two-Factor Interactions (Output of the equation is in degrees of bend.)

Predictor	Coeff.	St. Dev	T
Constant	76.9	0.9363	82.13
Sheet thickness (sht-thk)	10.75	0.6621	16.24
Power supply * thickness (pwr*thk)	–5.475	0.6621	–8.27
Power supply (pwr)	5.3125	0.6621	8.02
Stud coating * Power supply (sdc*pwr)	5.2313	0.6621	7.9
Sheet coating (sht-coat)	6.325	0.9363	6.76
Sheet coating * Sheet thickness (shc*thk)	–6.325	0.9363	–6.76
Power supply * stud design (pwr*sd)	–2.7312	0.6621	–4.13
Collet wear (coll-wr)	2.5438	0.6621	3.84
Sheet coating * Power supply (shc*pwr)	–3.075	0.9363	–3.28
Sheet coating * stud design (shc*sd)	–2.825	0.9363	–3.02
Polarity * stud design (pol*sd)	1.7875	0.6621	2.7
Sheet coating *Polarity (shc*pol)	–2.5	0.9363	–2.67
Sheet coating * sheet coating (shc*shc)	3.225	1.324	2.44
Collet wear * Polarity (cw*pol)	1.3125	0.6621	1.98
Stud design * Polarity (sdc*pol)	1.2875	0.6621	1.94
Oil (oil)	–1.15	0.6621	–1.74

S = 11.84 R-Sq = 67.6% R-Sq(adj) = 65.9%
The regression equation is: angle = 76.9 + 10.7 sht-thk-5.47 pwr*thk + 5.31 pwr + 5.23sdc*pwr = 6.32sht-coat-6.32shc*thk - 273 pwr*sd + 2.54coll-wr - 3.08shec*pwr -2.82shc*sd + 1.79pol*sd - 2.50shc*pol + 3.23shc*shc + 1.31cw*pol + 1.29 sdc*pool -1.15 oil

(no correction appeared adequate), so predicted best conditions extrapolate in a linear way beyond measured conditions. This can be considered analytical error; however, the trends still represent the performance of the data.

Metallographic Analysis Results

In general, it was found welds made with larger studs showed considerably higher levels of porosity. Metallographically, welds made on the three coating configurations of steels with the small studs were quite similar. However, when welding with the larger studs, a greater degree of resolidified metal on the bare steel compared to the coated steel was noticed. Also, the coated steels showed far greater porosity in the joints. Sheet thickness was found to have very little impact on the metallurgical quality of the welds. However, substantial distortion of the substrate sheet was noted with the thin-gauge steels. Effects were also noted with regard to the power supply type on

Table 6 — Estimated Optimized Values of the Factors Considered in this Study (Optimizations have been done separately for each measure of weld quality.)

Quality Measure	Stud Coating	Collet Wear	Polarity	Type of Power Supply	Stud Design (size flange)	Sheet Thickness (mm)	Oil	Sheet Coating
Shear strength	Cu	New	Stud Neg.	TMP	Large	1.4	No	Bare
Tensile strength	Cu	New	Stud Neg.	TRANSREC	Large	1.4	Light	Bare
Torque strength	Zn	New	Stud Neg.	TRANSREC	Large	1.4	No	Bare
Bend angle	Cu	10,000	Stud Neg.	TRANSREC	Large	1.4	No	Bare

larger-diameter studs. In this case, greater degrees of melting were noted with the TRANSREC power supply. Similar effects were not noted with smaller-diameter studs. Finally, polarity was noted to affect the smaller-diameter studs, but not the larger diameter ones.

Discussion

Summary of Factor Effects

Based on the results taken from the process robustness plots and augmented with those from the metallographic interpretations, it is possible to interpret the effects of the various process conditions under study. This is done for the various factors in the following paragraphs. These factors are described in decreasing order of apparent importance to the process.

Stud Design

The design of the stud influenced the working area of the stud surface. This factor was found to completely dominate the torque results, as well as contribute as a major factor to the other measures of weld quality. This, in spite of the fact that metallurgically, these joints were far more susceptible to porosity compared to smaller-diameter studs. Largely, this appears to be a geometry effect. Clearly, larger studs are going to have a greater bonding area and subsequently greater strengths. Also, as described previously, larger studs have substantially greater torsional rigidity and, thus, dominate in the torque tests. This effect also appears to dominate the apparent reduction in microstructural quality observed for these larger studs.

Sheet Thickness

Sheet thickness was found to be a dominant factor in all but the torsion test and was the most dominant factor in both tensile and bend tests. However, sheet thickness had little or no effect on metallurgical weld quality. As mentioned previously, increasing sheet thickness has two effects. First, a thicker sheet is stiffer during mechanical testing. This minimizes the peel characteristic of the tests and increases strength. Also, thicker steels present a greater cross section to tearing, creating inherently stronger welds. As mentioned, there was only a very minor effect of sheet thickness on the torsion tests. This is because during torsion loading, all shear stresses are normal to the through-section thickness of the sheet. As a result, stiffness of the joint is only slightly affected by sheet thickness, with subsequently little impact on torsion strength performance.

Sheet Coating

Metallographically, the presence of the sheet coating had two effects. First, galvanizing appeared to result in greater porosity in the joints. Also, there appeared to be considerably less heat and retained liquid metal in the joints on Zn-coated steels. The test correlating most strongly with variations in coating condition was that which applied stress over the greatest area affected by this porosity. This was the shear test. For this test, shear loads were uniformly distributed over the entire bond area. The other tests all tended to concentrate the load at the outside edges of the weld. As a result, internal porosity was not as big a factor for these tests and the presence of the coating not as big a concern.

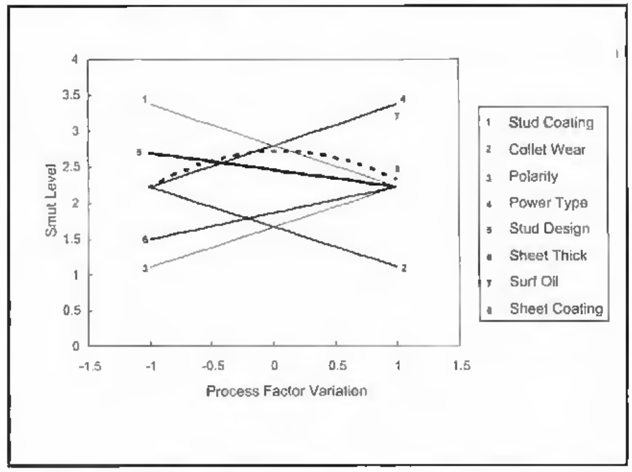

Fig. 13 — Effect of studied factors on the smut level surrounding the stud. The values of the individual factors include the following: stud coating, –1 = Zn, +1 = Cu; collet wear, –1 = new, +1 = 10,000 welds; polarity, –1 = stud positive, +1 = stud negative; power type, –1 = TMP, +1 = TRANSREC; stud design, –1 = small flange, +1 = large flange; sheet thickness, –1 = 0.7 mm, +1 = 1.4 mm; surface oil, –1 = no oil, +1 = light oil; sheet coating, –1 = bare steel, 0 = EG steel, +1 = HDG steel.

Stud Polarity

Stud polarity was found to have a strong effect on shear strength results, apparently affecting the level of heat in the workpiece. Electrode negative was found to be the desired configuration. In this case, heat was preferentially generated at the sheet, rather than the stud. Since heat flow into the stud is one dimensional and heat flow into the base sheet is two or three dimensional, better heat balance can be achieved with the stud negative condition. It is of interest beneficial effects were seen only with the shear results. It is believed, again, the other tests are predominantly governed by conditions at the edge of the weld rather than across the entire weld section. As a result, these measures of weld performance are less affected by appropriate heat balance.

Type of Power Supply

Power supply type affected nearly all measures of weld quality in a contrary way. Metallographic results indicate that for larger studs, there are greater degrees of retained liquid metal for the TRANSREC stud welding process. These effects are ambiguous at best and may be related to how the trials were conducted. Clearly, more consideration is required in this area.

Other Factors

Other factors considered in this study included the presence of a coating on the stud, level of wear in the collet, and the presence of oil on the sheet. None of these factors appeared to strongly affect the performance measures. It seems the process is sufficiently robust to perform well over observed variations in these factors.

Comparison of Weld Quality Measures

One facet of this study worth considering is the relative performance of different quality measures. For production stud welds, torque tests are commonly used as both destructive tests for quality control and at reduced loads for nondestructive proof tests. The results of this study raise concerns with such an approach. Torque tests appear to be among the least sensitive to variations in process, manufacturing, and material conditions, and are relatively poor at representing underlying microstructural weld quality. This appears to be because torque tests are sensitive only to the size of the attached stud, as well as the condition of the weld at its periphery. This suggests torque tests may be least appropriate for assuring field weld quality.

Of the tests examined, shear testing appears to be the most sensitive to variations in process, manufacturing, and material conditions. As such, where quality assurance is done by destructive testing, shear testing offers considerable advantages. This appears to be true due to the sensitivity of the results, even over more direct tests such as tensile and/or bend testing the stud. Except for shear tests, all the other tests, by design, preferentially load only the periphery of the joint and tend to be dominated by geometric effects. Use of an instrumented shear test gives a quantifiable result that apparently represents variation in both bond quality and microstructure. This test, of course, is strongly affected by geometry effects but still appears advantageous over other tests studied.

Supplementary Analysis of Process Effects on Smut Levels in Weld

Another important aspect of the stud welding process is the degree to which the surrounding sheet metal surface is degraded with weld smut (surface contamination). The effect of each process variable on the level of surface smut was examined using the original DoE matrix. The smut level was characterized for each group of samples on a 0–5 basis with a 0 value indicating a clean surface after the weld and the larger numbers indicating progressively larger areas of surface contamination.

Analyzed results are presented in Fig. 13. From these results, it is clear every variable considered in the DoE had an effect on the smut level. Using the minimum coating of oil reduced the smut level significantly since an oily surface provides more organic material for oxidation and apparently a greater degree of smut than a cleaner surface. Using a TMP power supply appears to reduce variation in weld current and probably lowers peak currents in the weld. This would minimize spatter and also reduce levels of smut. Using a stud positive configuration greatly reduced smut levels, although the reason for this is not clear. Using a Cu-coated stud reduces the amount of Zn available to produce zinc oxide and also reduces the smut level. (Analysis of the smut indicated it was predominately a form of zinc oxide.) Using a new collet also produced much less smut than a used collet, probably due to better delivery of welding power to the stud with less variation in the current and voltage, again minimizing expulsion.

Other factors in the study that affected the smut level on the sheet to a lesser degree included sheet thickness, sheet coating, and stud design. The larger stud design produced more smut than the smaller one, most likely due to the increased volume of metal molten under the arc. Less smut was also observed on thin sheet, most likely due to the greater volume of molten metal associated with the thick sheet. Sheet coating had the least affect on smut of any factor investigated. Of these, the EG coating had the greatest amount of smut, probably due to its porous nature and ability to retain oil.

Many factors that produced the best mechanical performance also produced the worst smut levels. Polarity, the most significant of these factors, showed a small decrease in mechanical performance using stud positive but showed a large decrease in smut levels in this configuration.

Conclusions

A DoE study has been conducted to examine the effects of a range of process, manufacturing, and materials effects and testing on the quality of arc stud welds.

Variables studied included the following:

- Type of stud coating
- Level of collet wear
- Stud polarity
- Power supply type
- Stud design
- Sheet thickness
- Presence of surface oil
- Type of coating on the sheet
- Testing methods.
- Measures of weld quality in this study included shear testing, tensile testing, torque testing, bend testing, and some qualitative metallography. Results were analyzed using statistical techniques and used to produce a series of robustness plots. These robustness plots allowed direct observation of how each weld quality measure was affected by each factor of interest. Specific conclusions from this study are as follows:

1) Dominant Factors in the Performance of Stud Welds — The performance of stud welds in this study was dominated by geometric factors. These included the diameter of the stud and the thickness of the attached sheet.

2) Effect of Stud Diameter — Increasing stud diameters appeared to increase all measures of mechanical performance. This was true even though the levels of internal porosity also increased with the larger studs. The geometry effect appeared to dominate the microstructural quality effect.

3) Effect of Sheet Thickness — Increasing thickness led to increases in most mechanical measures of weld quality, even though microstructural integrity appeared to be unaffected. The benefits appeared to come from increased stiffness of the joint as well as increased peel strengths associated with the thicker material.

4) Effect of Sheet Coating — Welding onto galvanized sheets appears to result in substantial porosity in the joint. However, this porosity appeared to not manifest itself in the various quality tests. Only the shear test showed a substantial drop in performance.

5) Effect of Stud Polarity — Conducting the process in the stud negative configuration resulted in greater heating of the attached sheet. This appeared to result in better shear test results.

6) Effect of Other Factors — Most weld quality measures as well as metallographic sections suggest the other variables in the study, particularly stud coating, collet wear, and the presence of oil all had little impact. This suggests stud welding is very robust to these variations.

7) Shear Testing — Shear testing was found to be the most sensitive destructive method of assessing weld quality. This method also appeared to correspond best with metallographic interpretations.

8) Torsion Testing — Torsion testing was found to be the least accurate method of assuring weld quality. Torsion tests were dominated by stud size considerations, which made this method of evaluation insensitive to most other process, manufacturing, and materials variations.

9) Bend and Tensile Testing — Both bend and tensile test, by design, preferentially load only the periphery of the joint and tends to be dominated by geometric effects.

References

1. Lehman, L. R., and Gould, J. E. 1994. A study of resistance spot welding manufacturability using design-of-experiments. *International Body Engineers Council (IBEC) 94 Proceedings, Advanced Technologies and Processes*, pp. 154–163. Warren, Mich.: IBEC Ltd.

2. Lehman, L. R., and Gould, J. E. 1995. A design-of-experiments evaluation of resistance spot welding manufacturability — Part 2: multiple factor effects. *IBEC 95 Proceedings, Advanced Technologies and Processes*, pp. 89–99. Warren, Mich.: IBEC Ltd.

3. Lehman, L. R., and Gould, J. E. 1996. A design-of-experiments evaluation of resistance spot welding manufacturability — part 3: optimization and process robustness studies. *IBEC 96 Proceedings, Advanced Technologies and Processes*, in press. Warren, Mich.: IBEC Ltd.

4. Gould, J. E. Unpublished research. Columbus, Ohio: Edison Welding Institute.