ROBUST SCHEDULES FOR SPOT WELDING ZINC-COATED ADVANCED HIGH-STRENGTH AUTOMOTIVE STEELS

by

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ABSTRACT

ROBUST SCHEDULES FOR SPOT WELDING ZINC-COATED ADVANCED HIGH-STRENGTH AUTOMOTIVE STEELS

Master of Applied Science in the program of Mechanical Engineering
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Spot welding is the prominent joining process for assembling steels in vehicles. Spot weldability is measured in terms of weld lobes. A wider (robust) lobe represents better weldability. Unfortunately, recently developed advanced high-strength steels (AHSS) exhibit poor spot weldability (narrow weld lobes) with conventional weld schedules. The present work is thus aimed to develop a robust spot welding schedule for selected AHSS combinations.

Weld lobes were plotted with upsloping pulse, single pulse and multiple pulse weld schedules. Nugget growth study for zinc coated Dual Phase (DP) 600 was conducted. Fast nugget growth in DP600 steels was controlled by interrupting the heat input during a weld pulse. An enhanced weld schedule consisting of two pulses with reduced current on the second pulse was designed. It was found that the first pulse removed zinc and the second pulse controlled the nugget growth. The enhanced weld schedule showed a considerable increase in the lobe width over the conventional weld schedule for DP600 steels.

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Finally, I would like to thank God for everything!

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NOMENCLATURE

Symbol		*Units*
English		
I	Welding current	kA
60G	Coating weight of zinc	Grams
H	Heat generated during welding	Cal/gm
R	Resistance	Ω
Rb	Bulk resistance of material to be welded	Ω
Rc	Contact resistance at the electrode-sheet interface	Ω
Rf	Contact resistance at the sheet-sheet interface	Ω
T	Welding time	Seconds
t	Sheet thickness	mm

Abbreviations

AHSS	Advanced high strength steels
A/SP	Auto-steel partnership
BIW	Body in white
DP	Dual Phase (steel)
EDDQ	Extra deep drawing quality (steel)
HSLA	High strength low alloy (steel)
MWS	Minimum weld size
SAE	Society for automotive engineers
YS	Yield strength
UTS	Ultimate tensile strength
PIF	Partial interfacial fracture
13/2/13	Two hold time cycles maintained between two weld pulses of 13 cycles
RMS	Root mean square

Definitions

Anchor Weld	The first of two welds made on a peel test sample.
Coupon	A single, small piece of test material with specified dimensions that is used to make up test samples.
Current	The effective (RMS) welding current of a spot weld that is measured at the secondary side of the welding transformer.
Current Range	Also known as "weld lobe" is the difference in welding current between the I_{min} and I_{max} currents on lobe diagram.
Electrode Face Diameter	The mean diameter of the electrode surface (which contacts the sheet surface) before the electrode is dressed. This dimension is the as-ordered or as-machined diameter measured prior to electrode installation.
Electrode Sticking	"Severe" sticking between the electrode and the peel test sample, so that pressure, applied with a finger at the farthest end of the sample that is stuck to the electrode results in permanent deformation (bending) of the peel test sample.
Expulsion	The ejection of molten metal from the faying interface (interface between the two test coupons) of the sample.
Fracture or Pullout Mode	The failure pattern of the weld button after peel testing.
Full Interfacial Failure	A spot weld fracture mode where the entire weld nugget (fused area of a spot weld) fails through the plane of the weld.

Minimum weld size	The minimum weld-button size is calculated by using the following formula: $MWS = 4\sqrt{t}$, where t = avg. sheet thickness in mm, rounded to the closest 0.01 mm, and where MWS is rounded to the closest 0.1 mm.
Panel Coupon	A coupon used to make up a panel sample.
Panel Sample	A stackup of two panel coupons used for making rows of welds during the weld quality endurance test.
Peel Test Coupon	A coupon, cut from a coupon strip with its length parallel to the direction of rolling, used to make up a peel test sample.
Peel Test Sample	A lap-joint test sample, composed of two peel test coupons having a specified overlap and standard size, which is used to determine weld button size and fracture mode of a resistance spot weld.
Stabilization Weld Size	The stabilization weld size, used during the electrode-face and weld-size stabilization procedure, is calculated by using the following formula. SWS = 0.9 X (target dressed face diameter) SWS is rounded to the closest 0.1 mm.
Test Weld	The weld made on any sample that is to be used to determine weld size, weld strength, and/or button fracture mode.
Weld Button	The part of a spot weld, including all or part of the nugget, which tears out during destructive testing of welded samples.

CHAPTER 1

INTRODUCTION

Advanced high strength steels (AHSS) are multi-phase steels composed of martensite, bainite, ferrite and/or retained austenite to produce unique mechanical properties through transformation hardening. AHSS exhibit a better combination of superior strength and good formability than conventional high strength or micro-alloyed steels[1]. Dual Phase (DP), Transformation Induced Plasticity, Complex Phase and Martensite Steels are some of the AHSS types. AHSS offer improved crash performance (passenger safety) and weight reduction (fuel economy) for next generation vehicles while being cost competitive[2]. This is the principal reason why car manufacturers want to increase the use of AHSS from the current 4% to 43% in the near future for automobile assembly[3].

Spot welding is the most extensively used process in the automobile industry with typically 2,000 to 5,000 welds in a vehicle assembly[4]. For vehicle weight reduction, more integration of automobile body structure parts is necessary. This can be achieved through spot welding steels with different chemistries and thicknesses of AHSS. AHSS are recently developed steels and there is less knowledge available about their spot weldability. The spot weldability of a given material is determined with the weld lobe diagram[5]. For a specific material, the lobe diagram provides a range of welding parameters to produce an acceptable spot weld[5].

AHSS have higher hardenability elements[6] than low carbon and high strength low alloy steels[7,8] (HSLA). Hardenability elements are usually considered detrimental to resistance spot welding because they can lead to narrower weld lobes[9]. A narrower weld lobe represents a limited selection of welding parameters for achieving acceptable welds. Developing a weld schedule with a large lobe width for these steels will allow greater flexibility for a production welding environment.

There are very few results available on the spot weldability of AHSS. The earlier work focuses more on the dynamic resistance analysis, effects of types of coating and effects of various weld schedules on mild and high strength steels[4,5,10,11,12]. These discussions were especially on mild steels and conventional high strength steels. It involved less discussion on AHSS. Therefore the focus of the current work is to develop robust (large) weld lobes for welding DP600 to itself and other grades of HSLA, as well as extra deep drawing quality (EDDQ) steels. Different welding pulses and electrode tip designs were used to increase the lobe width and achieve heat balance.

CHAPTER 2

LITERATURE SURVEY

2.1 INTRODUCTION TO RESISTANCE SPOT WELDING

Resistance spot welding (RSW) is an established manufacturing process for joining metal sheets[4]. Professor Elihu Thompson invented the process in 1877[13]. RSW applications have grown enormously since the first sheet welded automobile was introduced in 1933[14]. Due to the higher joining speed, resistance spot welding machines can be associated with automated robotic welding cells in a car assembly plant. On an average 2,000 to 5,000 spot welds are necessary for assembling a car[4].

The fundamental aspect of resistance spot welding is to join two or more sheet metals by melting the interfacial surfaces through the means of Joule heating. Parts to be welded are squeezed between two copper electrodes and very high current is passed for a short interval of time. Within the short period, the material undergoes thermal expansion, yielding and melting. RSW is an extremely fast process involving electrical, thermo-mechanical and metallurgical variables[14]. The complexity also arises from the variety of base metals to be welded and types of welding machines. Approximately 90% of spot welding applications are used for steel based sheets[14]. Commercially available machines include pedestal press type welders and various gun-type welders, e.g., C-gun and scissor gun welders. The power source of these guns can be single phase alternating current (AC), three phase alternating current or medium frequency direct current (MFDC)[14].

2.1.1 Principle of resistance spot welding

Figure 2.1 shows a schematic diagram of the spot welding operation. Two or more metal sheets (base metals) are placed between two water cooled copper electrodes and are subjected to a large squeeze pressure[15]. A relatively large current is then passed at low voltage through the sheets being welded. The resistance offered to the flow of electric current produces heat. The amount of heat (H) produced can be expressed as[16],

$$H = I^2RT \qquad (1.1)$$

where, I is the current, R is the resistance and T is the time for which the weld current is passed through the sheets (weld time). The heat produced causes the interface to melt and form a solid joint. The joint formed at the interface of the two sheets (faying interface) is called a 'button' or 'nugget'[15].

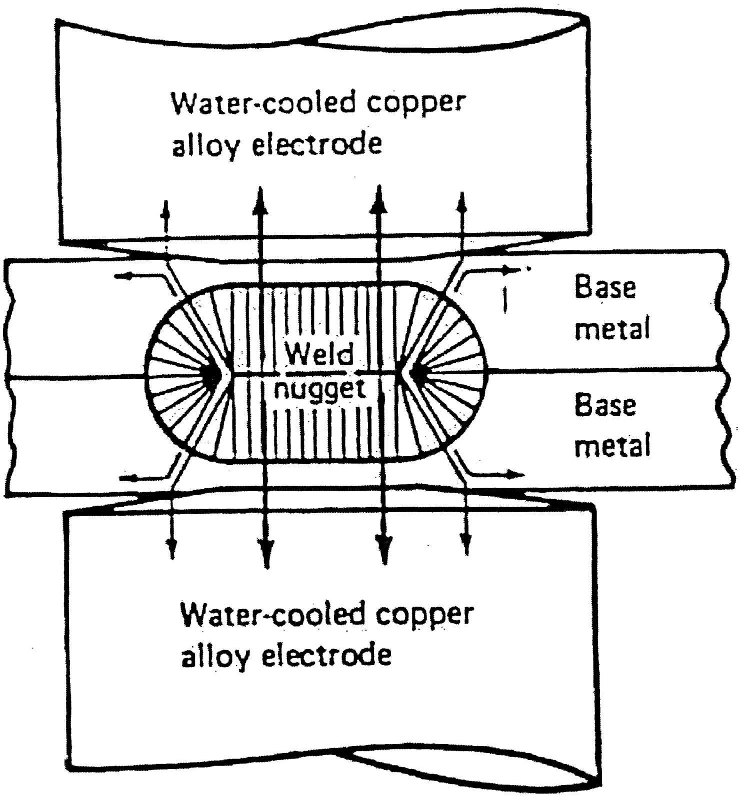


Figure 2.1 Principle of resistance-spot welding[16]

The total resistance 'R' between the two electrodes can be decomposed and analyzed. The 'R' consists of three components: the bulk resistance of the sheet, R_b, the contact resistance at electrode-sheet interface, R_c and the contact resistance at the faying interface, R_f. Thus, for sheets of same material and equal thickness[16],

$$R = 2\,R_b + 2\,R_c + R_f \tag{1.2}$$

The maximum resistance to the flow of current is offered by the faying interface[16]. Therefore, maximum heat is generated at the faying interface causing local fusion. Figure 2.2 shows a schematic of the resistance and temperature distribution at the faying and electrode-sheet interface during spot welding.

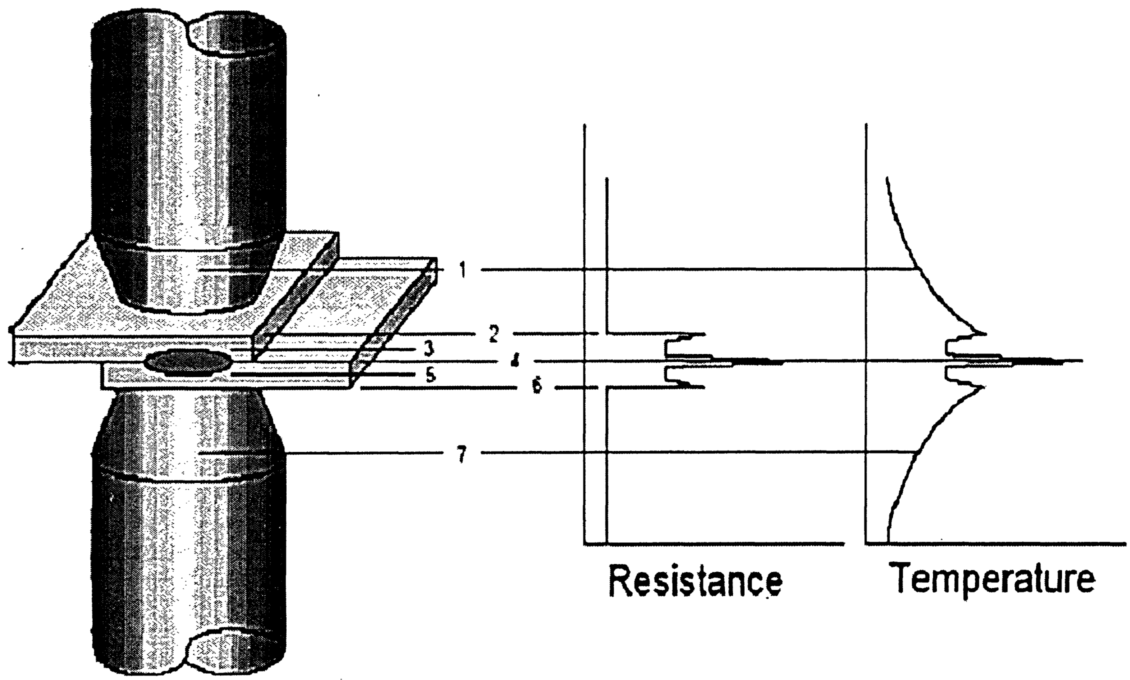


Figure 2.2 Schematic resistance and temperature distribution on sheets[17]

(Note: 1 = Top electrode, 2 = Top electrode-sheet contact, 3 = Top sheet, 4 = Faying interface, 5 = Bottom sheet, 6 = Bottom electrode-sheet contact, 7 = Bottom sheet).

Electrodes transmit sufficient pressure (about 2 kN to 7 kN) to upset the joint slightly to produce a better joint. The amplitude and duration of the welding current must be controlled accurately to facilitate the growth of the nugget. Burn-through, cracks, porosities or distortion are avoided by controlling heat input through suitable current and weld time selection. During the spot welding of two sheets, a joint should be formed at the faying interface and not at the electrode-sheet interface. The cooling water circulated inside the electrodes avoids excessive electrode heating and joint formation (sticking) at the electrode-sheet interface.

2.1.2 Weld and pressure cycle in resistance spot welding

Figure 2.3 shows a typical current and force cycle for the spot welding operation. A typical spot welding operation consists of three different stages namely, squeeze, weld and hold, which are discussed below. Each stage is measured in terms of cycles. For a 60 Hz power supply 1 cycle = 1/60th of a second.

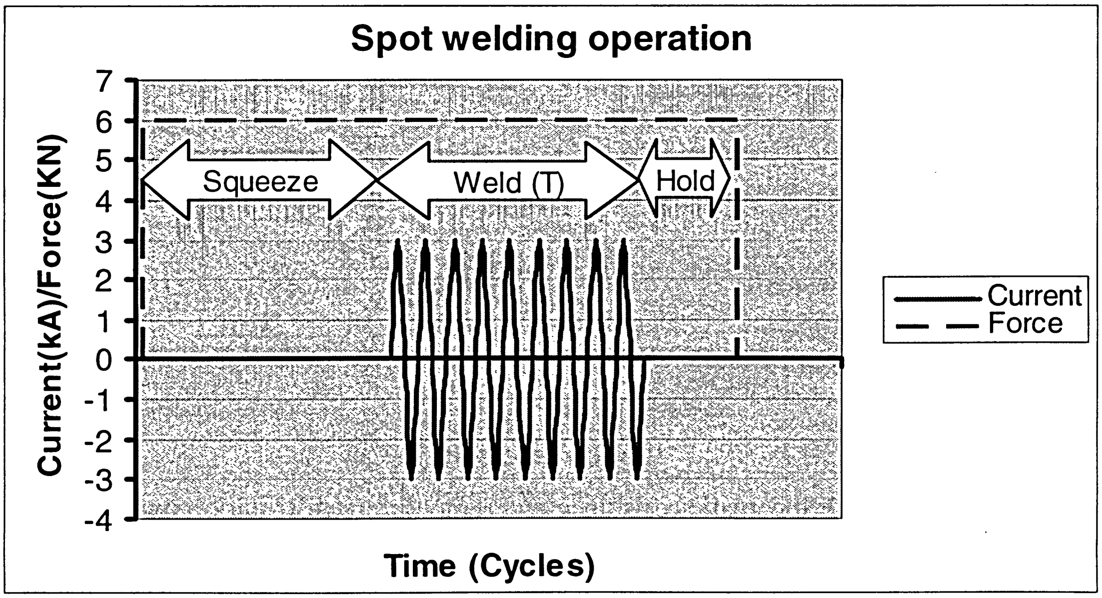


Figure 2.3 Pressure and weld cycle for a typical spot welding operation[13]

Squeeze: During the squeeze time, two or more sheets are squeezed between the two electrodes. A typical squeeze time for sheets with thicknesses between 0.6 mm to 3.0 mm is 35 cycles[18]. The actual force to be applied depends upon the electrode contact area. A lengthy squeeze time is not favored, as it will slow down the process.

Weld: During the weld stage, current (AC/DC) is passed through the sample for a specified interval of time. A weld nugget can be formed within 10 to 40 weld cycles[18]. The actual weld time depends on the type of material, electrode force and electrode current. When the welding current starts flowing through the sheets, the temperature of the sheets rise due to the bulk resistance. The resistance changes with temperature[19]. This response of the resistance to temperature variation is called dynamic resistance pattern.

Hold: During the hold stage, the current is shut off while keeping the force constant. During the hold time, the weld is forged to remove any defects like shrinkage or porosity. Two hold times, namely long (90 cycles) and short (5 cycles) are generally used[18]. The selection of hold time depends upon the sheet thickness, material and welding schedule. Thicker sheets need longer hold times as they have higher tendencies to form shrinkage and porosity defects.

Electrical current (I) and weld time (T) (figure 2.3) are two influential welding parameters in determining the final size and shape of the weld nugget. In general, a larger electrical current causes higher Joule heating, and a shorter weld time should be applied to form an acceptable weld nugget. However, different settings of electrical current and weld time will influence the strength of the weld nugget. The rate of cooling of the spot welded nugget and the heat affected zone in the sheet is very rapid. As a result, even welds in low hardenability steels may be martensitic and may develop cracks. Filler addition can not be made to alter the composition of the nugget to achieve favorable metallurgical improvements[15].

The cross section of the weld joint can be polished using the standard metallographic procedure to observe the soundness of the weld[13]. This is also called cross section analysis. Figure 2.4 shows a typical cross section of a weld nugget. The weld, the heat affected zone (HAZ) and base metal can be clearly distinguished in an etched sample.

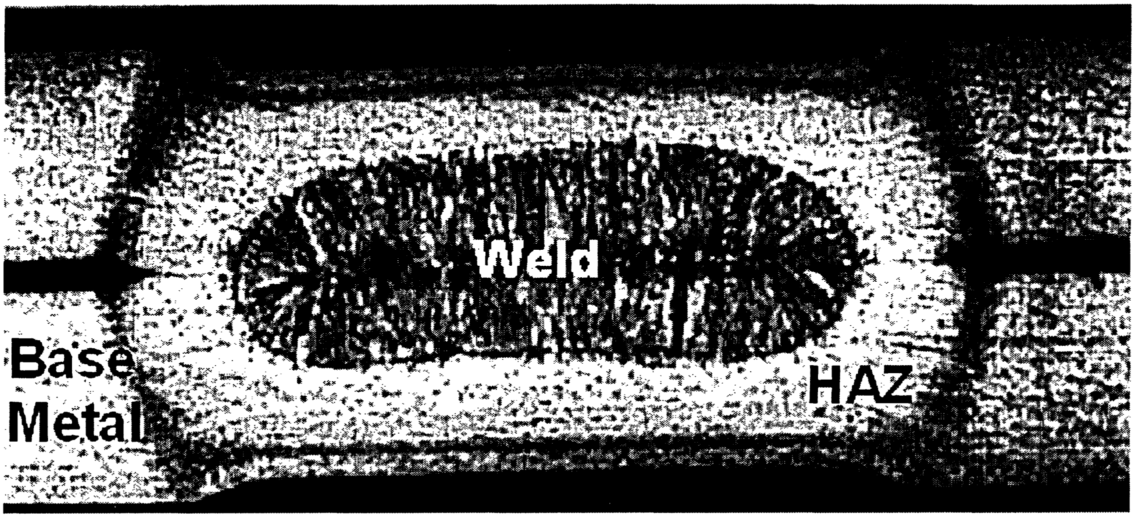


Figure 2.4 Cross section of the weld nugget formed by spot welding[17].

2.1.3 Mechanism of weld nugget formation and growth

Among the three stages, squeeze, weld and hold, the weld stage is important. During the weld stage, the interface melts to form a solid joint. The joint formation in uncoated steel sheets is different from that of coated steels. Galvanized steels (steels coated with zinc) require a different welding approach than uncoated steels. The following discussion explains details about the nugget formation in a spot welding operation.

During the squeeze cycle (figure 2.3), the sheets are squeezed between the two electrodes. There is no thermo-mechanical phenomenon taking place during this stage. Gedeon and Eagar[19] conducted a detailed study on the nugget growth mechanism for 1.5 mm thick mild steel spot welded in 12 cycles. They found that most metal surfaces, unless and otherwise specially treated under ultra clean conditions, are usually covered with insulating films of contaminants and layers of oxide. For most practical purposes, they act as insulators and their presence at the contact interface enhances the contact resistance[19]. Moreover, when two metal sheets are brought into contact, their surfaces will touch only at points where the tips of asperities on one surface meet those of the other. With increasing pressure, these asperities will flatten, but the actual points of contact will only be a fraction of the apparent contact area. Once the current begins to flow, the regions of points of contact will heat up and soften, thereby allowing other asperities to touch and become heated. This process continues until the entire area softens and all the asperities come into contact. Thus, for the first few welding cycles, the breakdown of insulating films and asperities takes place. This complex phenomenon involving surface film breakdown is called 'fritting'. Fritting and breakdown of the asperities occur at both the faying and the electrode-sheet interface. The fall of asperities is much faster for galvanized steels due to the softness and low melting temperature of zinc[19]. It has been suggested that fritting is largely responsible for increased peripheral heating (i.e., heating along the periphery of the electrodes rather than at the centre). This can be detrimental since the weld should be formed at the centre of the electrode rather than at the periphery[19]. Also fritting and surface contaminants form local hot-spots which may be detrimental to the electrode tip life.

In zinc coated steels, the first few cycles involves heating of zinc and Fe-Zn alloys (from the coating) on the electrode-sheet interface. After the first three to four cycles, zinc coating at the faying interface starts melting, whereas little or no melting occurs at the electrode-sheet interface (due to effective cooling of the electrodes). The presence of molten zinc at the faying interface will greatly decrease the contact resistance. The molten zinc will then start to be forced away from the centre of the electrode tips to form a liquid 'halo'[19]. After 6-8 welding cycles, most of the zinc is displaced and a mechanical seal starts to develop at the periphery of the electrode contact area. The seal is formed at both the faying and electrode-sheet interfaces. The electrodes are forced through the zinc coating at the periphery. The seal traps the remaining zinc and weld metal between the electrode tips at both interfaces. The increase in the halo size with the formation of the seal increases the area of current flow. The zinc halo is an excellent conductor, and higher currents are necessary to fuse the substrate. At this point, iron to iron contact formation starts. When a substantial amount of the metal reaches the melting or softening temperature, the faying interface collapses to form a softening of the surrounding material. If the same amount of current continues to flow, the material is abruptly expelled at the sheet-sheet interface. This is called expulsion.

2.1.4 Expulsion phenomenon in resistance spot welding

It was mentioned earlier that a seal begins to form along the electrode periphery at the faying interface during the welding stage in a coated sheet. This seal keeps the substrate (steel) in place as it is heated to the softening temperature, melts and forms a weld. The seal also keeps the material from squeezing out radially as the molten zinc did earlier. As a result, the material is constrained and thermal expansion pushes the electrodes apart (away from each other). Once the thermal expansion becomes large enough, the seal is broken and molten metal is suddenly free to expel radially. Another mechanism of expulsion occurs when the molten steel over 1500 C gets close to the zinc, which boils, at 907 C[19]. This boiling zinc may force the electrodes apart and expel both zinc and iron. Figure 2.5 shows a macrograph of the expulsion.

Figure 2.5 Nugget expulsion showing breaking of zinc halo and metal seal

2.2 TESTING OF SPOT WELDS

Although resistance spot welding has been used for many decades, it suffers from a number of drawbacks, such as the inability to produce quality welds consistently, and the lack of a reliable and effective quality evaluation method[14]. The current practice of evaluating weld quality is the destructive test. In fact, a small number of vehicle subassemblies are torn apart every day to evaluate the weld quality on an automobile production floor[14]. Spot welds can be tested in the laboratory with the following tests:

1. Peel Test
2. Chisel test
3. Weldability test (lobe test)

2.2.1 Peel test

Peel test sample: A lap joint test sample, composed of two peel test coupons, having a standard size and a specific overlap, which is used to determine the weld nugget size and fracture mode of the spot welds is called a peel test sample[18]. Thus, one peel sample consists of two peel test coupons (figure 2.6).

Figure 2.6 shows a peel sample. The peel test is a destructive weld inspection technique for evaluating the quality of spot welds. The peel test consists of peeling apart a test weld on the peel test sample with a vise and pliers[18]. The test weld is the second weld made on the peel sample. The weld (button) diameter is measured across its minimum and maximum axes. The minimum and maximum axes may not necessarily be perpendicular to each other. The average diameter is calculated from the two measured values as shown in Figure 2.6. The anchor weld is the first weld made on the peel sample.

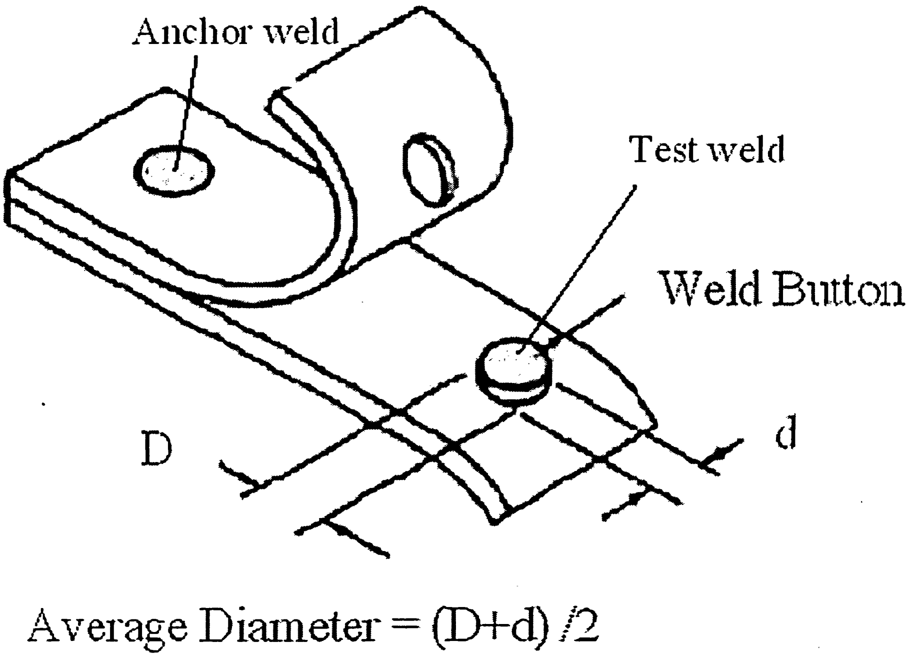


Figure 2.6 Schematic peel test sample[20]

2.2.2 Weld button criterion

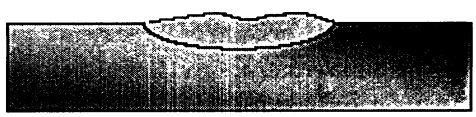
The nugget diameter plays an important role in RSW as the joint strength is directly proportional to the nugget diameter. The spot weld is said to be good if the average nugget diameter on the test weld is between the minimum and maximum nugget diameters. Minimum and maximum nugget diameters can be defined as follows[18],

- Minimum nugget diameter $= 4\sqrt{t}$

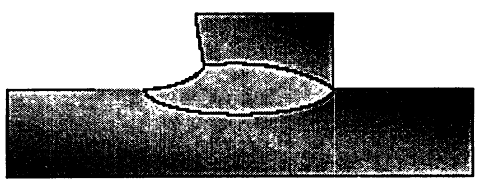
  where, t = Average sheet thickness of the thinnest sheet
- Maximum nugget diameter = Nugget diameter at expulsion[4.1]

2.2.3 Button failure modes

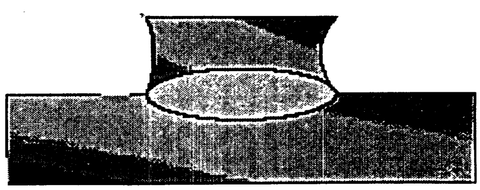
Figure 2.7 shows various fracture modes that can be observed from a peel test[17].



(A) Interfacial Fracture



(B) Irregular fracture



(C) Full button pullout

Figure 2.7 Fracture modes in peel test[17]

Full button pullout failure modes represent better joint strength and good weld conditions than interfacial or irregular button failures. Interfacial failure modes are not acceptable failure modes. They represent a weak joint and crack propagates through the weld. In addition to the weld button criterion, the welds should look uniform, have a small indent from the electrode tip, and should show very little expulsion[14]. The buttons having diameters in the range of minimum to maximum button diameters and full button pull out fracture mode, are called acceptable button diameters.

2.2.4 Chisel test

The chisel test consists of forcing a tapered chisel into the gap on each side of the weld being tested until the weld or base metal fails (Figure 2.8). The edges of the chisel must not touch the weld being tested[20]. This type of test is to be used when the peel test is not feasible. The button size is determined in the same manner as that in the case of a peel test.

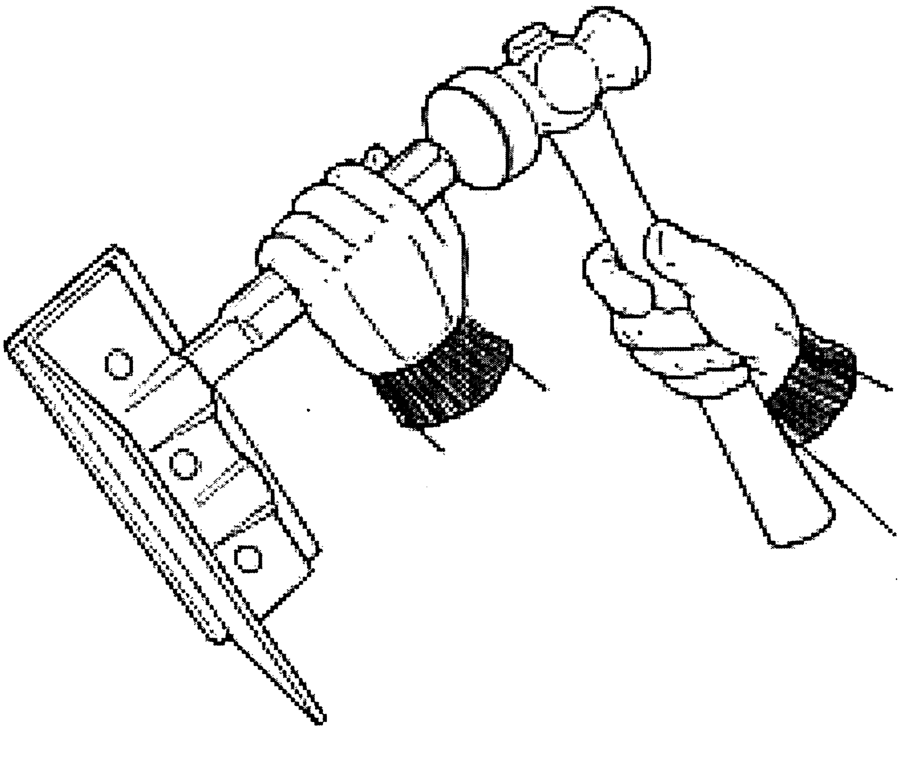


Figure 2.8 Schematic diagram showing chisel test[20]

2.2.5 Assessment of spot weldability

Spot weldability of a specific material can be determined with the weld lobe diagram. A schematic weld lobe diagram is shown in Figure 2.9. The lobe diagram is the plot of welding current (X-axis) versus welding time (Y-axis). It consists of two curves, e.g., curves ABC and DEF, as shown in figure 2.9. If the welding parameters are set along any point on the curve ABC, and a peel test sample is welded with these parameters (I and T), the peel test will result in the minimum acceptable nugget diameter ($4\sqrt{t}$) on the test weld. Welding parameters set along the curve DEF will produce expulsion nugget diameters on the test weld. The points inside the lobe curve will guarantee a weld with an acceptable nugget size. Since the weld strength is directly proportional to the weld diameter, acceptable nugget size represents acceptable nugget strength. The welding parameters set along points to the left of curve ABC will result in a nugget, smaller than the minimum acceptable diameter ($4\sqrt{t}$). The welding parameters set along points to the right of DEF will result in expulsion or burn through.

At a specific time the current range with which an acceptable button diameter can be formed is called the 'lobe width'. Lobe width at a specific time can be calculated from the lobe diagram. For instance in Figure 2.9, at 30 cycles, the lobe width is calculated by subtracting I_{min} (A) from I_{max} (D). A larger (robust) lobe width represents bigger window for the selection of welding parameters. A narrower lobe width represents a smaller window for selection of welding parameters which will result in an acceptable button diameter. A lobe width larger than 2000 ampere is an acceptable lobe width.

To summarize, based on the destructive peel test, the range of acceptable buttons for a specific joint design can be plotted on a chart called a 'lobe diagram'. The predetermined lobe diagram gives information about the suitable settings of electric current and weld time to achieve acceptable button diameters[4].

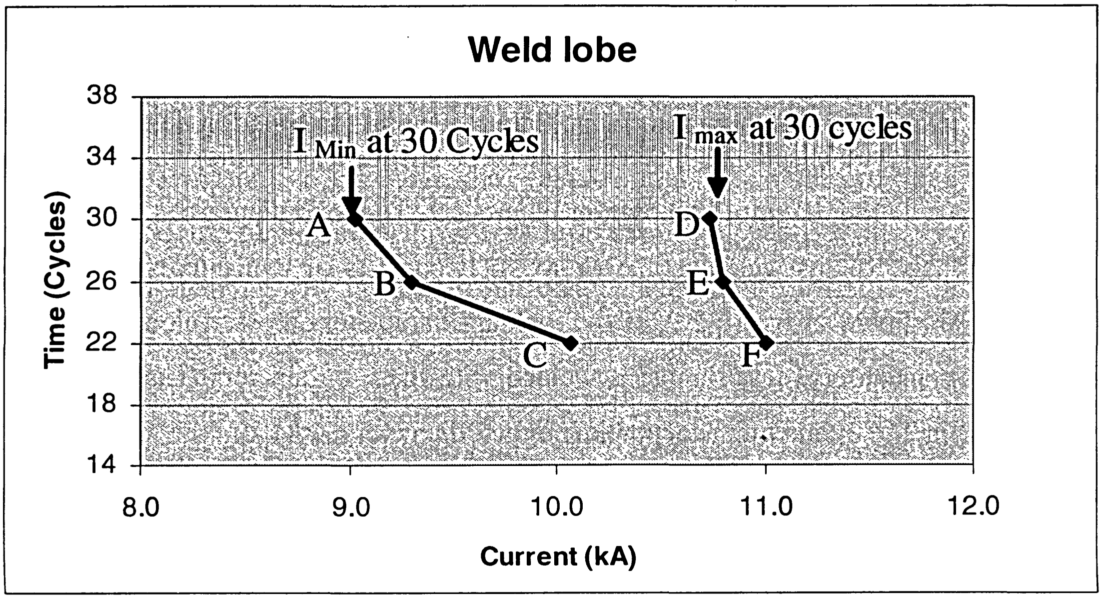


Figure 2.9 Schematic weld lobe diagram

Figure 2.10 shows the weld lobe established by Howe and Kelley[10] for 0.8 mm mild steel (Carbon 0.037%, Manganese 0.3%). Lobe widths at various welding time are shown in Table 2.1. Thus, uncoated mild steel shows lobe widths bigger than 2000 amperes when the weld cycles are greater than 10 cycles. In the past, most of the research on spot welding was focused on comparison of weld lobes for bare, hot-dippped galvannealed and electrogalvanized steel sheets. It was reported that weld lobe widths and their positions depend upon the type of coating as well as the amount of coating (coating weight). In general coated steels have less contact resistance, and higher currents are necessary to weld them[10]. Electrode tip wear was an important issue for spot welding of coated sheets. Howe and Kelley[10] showed that coating is constantly picked up by electrodes. Zinc on the electrode face changes the topography and electrical characteristics of the electrode face. The degree of topography change depends upon the welding conditions and type of coated sheet being welded. Various standard procedures[21,22] are being established for plotting the lobe which eliminate effects the of tip wear.

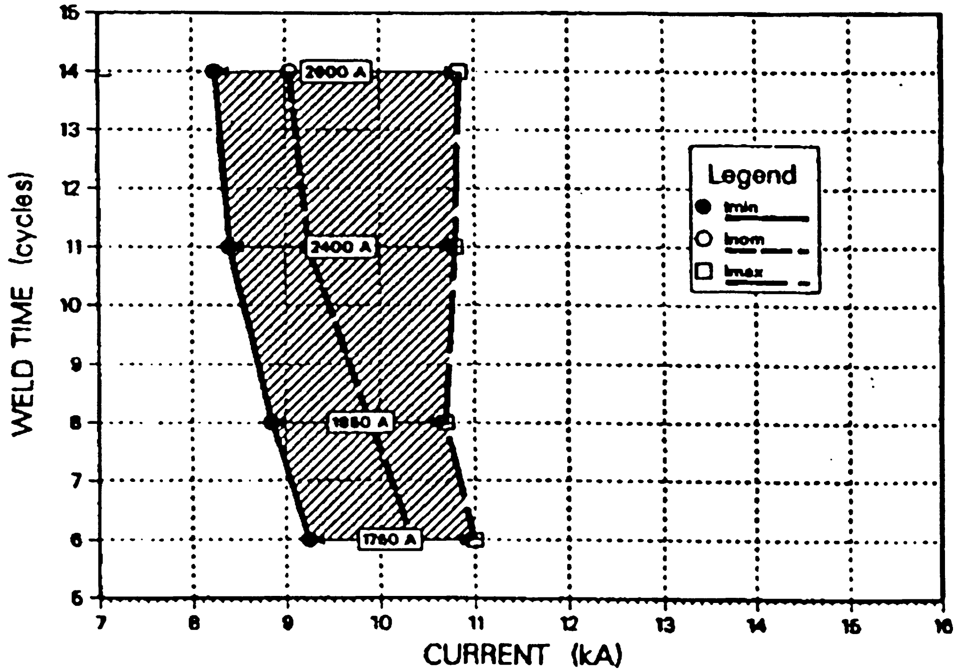


Figure 2.10 Weld lobe for bare steel (0.8 mm mild steel)[10].

Table 2.1 Lobe widths for bare mild steels[10]

Weld time (Cycles)	Lobe width (Amperes)
6	1760
8	1880
10	2400
14	2800

2.2.6 Relative weld lobes for coated steels and aluminum

Figure 2.11 shows the position of lobes for coated, bare steel sheets and aluminum[23]. Higher currents are necessary to weld aluminum due to its higher conductivity as compared to steel. In the case of coated sheets (galvanized, i.e., zinc coated and galvalume), the zinc coating results in lower interfacial contact resistance. Zinc provides an additional heat sink because the zinc coating melts and vaporizes well below the melting temperature of the steel[19]. Therefore, higher levels of current are required to weld zinc-coated steels. (Note: Galvalume Plus is an aluminum-zinc hot dip coated steel product and a trademark of Dofasco Inc.)

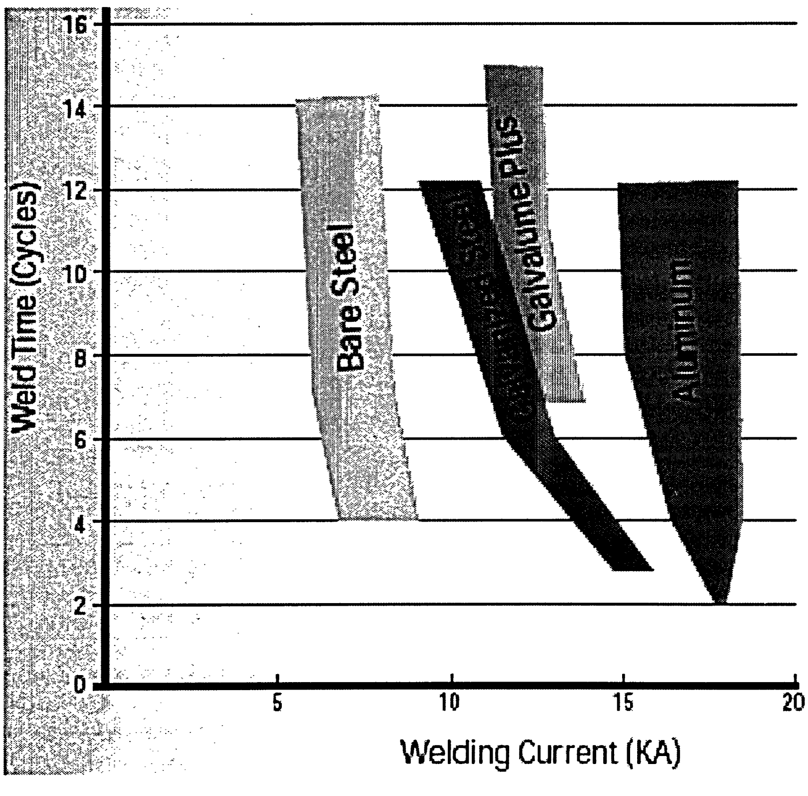
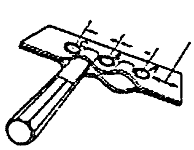
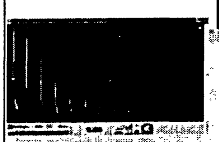
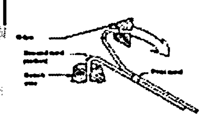
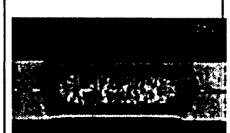


Figure2.11 Weld lobes for various steel sheets and Aluminum[23]

2.2.7 Critical weld quality measurement

It is crucial to measure the quality of spot welds in a production environment. The real issue is not what is meant by a quality weld, but rather the determination that a quality weld has been achieved[24]. The most reliable way is a destructive test (peel or chisel test). That is why manufacturers end up in over-welding automobiles and subassemblies. Over-welding slows down the production rate and increases the cost of the product.

Bhor[24] proposed that the best way to determine the quality weld is the peel test. The Figure 2.12 shows the critical accuracy with which spot weld quality can be checked. Critical accuracy is the ability to identify discrepant welds[24]. Cross section analysis involves cutting a spot welded nugget and polishing it according to a standard metallographic procedure. Samples can be etched with suitable etchant to observe the weld, heat affected zone and base metal. Cross section analysis is good, but cutting every spot weld, polishing it and observing it are a tedious task.

	Nondestructive		Destructive Peel Test	Cross Section Analysis
	Deformation Check	Ultrasonic Test		
Critical Accuracy Estimate	20% - 70%	70% - 95%	95% - 99%	99% - 100%
				

2.12 Critical accuracy for determining spot welding quality[24]

The evaluation of quality becomes difficult whenever new materials are developed and introduced in various applications. Thus, the reliable methods for evaluating spot weld quality are cross section analysis and destructive peel test.

2.3 RECENT ISSUES IN SPOT WELDING AHSS

Spot welding issues in conventional steels are different from those in AHSS. A study on conventional steels was more focused on electrode life studies and effect of coating thickness on weld lobes. Conventional steels showed weld lobes greater than 2000 amperes (Figure 2.10), which is considered a good lobe width. Recently some researchers[9,24,26,29] have started to evaluate the spot weldability of AHSS. It was proposed that major issues involved in spot welding of AHSS are lower lobe widths and different fracture appearance in the peel test. Moreover, AHSS have richer chemistry (> 0.1 % Carbon) than conventional low carbon sheet steels (< 0.1% Carbon). Therefore the weld schedules used for conventional steels could not be appropriate for the spot welding of AHSS. There is limited literature available on spot welding of the recently developed steels. With an ever increasing demand for AHSS, it is necessary to know more about spot welding of these steels[27,28]. In the following section recent developments on spot welding of AHSS are discussed.

2.3.1 Complex welding schedules for AHSS

The tendency of interfacial fracture and partial interfacial failures increases with increasing strength, composition and sheet thickness. Natale[30] suggested post weld annealing or tempering to improve the fracture mode in AHSS. Moreover, Peterson[17] suggested investigating more complex welding schedules to get an acceptable failure mode during the peel test. Figure 2.13 shows the complex weld schedules.

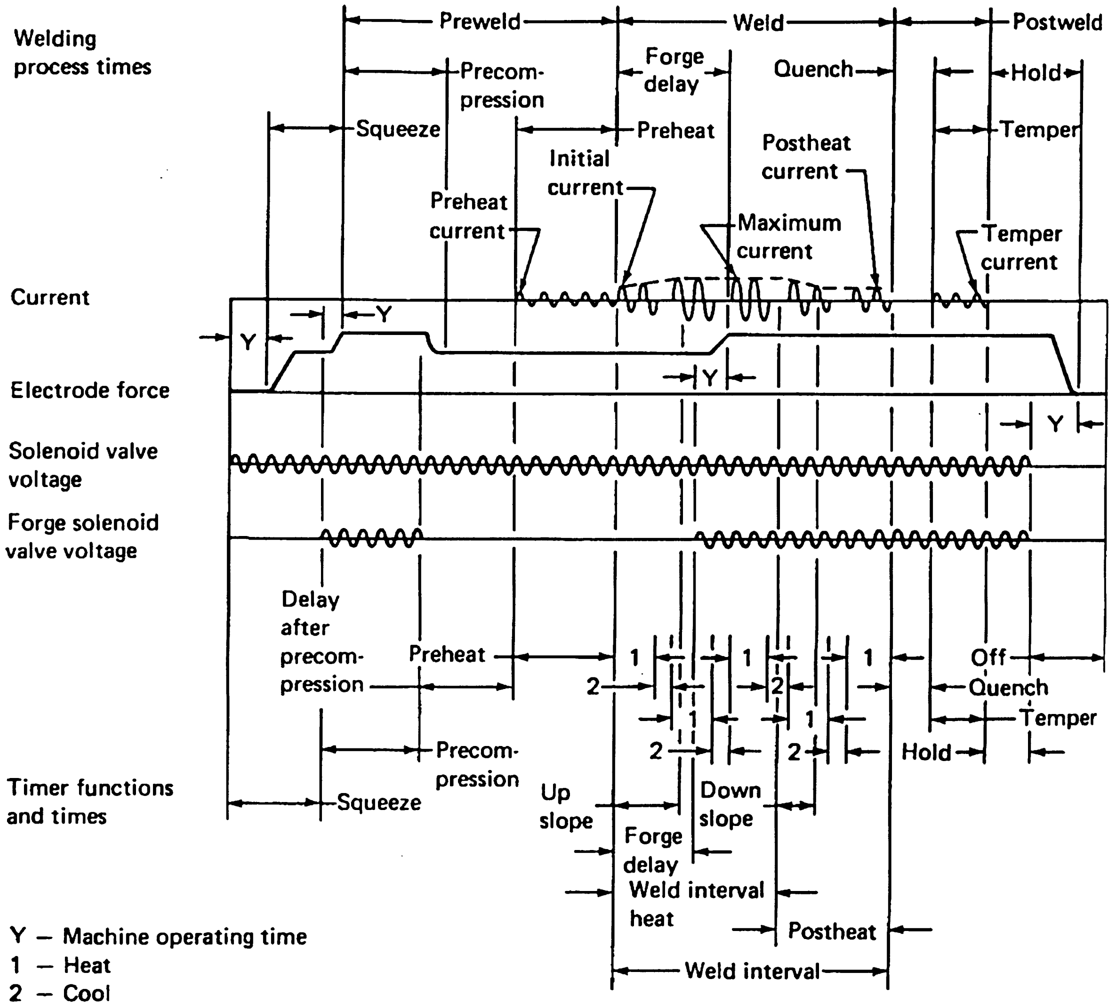


Figure 2.13 Complex weld schedule variation[31]

The complex welding schedules involve upsloping, downsloping, pre-pulsing and post-pulsing welding current during the weld pulse. As seen from Figure 2.13, the electrode force can also be varied during a welding pulse. Although the idea of a complex welding schedule is not new, a specific complex welding schedule for DP600 or other AHSS types has not been developed.

Peterson[32] also suggested that the best selection of welding parameters for the 1.8 to 2.0 mm thick steel are high electrode force, long weld time and long hold time. Further, it has been well documented that a higher electrode force is necessary to achieve porosity free and a crack free nugget[33]. Electrode force has a significant effect on the position of the weld lobes. A higher electrode force can shift the lobe towards the right, i.e., towards higher welding current[33]. In other words, the higher electrode force can increase the expulsion limit. This phenomenon can be explained by the fact that the higher electrode force has an enhanced compressive effect on the rapidly growing weld nugget. The force due to thermal expansion and the electrode force act in opposite directions. Expulsion occurs when the force due to thermal expansion of the sheet and nugget overrides the electrode force[33]. Obviously, a higher electrode force can prevent expulsions and allow better nugget growth.

2.3.2 Multiple pulse welding schedules for DP600

Milititsky et al. [9] conducted a spot welding study on four hot dip galvanized steels. He used DP600, 350 HSLA and mild steel with various gauges. Trials were conducted to spot weld 2.0 mm DP600 to itself. He proposed a multiple pulse weld schedule for spot welding DP600 steels for better lobe widths. Figure 2.14 shows a graphical representation of a double pulse welding schedule. The double pulse weld schedule can be developed by maintaining two hold time cycles between two consecutive weld cycles.

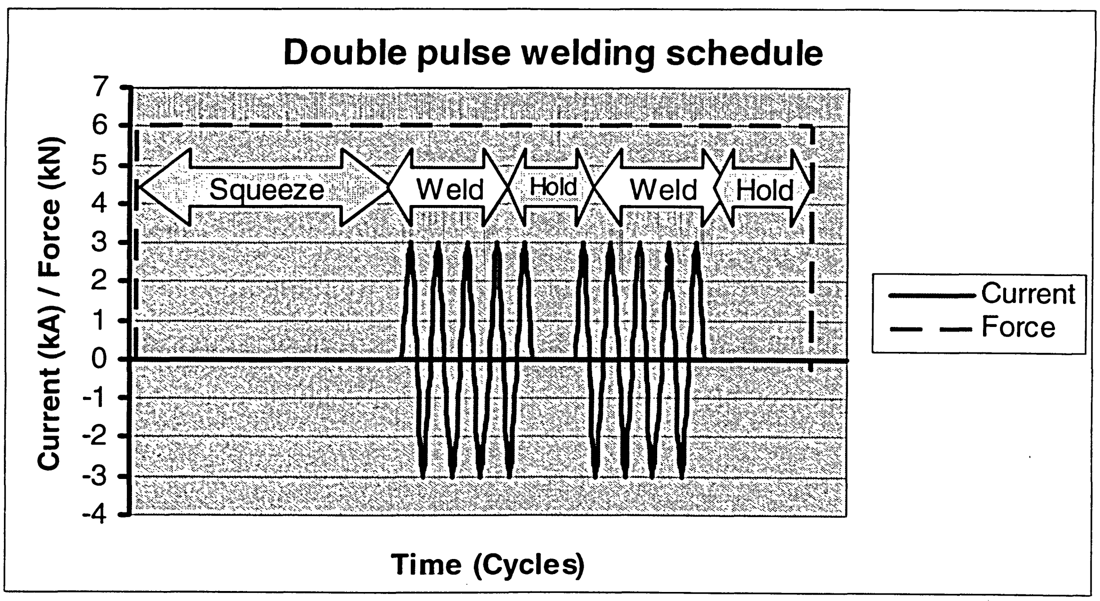


Figure 2.14 Double pulse welding schedule[9]

Militistky[9] et al. established lobes with the double pulse and compared them with the single pulse. Their results showed that higher lobe widths for DP600 steels can be achieved with multiple pulsing and a higher electrode force. Current levels measured for RSW of DP600 steel were lower than those for the conventional high strength steels. Multiple pulsing helped grow larger button sizes[9]. Figure 2.15 shows the lobe widths with single, double and triple pulse weld schedules.

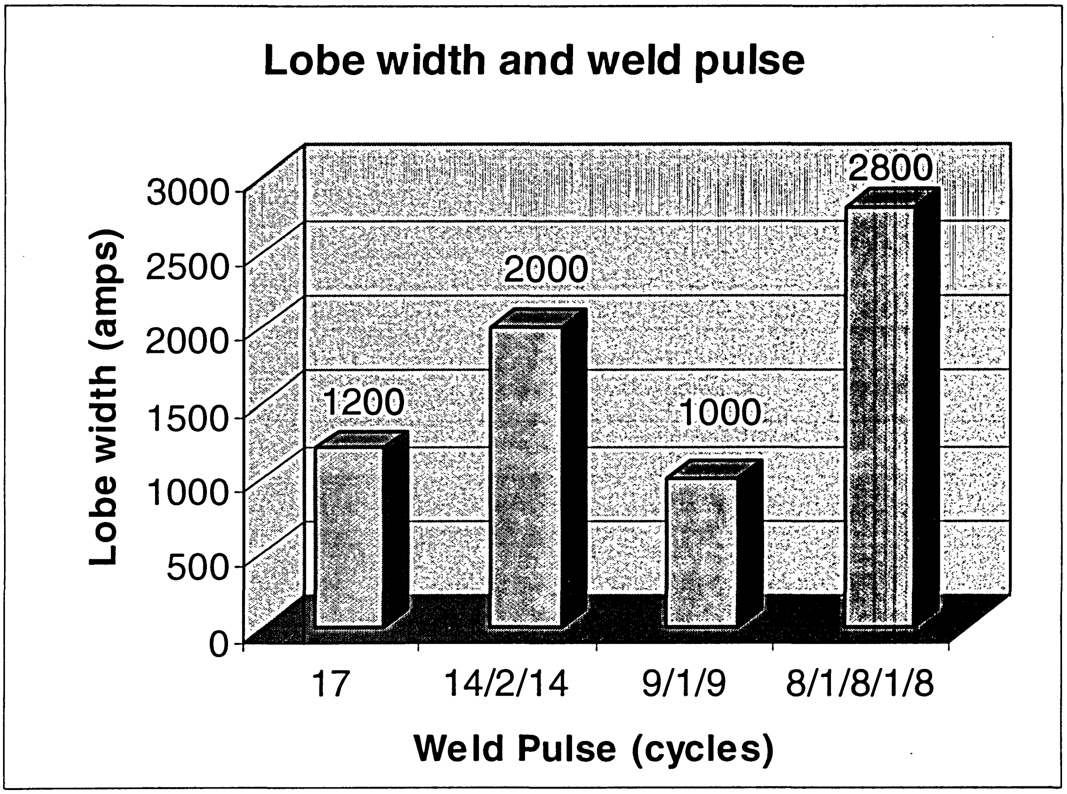


Figure 2.15 Lobe widths with single and multiple pulse schedules[9]

(Note: 14/2/14 represents a hold time of 2 cycles between two weld pulses of 14 cycles)

Militistky et al.[9] also tried to weld nonsymmetrical weld stack-ups. Non-symmetrical stack ups can yield unbalanced heat distribution, making it more challenging to obtain the minimum weld button diameter. Therefore, they modified the tip design as shown in Figure 2.16. They proposed that, during the spot welding, the heat is concentrated at the geometric mean of the two electrodes. In case of Figure 2.16-A heat is not concentrated at the DP-DP or

DP-mild steel sheet interface. With the appropriate modification in the electrode tip design (Figure 2.16-B) the heat can be concentrated at the DP-mild steel interface. With the tip design shown in Figure 2.16-C the heat can be concentrated at the DP-DP interface. They plot the lobes with tip designs A, B and C. It was observed that weld lobes were greatly reduced even with the new weld pulse design (B and C)[9].

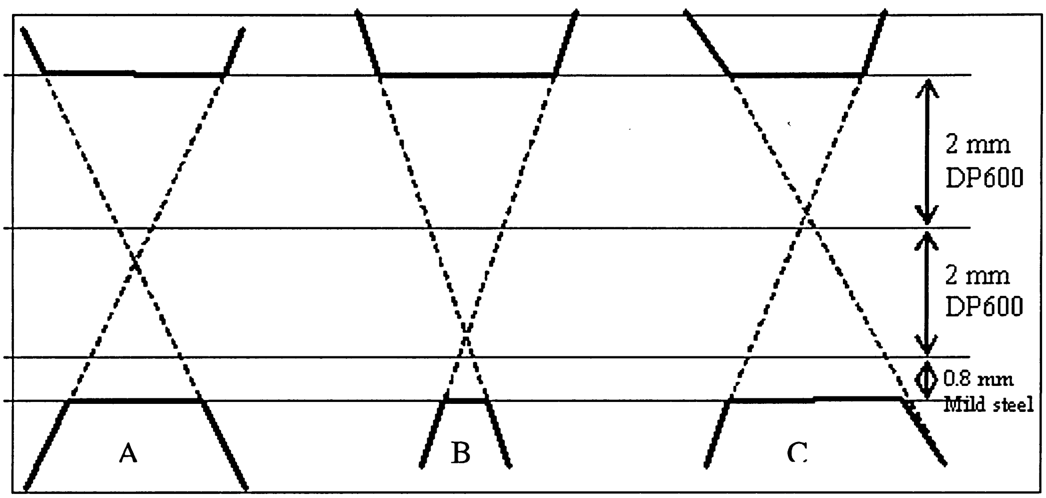


Figure 2.16 Schematic heat balance weld tip design[9]

2.3.3 Optimization of spot welding pulse

Gedeon[34] conducted optimization of the spot welding process. He used upsloping and downsloping of the weld current to plot the weld lobes. Figure 2.17 shows a weld schedule with upsloping and downsloping of the welding current. Weldability lobe behavior is shown in figure 2.18. It was found that when using truncated cone electrodes, both upsloping and downsloping increased the lobe width for hot dip galvanized materials, which have free zinc in their coatings[34]. In Figure 2.18, the vertical axis is weld time not including the upsloping or downsloping time. It was further observed that upsloping or downsloping does not have a beneficial effect while welding bare steel.

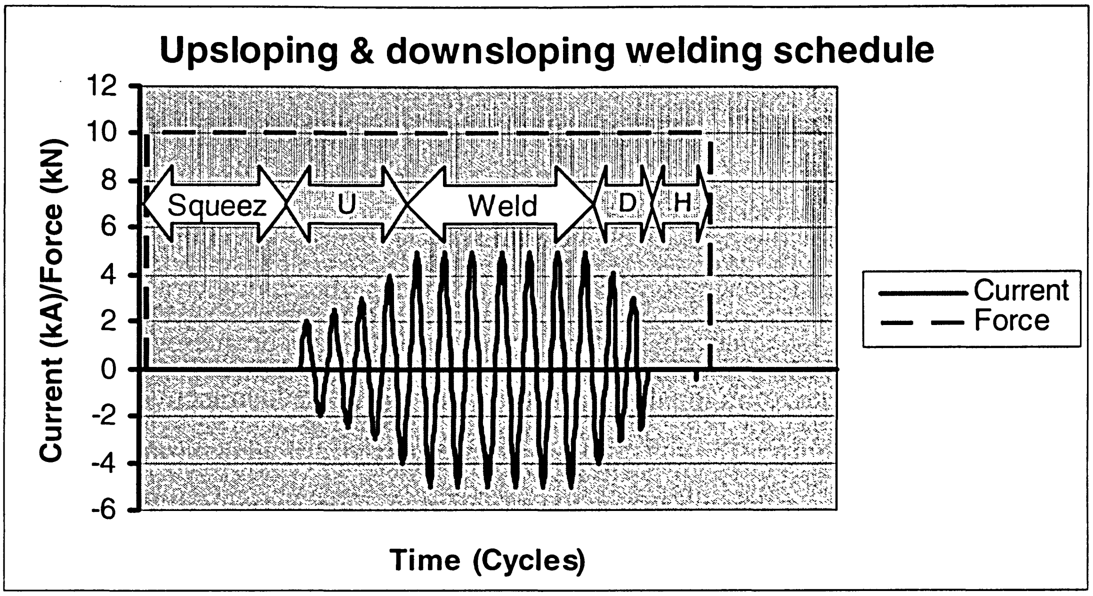


Figure 2.17 Weld schedule with upsloping and downsloping of weld current

Note: U = Upsloping, D = Downsloping, H = Hold

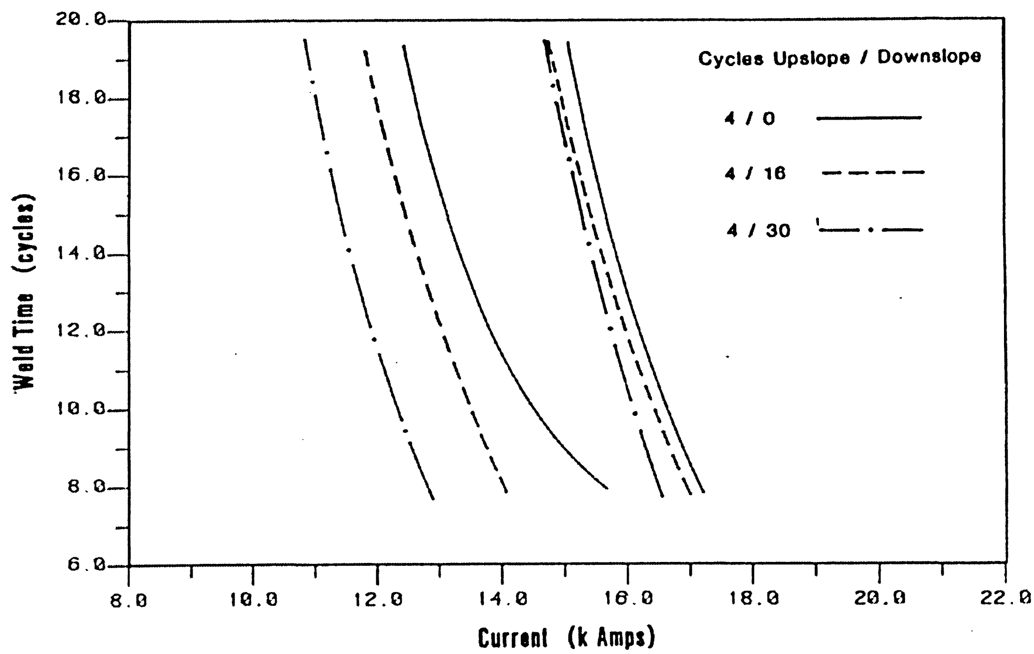


Figure 2.18 G-90 lobes with upsloping and downsloping current[34]

(Note: 4/16 represents 4 upsloping cycles and 16 downsloping cycles)

In order to explain why upsloping and downsloping are beneficial only for free zinc coated steels when truncated cone electrodes are used, Gedeon[34] conducted other specific experiments. The dynamic inspection monitoring of the displacement, force and electrical resistivity was evaluated[19]. It was found that by gradually increasing the current during upsloping, the zinc coating gradually heats up with little melting taking place. This develops a more favorable heat generation pattern by allowing the entire cross section to rise in temperature before the zinc coating completely melts and decreases the faying surface contact resistance. Due to gradual zinc melting, there is no sudden increase in the 'halo' size with the upsloping current as the heat is more evenly distributed throughout the material. Once the seal is formed it is wider than that formed with no upsloping. The wider seal needs larger currents to produce expulsion. Hence the expulsion line can be shifted further to the right[19]. This increases the lobe width. Gedegon[34] also showed that upsloping of the welding current can more effectively increase the weld lobe width than with upsloping and downsloping. Figure 2.19 shows the welding schedule with the upsloping cycle. Figure 2.20 shows a comparison between the lobes with upsloping and the single pulse.

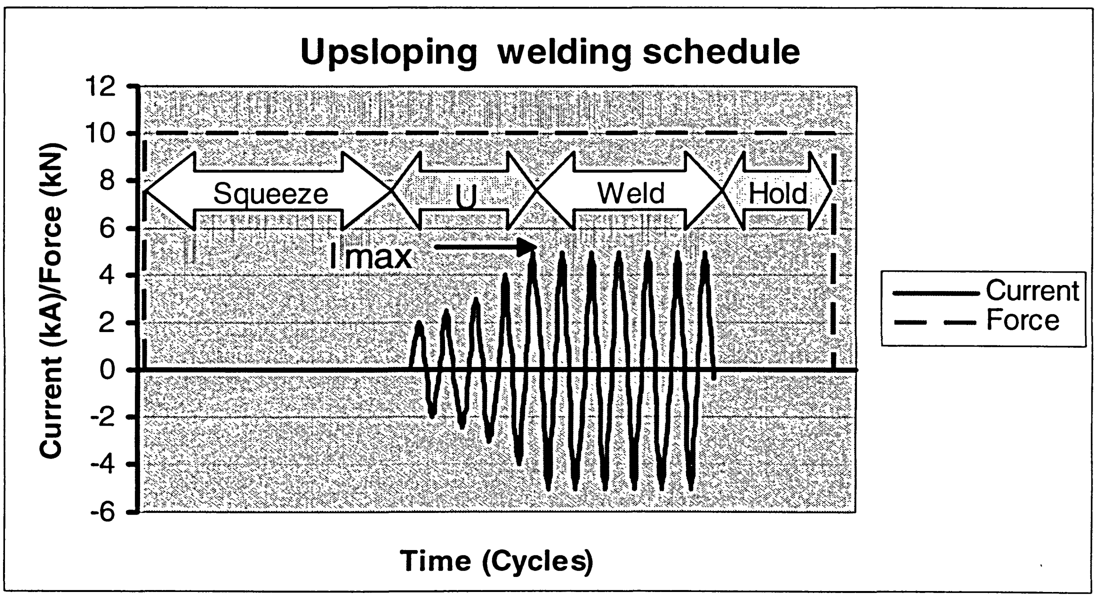


Figure 2.19 Weld schedule with upsloping weld current (Note: U = upsloping)

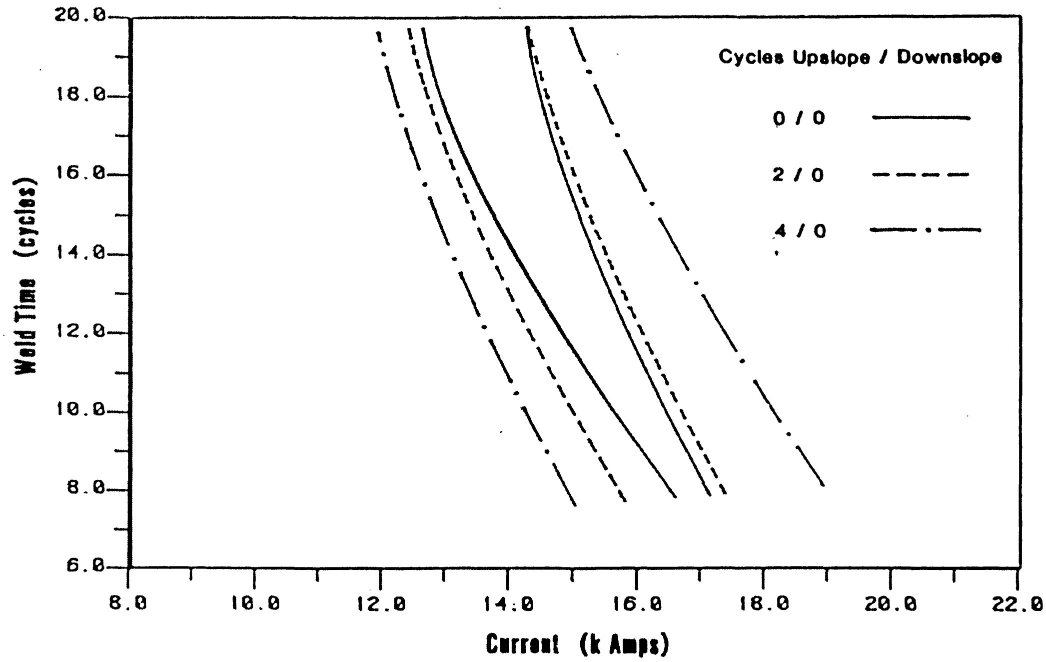


Figure 2.20 G-90 lobes with upsloping current[34]

Agashe and Zhang[36] proposed selection of welding schedules based on heat balance for RSW. These schedules were developed empirically by heat generation (I^2RT) and dissipation calculations (radiation, conduction and convection). These schedules can not be developed unless exact values of thermal properties (e.g., specific heat, coefficient of thermal expansion, latent heats of fusion) are known for each material to be welded. Since it is difficult to obtain the exact values of all the thermal parameters of each sheet, this method can not be used in finding schedules for production applications. In the past much study was conducted on spot weldability of mild steels, but the spot welding issues in mild steel were different from those of AHSS.

2.3.4 Spot weldability of AHSS using AC and MFDC power source

The automotive industry presently uses an alternating current (AC) power source for spot welding mild and other high strength steels. Lalam and Agashe[29] proposed that better weld quality and larger lobes can be achieved with a direct current (DC) power source for AHSS applications. A DC power source is not new for the RSW applications. In fact, most of the spot welding of aluminum sheets is accomplished using a DC power source. Moreover, it is documented that larger lobes can be achieved using 27% less current in DC than in AC[29]. Therefore, use of DC power can contribute to cost savings. This is because better weld quality and larger lobes can be achieved with a lower welding current.

In an AC power source, current and voltage change with time. A 60 Hz power supply changes electrode polarity 60 times per second. In a DC power source, both current and voltage remain constant with time. DC power is generated by rectifying the three phase AC power supply. During manual DC spot welding, use of high DC can cause hazards to the operator. Therefore, instead of continuous DC, a high frequency (800, 1000 or 1200 Hz) rectified square wave pattern is used. This rectified high frequency DC is called medium frequency direct current (MFDC)[29].

Lalam and Agashe[29] compared spot weldability with AC (60 Hz) and DC (1000 Hz) power sources. They conducted trials on uncoated 1.4 mm HSLA, DP600, DP980 and M220. Weld lobes were plotted with A/SP procedures. Truncated class II electrodes were used. The Figure 2.21 shows that lobes established with MFDC were larger than those with AC, except for the M220. For the selected welding parameters, lobe widths of 2.5 kA or more were observed with either AC or DC power source. The lobes with AC as well as DC increased with the base material strength, except for the M220 materials[29]. It is important to note that all the steels were uncoated. Spot welding of hot dip zinc coated steels is more challenging than uncoated steels.

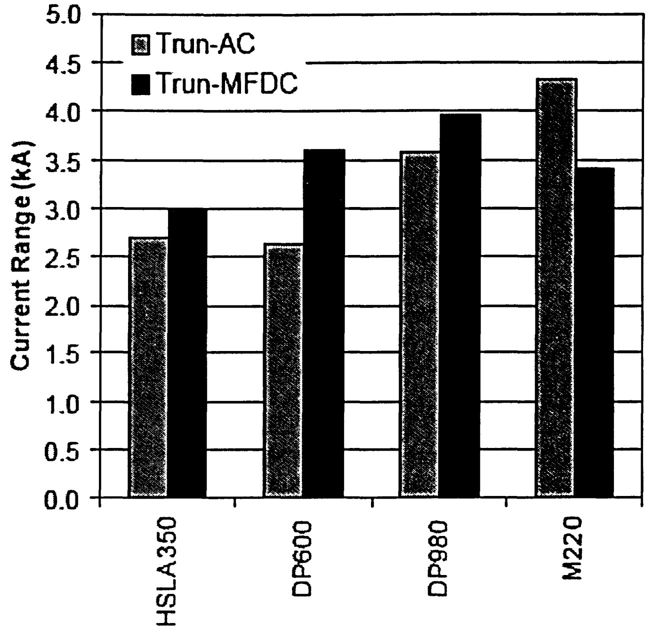


Figure 2.21 Lobe widths with AC and MFDC[29] (Note: Trun = Truncated electrodes)

Wei Li[35] investigated the relative position of the lobe with AC and DC power supplies. Figure 2.22 shows the relative position of the lobe with AC and DC power sources. It can be seen that the minimum weld nugget line with the DC can be shifted to the left and hence increased lobe widths can be achieved with the DC power[35]. The reason for this shift of line was explained with the dynamic resistance pattern of alternating and direct current. It was proposed that the dynamic resistance offered to the flow of DC is more than that offered for AC. Therefore for a specific material, the same amount of heat can be generated with the lower amount of DC. Hence the minimum nugget diameter can be formed with the lower value of DC, shifting the minimum nugget line in a lobe diagram to the left (Figure 2.22). At higher weld current the dynamic resistance offered to AC and DC is the same. Therefore the maximum nugget diameter line in a lobe diagram with AC and DC overlap each other (Figure 2.22). The overall result is the increased lobe width with the DC.

Although research has been initiated for using DC power for the spot welding of AHSS, from a production point of view the idea is expensive. Most of the automobile manufacturers have established manufacturing lines with conventional AC powered welding guns. Replacing those with the DC power source is an expensive task. Therefore replacing the power source will not give the ultimate solution to the problem. In the present work, an attempt was made to get better welds, while keeping the AC power source.

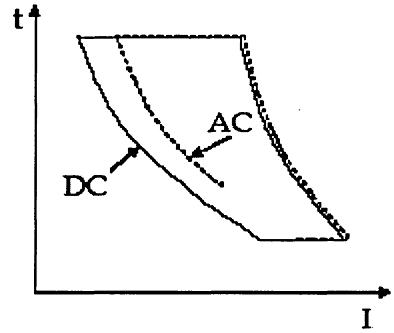


Figure 2.22 Weld lobes with AC and DC power sources[35].

2.3.5 Interfacial failures in martensite steels

Peterson[37] recently studied the failure modes in martensite steels. He found that these type of AHSS steels show interfacial failures. He conducted spot welding trials on 1.5 mm martensitic (1500 MPa) steels. The carbon percentage of these steels was 0.24%, phosphorus and sulfur were 0.009% and 0.008 % respectively. The steels show interfacial button fracture in the peel test. It was already mentioned that higher hardenability elements promote interfacial fracture. This is because alloying elements in such steels segregate along the grain boundary. A fracture propagates along the path that requires least propagation energy. The fracture through the cast microstructure of the weld nugget prefers to travel through the local areas enriched by chemical segregation, which are usually just beside the solidification voids. Full button pullout is the favorable fracture mode. The path of fracture for this type of fracture goes through the large grains in the heat affected zone. In this case strength of the joint can be related to the strength of base metal. This fracture path possesses greater ductility and hence better fracture toughness. Peterson[37] also suggested the following modifications in the weld schedules to avoid interfacial failures in martensite steels.

a. Changes in weld time and current
b. Higher electrode force

c. Weld and temper procedure (two pulses with short second pulse)
d. Downsloping schedules

Although Peterson[37] suggested the parameters that should be varied to get good welds, exact welding schedules were not proposed. His work was focused more on weld strength and fracture propagation than weldability.

2.4 OBJECTIVES OF RESEARCH

There are two major factors that have contributed to the limited application of AHSS for automobiles. One is the narrower weldability lobes and the other is interfacial and partial interfacial failures shown by AHSS. Recently various solutions have been suggested for spot welding these steels successfully. These solutions include the use of complex welding schedules, multiple pulsing, upsloping and downsloping weld schedules, DC power source, etc. In spot welding of AHSS, a primary concern for a spot welding operator is to select correct welding schedules, i.e., the selection of a set of welding parameters, such as welding current, weld time, electrode force etc., which would produce an acceptable nugget diameter. The specific schedule for spot welding DP and other combinations were not suggested by other researchers. The resistance welder manufacturers association (RWMA) and many other standards suggest specific weld schedules for spot welding conventional steels. These schedules can act as a good reference schedules for the spot welding of AHSS. The specific schedule for spot welding AHSS has not been suggested by these standards. The present work proposes a specific complex weld schedule for spot welding DP600 steels for popular combinations used in a production vehicle. Lobes were plotted as per A/SP recommended procedures with various types of weld schedules. Single as well as multiple pulse weld schedules were used to plot the lobes. A nugget growth study was conducted in single and multiple pulses. The nugget growth phenomenon in these steels was understood. A new weld pulse design was proposed for the DP steel.

CHAPTER 3

EXPERIMENTAL PROCEDURE

The current chapter describes the experimental procedure followed for exploring weldability of spot welded joints. Weld lobe diagrams were used for comparing weldabilities of different joint combinations. Detailed information about equipments used and procedures used to establish lobe diagram can be found in the current chapter. Three different joint designs, suggested by Dofasco's market development and product application department, were considered for the trials. These joints involved use of AHSS and were from a production vehicle.

3.1 MATERIALS

Various AHSS types are the potential candidates for the front rail, rocker and body side outer applications in an automobile[27]. Figure 3.1 shows the position of rocker, front rail and the body side outer in a vehicle. DP600 is popular material for the rocker, 350 HSLA (minimum UTS 350 MPa) is used for the front rail and 0.7 mm EDDQ is used for the body side outer. EDDQ is the Extra Deep Drawing Quality steels, especially used for exposed parts of car body which may have intricate designs. All materials were hot dipped galvanized 60G on either side, where 60G represents average coating weight of 0.60 Oz/ft^2. (i.e. an average coating thickness of 0.025 mm[40]). In the present work spot welding trials were conducted on following joint designs. (Application of each joint design is shown in the bracket)

A. 2.0 mm DP600 welded to 2.0 mm DP600 (rocker welded to rocker).
B. 2.0 mm DP600 welded to 2.0 mm 350 HSLA (rocker welded to the front rail)
C. 2.0 mm DP600 welded to 0.7 mm EDDQ (rocker welded to the body-side outer)

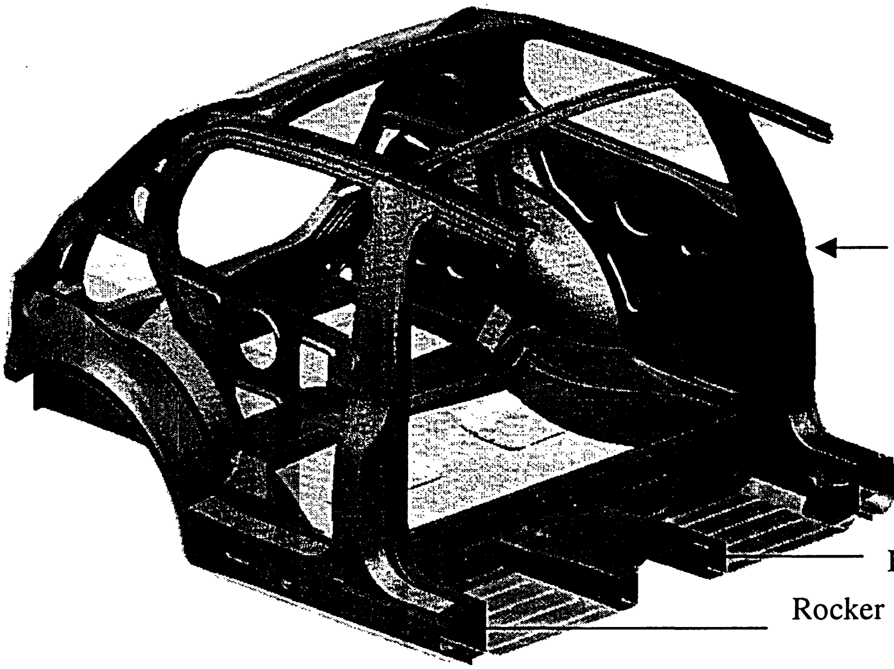


Figure 3.1 Automobile Body Structure[41]

Table 3.1 shows the tensile properties of the materials used in this study. The materials were supplied by Dofasco Inc. Hamilton, Canada. Longitudinal (length parallel to the direction of rolling) tensile samples were taken at the centre point of each material characterization panel (section 3.2.1). All tests were performed according to ASTM standards at, Dofasco Inc. Canada.

Table 3.1 Mechanical properties of base materials

Grade	Thickness (mm)	YS MPa	UTS MPa	TE (%)*	n**
DP600	2.0	385	626	26.1	0.22
350 HSLA	2.0	350	454	33	0.18
EDDQ	0.7	138	303	49	0.25

TE* = Total Elongation, n** = strain hardening exponent

3.2 SAMPLE PREPARATION

This section summarizes procedure followed for preparing peel and panel coupons from the supplied sheets. Samples were prepared according to Auto/Steel Partnership procedures [18].

3.2.1 Coil edge removal

Three materials, DP600, 350 HSLA and EDDQ were supplied in the form of sheets sheared to a size of 1200 mm x full coil width (1200 mm). All sheets were already marked with the top surface identification (ID) mark and the rolling direction ID mark with a permanent steel marker. Red ink was used to indicate top surface ID mark and black ink was used to indicate rolling direction ID mark. Precautions were taken to transfer these marks to each peel and panel coupon. About 100 mm of sheet from each sheet coil edge (X and Y in figure 3.2) were sheared and scrapped to eliminate any potential effects of edge coating weight and sheet thickness variations on the test results [18].

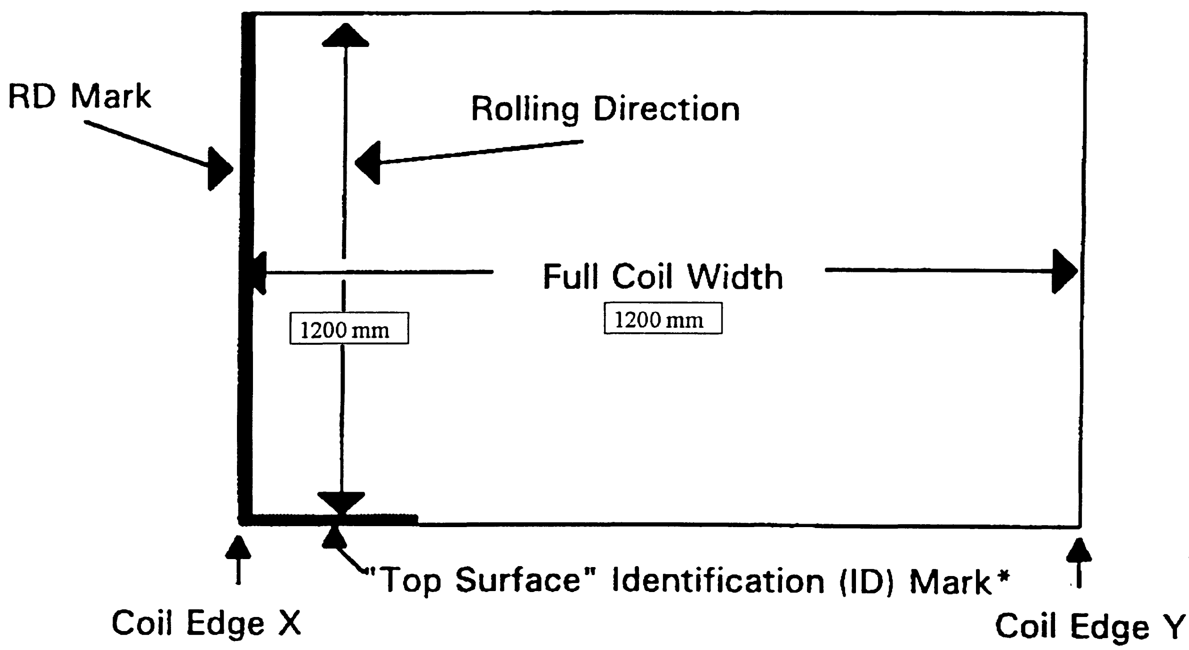


Figure 3.2 Surface and rolling direction marking of sheet[18]

After trimming edge X, the rolling direction mark was transferred to the sheet surface as shown in figure 3.3. Two types of strips, called peel coupon strips and material characterization panel were sheared from the sheet. Peel coupons were sheared from the peel coupon strip. The material characterization panel was used for determining sheet thickness, coating weight as well as coating and substrate composition [18]. Figure 3.3 shows a typical layout for extracting peel coupon strips from a trimmed sheet.

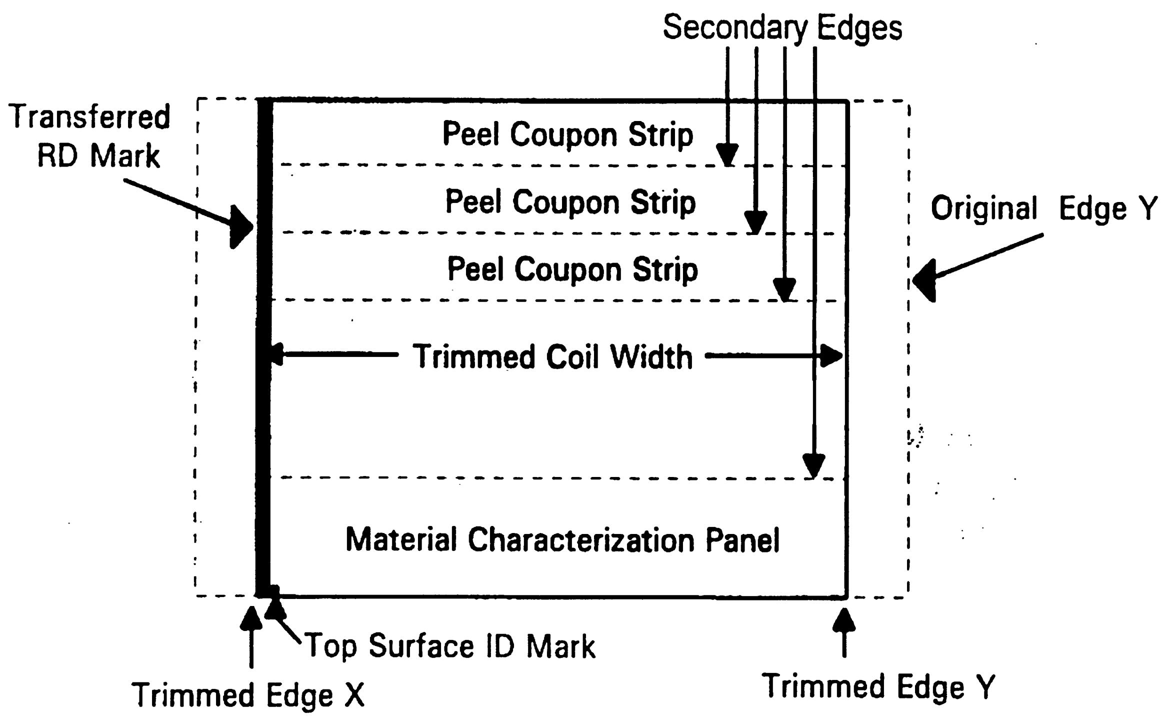


Figure 3.3 Trimmed coil width with transferred RD Mark on Sheet[18]

3.2.2 Peel and Panel Coupon Shearing

Figure 3.4 shows layout for shearing peel coupons from peel coupon strips. Table 3.2 gives the dimensions of peel coupons for 0.7 mm and 2.0 mm thick steel sheets. Using the RD mark as a reference, top surface ID marks were transferred to the secondary edge of each test coupon strip, as shown in figure 3.4. Special attention was taken to keep the transferred RD mark on each strip. From the trimmed test coupon strip, the desired numbers of test coupons were sheared. Around 600 peel coupons were necessary for establishing one lobe diagram.

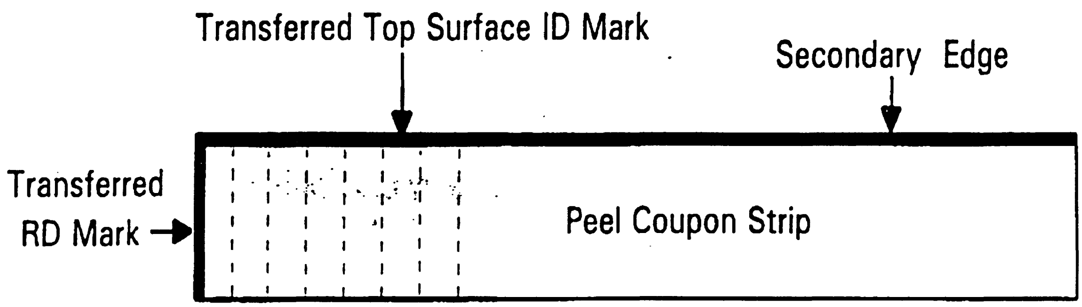


Figure 3.4 Peel coupons sheared from the test coupon strip[18]

Table 3.2 Dimensions for peel test coupons

Sheet Thickness (mm)	Peel Test Coupons	
	Length $^{(a,b)}$ (mm)	Width $^{(b)}$ (mm)
0.7-0.89	100	30
1.70-2.09	140	50

Note: (a) Rolling direction is parallel to length (b) Tolerance: ±1 mm

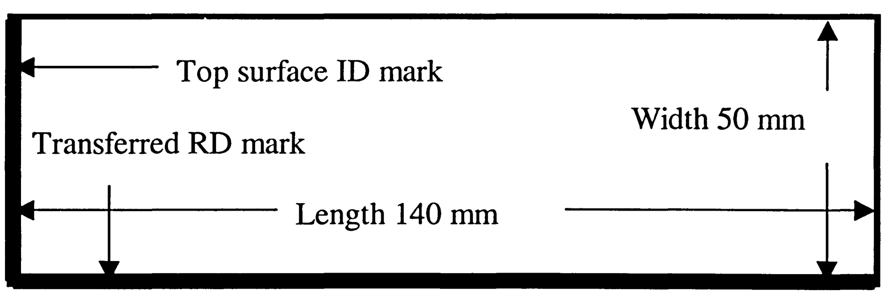


Figure 3.5 Schematic diagram of peel test coupon for 2.0 mm thick sheet

Figure 3.6 shows the layout used for cutting panel coupons. Panel coupons for weld and electrode face stabilization were sheared from the test coupon strips according to dimensions shown in Table 3.3.

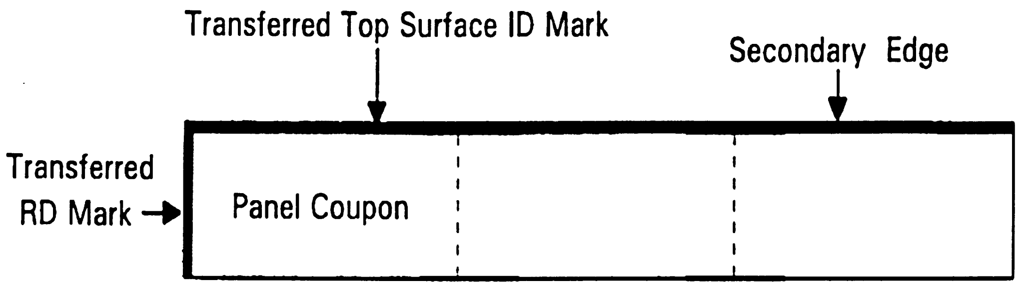


Figure 3.6 Panel coupons sheared from the test coupon strip[18]

Table 3.3 Dimensions for panel coupon

Sheet Thickness (mm)	Panel Coupons	
	Length (c) (mm)	Minimum Width (d) (mm)
0.7-0.89	340	55
1.70-2.09	520	82

Note: (c) Tolerance: ± 5 mm (d) Width may be increased to ease handling

3.2.3 Surface Preparation

All peel and panel coupons were lightly wiped with the cotton wash to evenly distribute mill oils and to remove surface contaminants such as dirt, grease, etc. No solvent of any kind was used to clean or degrease the samples. Any oil or dirt picked up during shearing operations was removed by lightly wiping the samples because it may show some effect on the position of lobe[34]. Samples with surface deposits that could not be removed by light wiping were discarded.

3.2.4 Sample Randomization

All peel coupons were collected in a plastic container. They were randomized thoroughly to mix coupons from within a sheet and between groups of sheets.

3.3 EQUIPMENT

3.3.1 Welding Machine (Spot welder)

Figure 3.7 shows a single phase, 60 Hz, AC, 75 kVA pedestal resistance spot welder used in the present work. The equipment is located in the spot welding research laboratory at Dofasco's Research and Development department. The present welder uses a microprocessor-based digital MEDAR legend control with automatic voltage compensation. The transformer was capable of producing the necessary secondary currents at the current settings of 60 to 92%. It was capable of producing about a 100 ampere secondary current increment per 1% current setting increment. The electrode force application system was pneumatic.

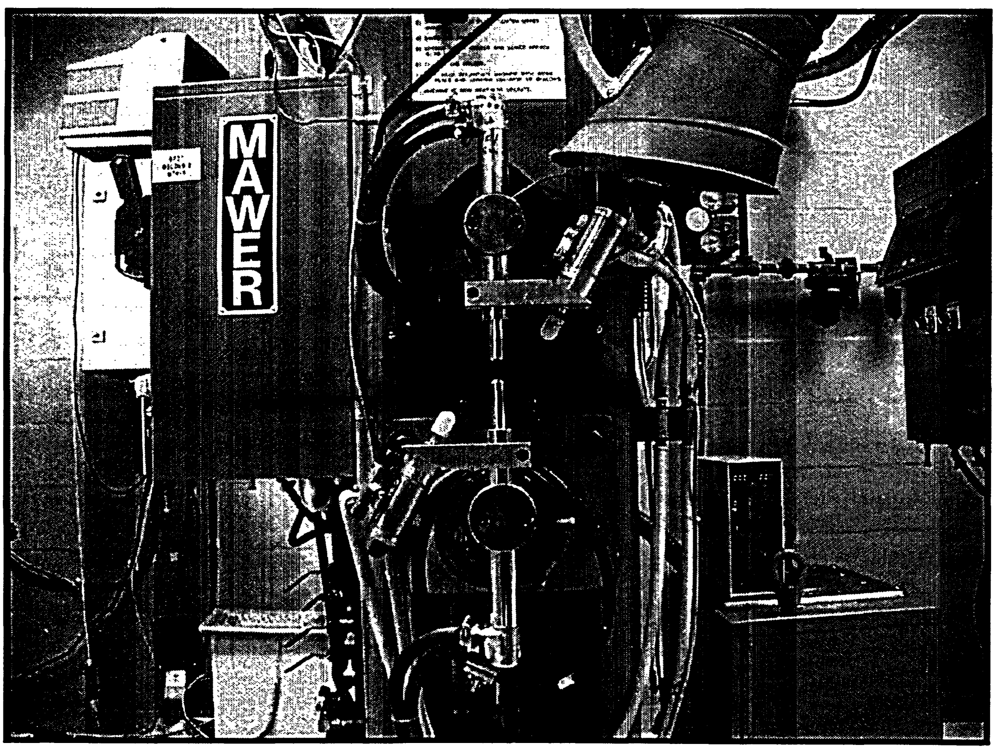


Figure 3.7 A 75 kVA AC Spot welding machine

3.3.2 Current weld timer meter

Figure 3.8 shows MIYACHI, MM-121 B high precision weld checker used to measure secondary current and time (cycles) in the present study. It could be used to measure and monitor welding current and time at every half cycle of AC. Measured values were displayed digitally on the front panel.

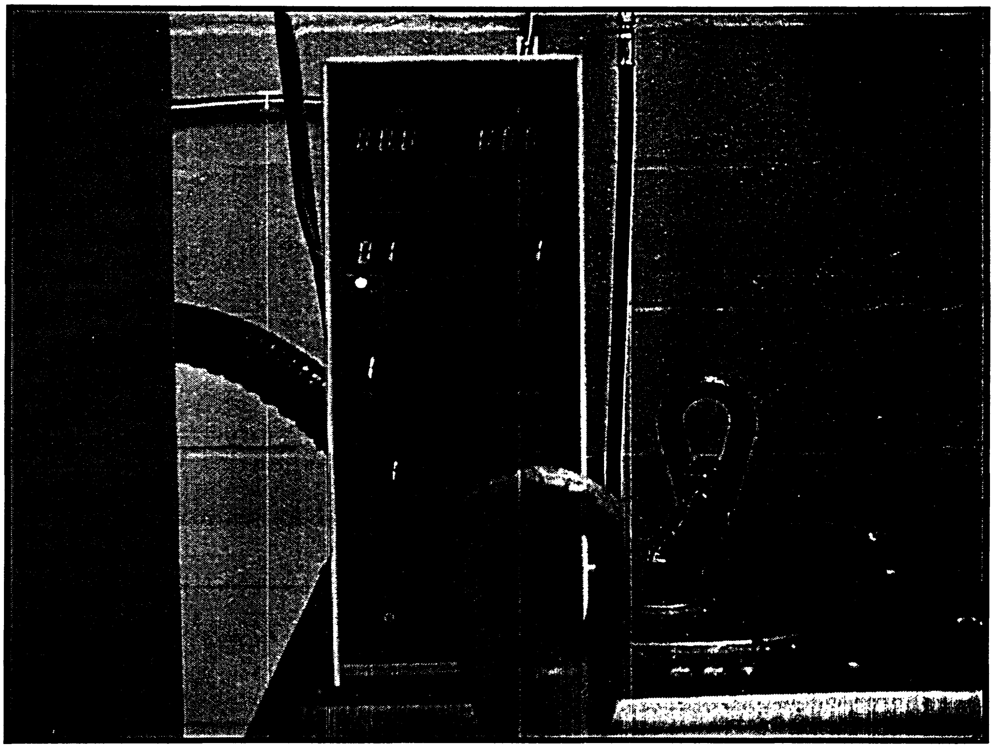


Figure 3.8 MIYACHI, MM-121 B high precision weld checker

3.3.3 Force gauge

The spot welder used in this study had a pneumatic force application system. A required valu of electrode force was set in the spot welder. In order to check if, the required force is maintained across the electrode tips, a portable force gauge shown in figure 3.9 (Piezo-electric type) was used. The tips of force gauge was inserted between the gaps of two electrodes. Force was applied by pressing the pedal. The force applied by the electrodes was displayed on the digital display of the force gauge. The digital electronic weld probe used in this study was, Tuffaloy made (model 601-8300MD, capacity 3000 lbs).

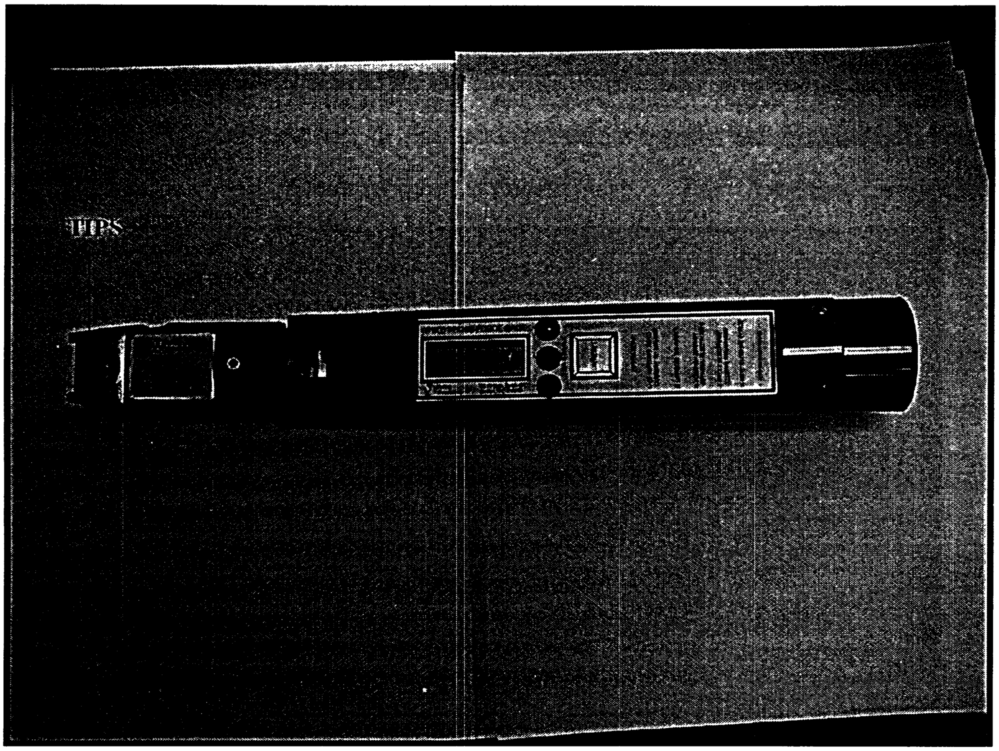


Figure 3.9 Portable force gauge

3.3.4 Equipments for the peel test

Figure 3.10 shows (left to right) edge cutter pliers, tongs, digital calipers and locking pliers used for the peel test. Mitutoyo, Series 500 Imperial model digital calipers with an accuracy of ± 0.02 mm was used for measuring the button diameter. Locking pliers (10 inch) were used for pulling two sheets apart in the peel test. Edge cutter pliers (8 inch) were used for removing burrs and lips from the weld button.

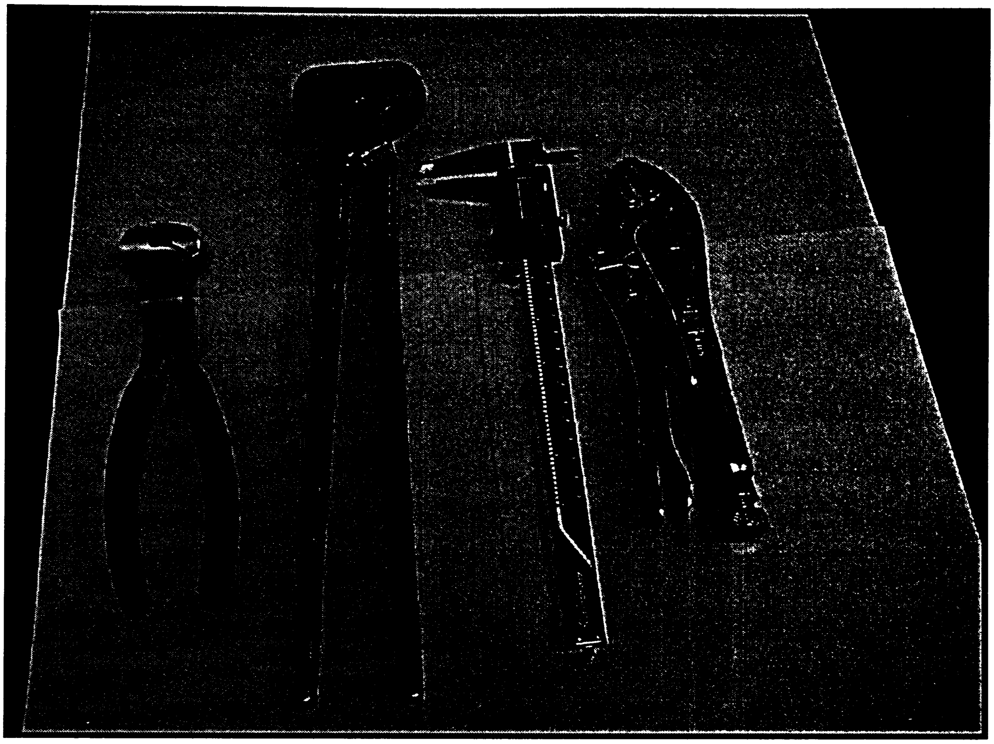


Figure 3.10 Tools for peel test

(From left to right, edge cutter pliers, tongs, digital calipers and locking pliers)

3.4 ELECTRODE INSTALLATION AND DRESSING PROCEDURE

Fresh electrodes were used for establishing each lobe. This section covers the procedure and precautions followed for installing electrodes in the throat of the welding machine. Fresh electrode faces possess machining marks and may need dressing before welding started with them.

3.4.1 Electrode Installation

Before installing the electrodes in the holders, they were coded T (for top) and B (for bottom) with a marker. The electrodes were installed in the adaptors and the cooling tubes were adjusted. Adequate electrode force (~ 2 kN, less than the target welding force) was applied temporarily, to set the electrodes. Electrode alignment was checked by visual inspection.

Adjustments were made if there was any misalignment. Full welding pressure was applied to seat the electrodes in the adaptors.

3.4.2 Electrode Dressing

Electrode dressing was applied if, electrode were not parallel or have less face diameters than specified. Following steps were followed in the dressing operation

A. Specific dressing file (400 grit) was inserted between the electrodes. Electrodes were brought together with a low (< 2 kN) electrode force to prevent excessive material removal. The file was rotated in ~180^0 and then back. Electrodes were retracted and file was cleaned. This procedure was repeated several times.

B. To achieve smoother finish on electrodes faces, an emery paper was folded on an uncoated steel sheet piece. Steel piece with emery paper was inserted in between the electrodes. Electrodes were brought together with low electrode force and emery paper was rotated in 180^0 and then back for 2/3 time. Electrode dressings were applied only if the machined electrode face diameter was less than the specified (± 1 mm) or if electrode face did not have a smooth finish.

3.5 ELECTRODE-FACE CONDITIONING

The Electrode face of each electrode was stabilized before using it for establishing the lobes. Stabilization of the electrodes is necessary because as-machined electrode faces did not show good repeatability.

3.5.1 Electrode and weld stabilization

Figure 3.11 shows variation in weld button size and current with increasing number of welds when welding with new electrodes. This shows that button diameter and weld current vary in a dynamic pattern if new electrodes are used. To compensate for this dynamic behavior of new electrodes, a weld size stabilization procedure is necessary at the start of each lobe test. This procedure conditions the faces of the fresh electrodes. The stabilization procedure requires approximately 80 to 250 welds. After the stabilization electrode faces get conditioned and show less variation in button size. Thus, stabilization promotes reproducibility of the test results. The stabilization procedure consists of adjusting the welding current as and when needed to maintain a specified or fixed weld size.

As seen in figure 3.11, during stabilization procedure current is increased till the button size reaches to a critical size called stabilization weld size (SWS). SWS can be defined as 90% of the dressed face diameter. (e.g., SWS = 7.2 mm for 8.0 mm dressed face diameter). The SWS was rounded to ± 0.1 mm.

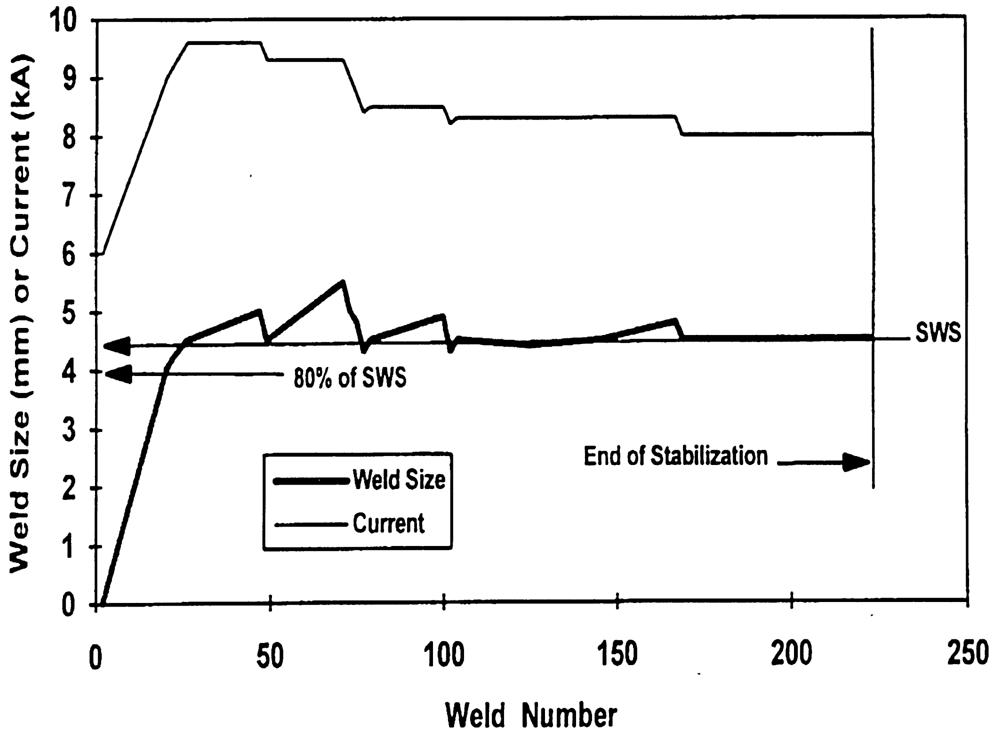


Figure 3.11 Graphical example of typical stabilization procedure[18]

The welding conditions, parameters, materials, etc. used in this stabilization procedure were the same as those used in the subsequent lobe test. In all cases, only the test weld (2nd weld) of the peel sample was used for establishing button size and fracture mode [18].

3.5.2 Stepwise procedure for electrode face and weld stabilization

Following steps were used for electrode stabilization procedure. The stabilization procedure described below is the standard procedure established by A/SP. During the stabilization process, button size was determined through the peel test[18].

1. Based on test data previously obtained, welding parameters were set to a value that results in a no-fusion condition on the test weld of a peel sample. No fusion is the condition where there is no button formation of any size at the faying interface.
2. If a button of any size was obtained, the current setting was reduced by 1000 Amperes interval.
3. If no fusion was obtained, the current setting was increased in the increments of 300 ampere until a test weld button size of about 70% to 80% of SWS was obtained.
4. Once weld button size was within 70% to 80% of SWS, the current setting was increased in the increments of 100 amps interval until the button size was within ± 0.1 mm of SWS.
5. If the weld size was within SWS ± 0.1 mm, without changing the weld parameter settings, one row of 19 welds was welded on the panel sample. All 19 welds should be welded without expulsion, if expulsion at any weld was observed, process was stopped, current was reduced by 300 Amperes and steps 4, 5 were repeated. The direction of panel movement with respect to the machine throat was maintained as shown in figure 3.12.
6. After welding a row of 19 welds without adjusting the current settings, two peel samples were welded and average button size was measured.
7. If the average button size was not greater than SWS + 0.1 mm, another row of 19 welds was welded.
8. Step NO. 7 was repeated once more. If three consecutive 19 weld row, were welded without expulsion and button diameter was within SWS ± 0.1 mm after each 19 weld row, stabilization was ended.
9. If the average button diameter after step 6 dropped below SWS, current was raised in 100 ampere interval and steps 4 to step 7 were repeated [18].

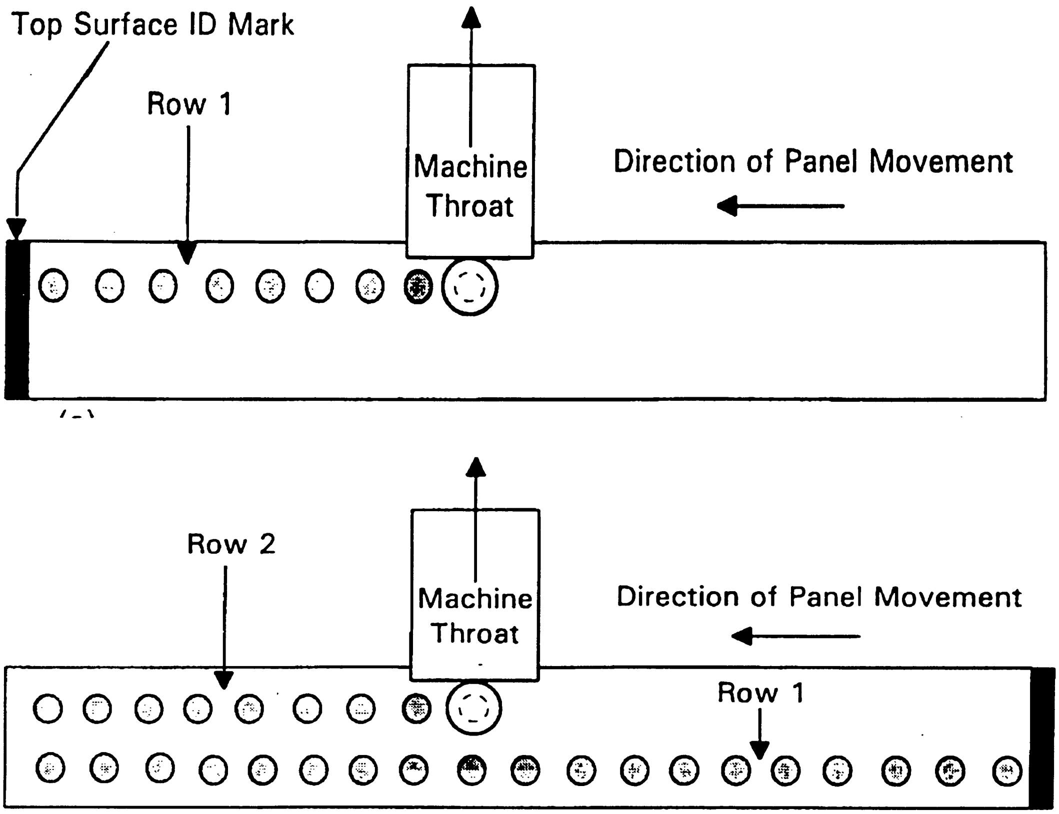


Figure 3.12 Panel sample orientations with respect to the welding machine throat[18]

After welding three consecutive rows of 19 welds on the panel sample without expulsion at SWS button size, it was assumed that the electrodes were stabilized. Lobes were plotted with the stabilized electrode tips. The stabilized electrodes show electrode life of around 2000 welds.

3.6 PROCEDURE FOR ESTABLISHING LOBE DIAGRAM

This section discusses about the procedure followed for plotting the lobe diagram. Each lobe was established at three different weld times. The selection of welding parameters and weld button criterion used in the present study is discussed in this section.

3.6.1 Selection of welding parameters

The welding parameters were selected from the Weld Quality Test Method Manual[18]. These schedules were developed under the guidance of the Auto/Steel Partnership standardized welding test task force. E.g. Table 3.4 shows weld schedule for 1.90 to 2.09 mm thick mild steels.

Table 3.4 Welding parameters for 1.90 to 2.09 mm thick sheets

Sheet Thickness (mm)	Electrode				Weld Time (cy)	Short Hold Time (cy)	Long Hold Time (cy)	Welding Rate (w/Min)
	Type NO.	Dressed face Dia. (mm)	Force (kN)	Cooling (l/mm)				
1.90-2.09	5	8.0	5.5	6.0	22	10	90	15

3.6.2 Establishing the weld lobe

Based on the test data previously obtained, the welding current was selected. Welding time was selected from the weld schedule (see appendix A). Three weld times were selected by adding and subtracting four cycles from the mean weld time given in A/SP schedule. (E.g. if A/SP suggested weld time is 26 cycles, selected weld times were 22 26 and 30). The welding current was set to a value that should result in a "no-fusion" condition on the test weld (2nd weld on the peel sample) at the highest welding time (e.g. 30 cycles in figure 3.13). The welding current was increased in intervals of 100 amperes by increasing the % current settings by 1%. Once the minimum acceptable nugget diameter (4 $\sqrt{t}$, as explained in section 2.2.2) was achieved for a particular weld time, the point showing corresponding current and weld time (e.g. points A, B, C in figure 3.13) was plotted on the lobe diagram.

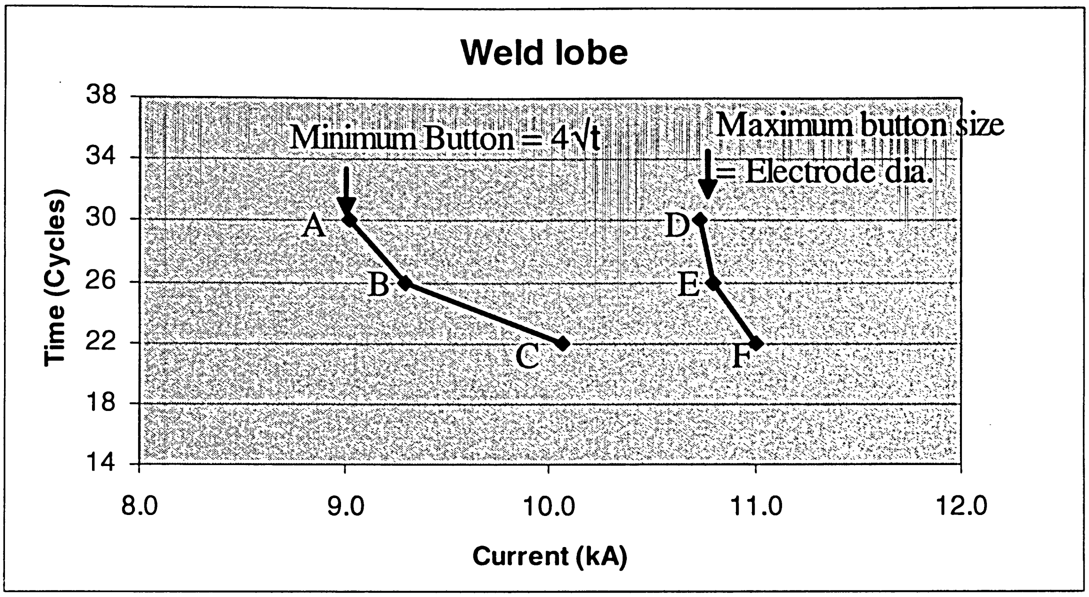


Figure 3.13 Schematic lobe diagram

The current was increased by another 100 amperes and three different peel samples were welded at each welding time (e.g. 22, 26 or 30 cycles). This procedure was repeated till expulsion was observed on the test weld for each weld time. The expulsion points (e.g. points D, E, and F) were plotted on the lobe diagram. Normally the button diameters at expulsion were equal to the electrode face diameter. While conducting this procedure the weld times were selected in the random order. Three identical coins were assigned three different weld times (e.g. 22, 26, and 30 cycles). Randomly one coin out of the three coins was selected. The spot weld was formed with the weld time assigned to this coin. Thus the random selection of weld time was ensured by selecting one coin out of the three coins. For every material combination under consideration, the final lobe plotted was the average of three different lobes. The weld lobe data can be found in appendix B.

3.6.3 Weld button measurement

This section explains the weld button criterion and weld button measurement details.

Figure 3.14 shows a schematic peel test sample. The button diameter was the average of two diameters measured perpendicular to each other.

Minimum weld nugget diameter = $4\sqrt{t}$ (3.1)

Where, t = Average sheet thickness

Maximum nugget diameter = Nugget diameter at expulsion[4] (3.2)

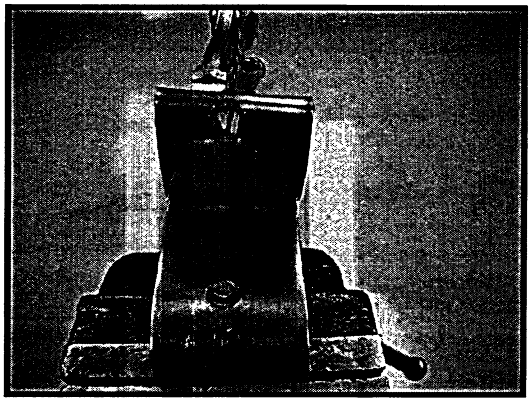


Figure 3.14 Weld button criterion

Weld buttons were measured with the digital calipers (Figure 3.15). Edge cutter calipers (8 inch) were used for the button lip removal. As shown in Figure 3.15 and 3.16 weld buttons were measured across their minimum and maximum axes. D_{MIN} and D_{MAX} may not necessarily be perpendicular to each other. Weld button readings were rounded to ± 0.1 mm[18].

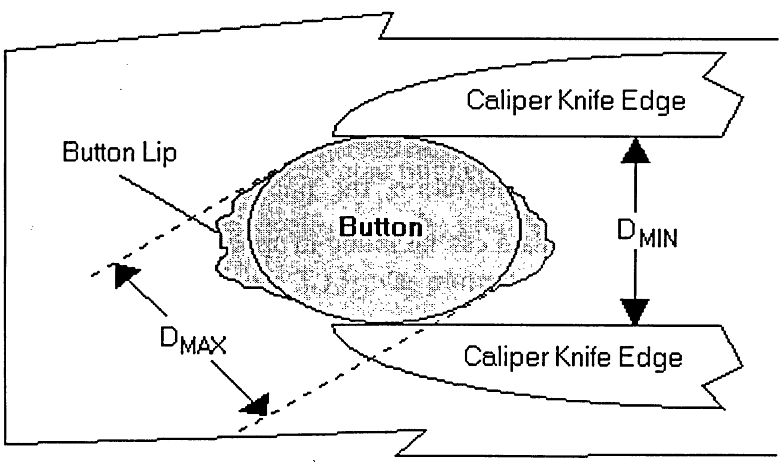


Figure 3.15 Weld button measurement[18]

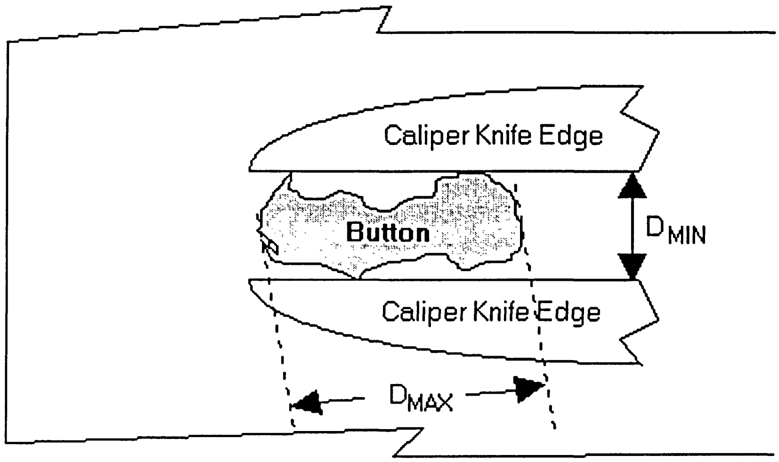


Figure 3.16 Measurement of irregular button diameter[18]

CHAPTER 4

RESULTS AND DISCUSSION

The current chapter presents the results and discussion on spot weldability of the following three material combinations. These joints composite spot welding of different thickness as well as different steel chemistries as follows:

(1) 2.0 mm DP600 spot welded to 2.0 mm DP600
(Same materials having same thickness welded together)

(2) 2.0 mm DP600 spot welded to 2.0 mm grade 350 HSLA
(Different materials having same thickness welded together)

(3) 2.0 mm DP600 spot welded to 0.7 mm EDDQ
(Different materials having different thicknesses welded together)

The focus of the current discussion is on the weld lobe analysis. Weld lobes for given material combinations were established according to Auto/Steel Partnership test standards. Different types of welding pulses and tip designs were used to increase the width of the established weld lobes.

4.1 WELD LOBES FOR DP600 WITH SINGLE PULSE WELD SCHEDULE

Table 4.1 shows the welding parameters used for plotting the DP600 lobe. A single type of welding pulse shown in Figure 4.1 was used for plotting all the lobes in the present section. During the single pulse, current (AC) is applied immediately after the squeeze stage, and 10 hold time cycles were maintained after the weld cycle. The lobe diagram is shown in Figure 4.2.

Table 4.1 Welding parameters used for establishing DP600 lobe[18]

Sheet Thickness (mm)	Electrode			Weld Time (cy)	Hold Time (cy)	Welding Rate (welds/Min)
	Dressed face Dia. (mm)	Force (kN)	Cooling water (l/mm)			
2.0	8.0	6.6*	6.0	22	10	15

*A/SP recommended force for 2.0 mm steel is 5.5 kN[18]

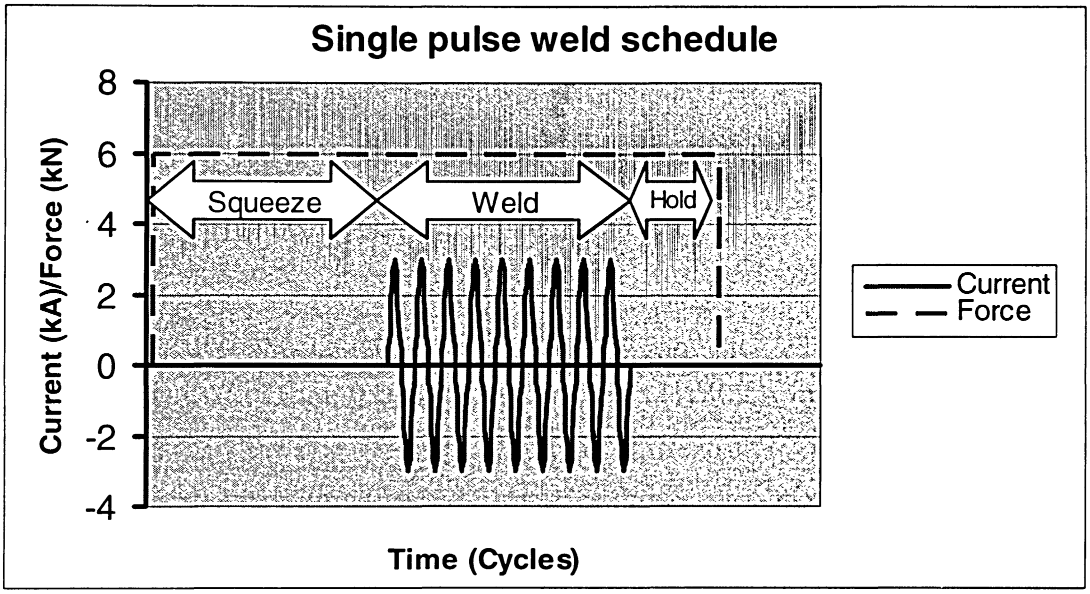


Figure 4.1 Single pulse welding schedule

The lobe shown in Figure 4.2 is the average of three repeat lobes. The error bars show scatter (standard deviation) among the individual lobes. One possible reason for the scatter may be the uneven coating thickness of the hot dip galvanized zinc layer[7]. However, more testing would be required to confirm the cause of scatter. A detailed study and analysis of the lobe diagram was conducted to understand the effect of various welding parameters on the lobe diagram. It can be seen from Figure 4.2 that the lobe width increases with the weld time. It was necessary to understand the behavior of the lobe at even higher weld times. Therefore more lobes were plotted at higher weld time. The same welding parameters were used (Table

4.1). Figures 4.3 and 4.4 show weld lobes at 26 and 30 cycles respectively. The weld lobe data for Figure 4.2, 4.3 and 4.4 can be found in the appendix B.

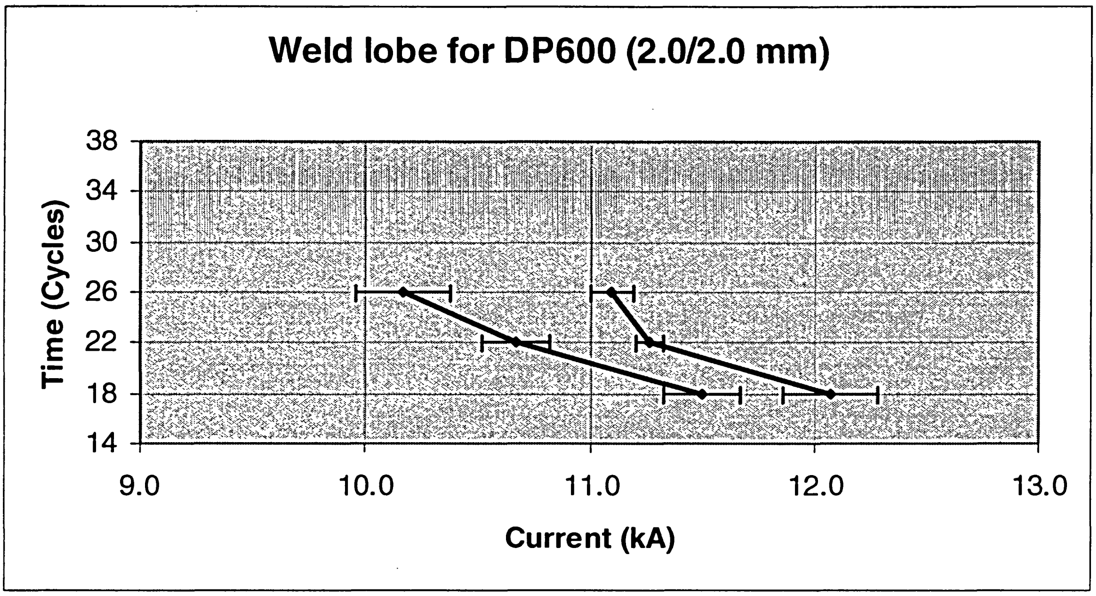


Figure 4.2 Weld lobe for DP600 (2.0/2.0 mm) at 22 cycles

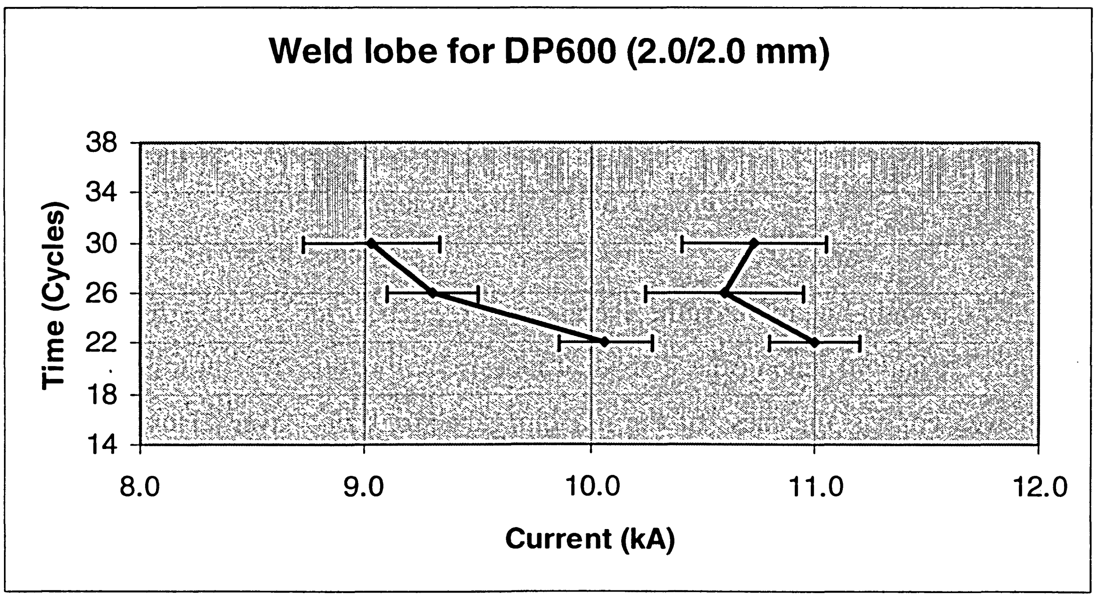


Figure 4.3 Weld lobe for DP600 (2.0/2.0 mm) at 26 cycles

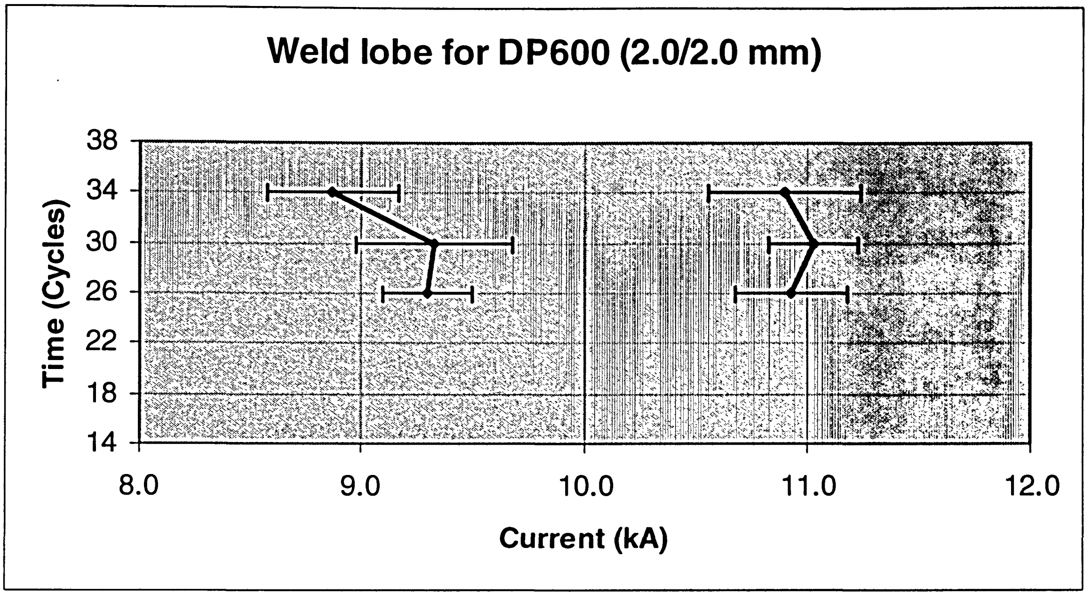


Figure 4.4 Weld lobe for DP600 (2.0/2.0 mm) at 30 cycles

Table 4.2 shows the average nugget diameters (minimum 3 reading) near expulsion at various weld times. The data from Figure 4.2, 4.3 and 4.4 was combined to plot overall lobe for DP600 which is shown in Figure 4.5. Figures 4.6 and 4.7 show the expulsion nugget macrograph at 18 and 34 cycles respectively. At 18 cycles, the expulsion button diameter was 6.75 mm, at the current of 11.90 kA. The failure mode observed during peel test was full button pullout. At 34 cycles, expulsion button diameter was 8.17 mm, at the current of 10.70 kA. The failure mode observed during the peel test was full button pull out.

Table 4.2 Weld time and nugget diameters for 2.0 mm DP600

Weld time (Cycles)	Average nugget diameter at expulsion (mm)
18	7.11
22	7.39
26	7.43
30	7.56
34	8.06

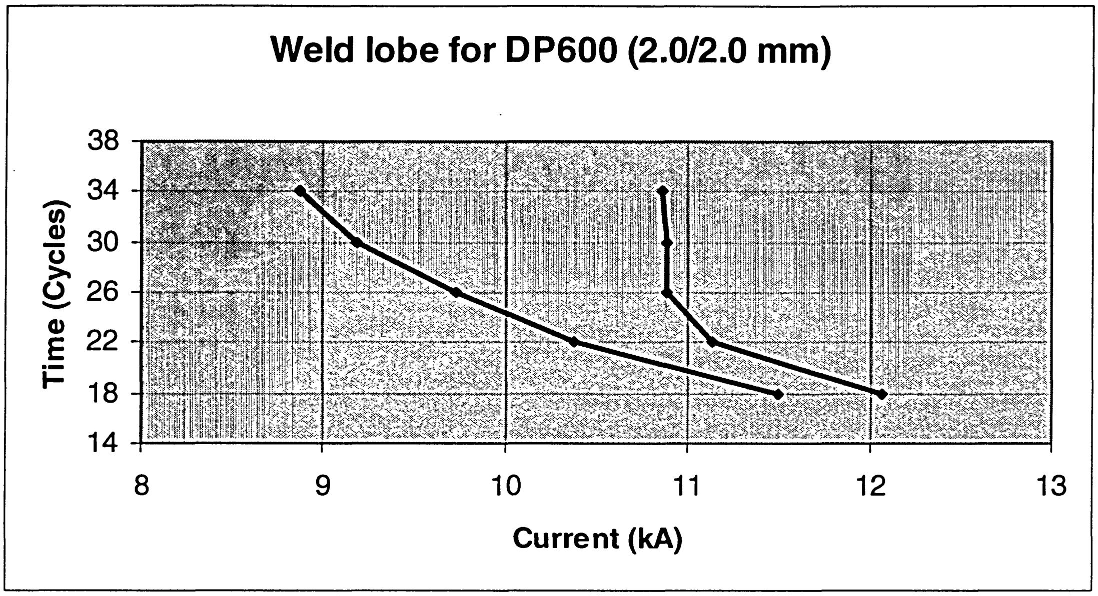


Figure 4.5 Weld lobe for DP600 (2.0/2.0 mm)

Observations and discussion

Figure 4.5 shows that, at lower welding time (18 cycles), higher welding currents are necessary to form minimum acceptable button diameter. Once the minimum acceptable button is formed, it grows quickly to the expulsion (maximum) button size with small increase in the current. While welding with 18 cycles, the time for welding is limited, therefore higher welding currents are necessary to achieve the minimum expulsion nugget diameter. Higher currents result in higher heat input, since

Heat input = I^2RT., where

I = welding current in kA.

R = Total (interface + contact) resistance in Ω

T = Welding time in cycles [15]

Higher welding current and lower welding time do not allow the whole cross section between the electrodes to melt and form a bigger button. Higher welding current results in quick heating and fast thermal expansion of the sheets. The force due to thermal expansion acts in opposite direction to the electrode force. Expulsion occurs when the force due to the thermal expansion exceeds the electrode force.

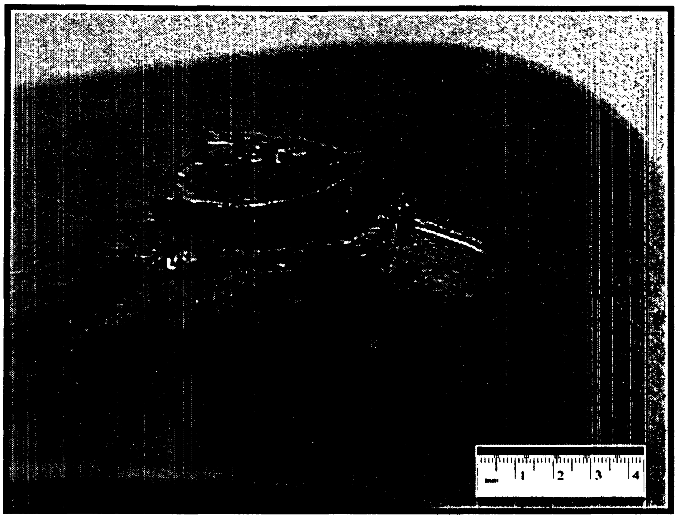


Figure 4.6 Expulsion nugget at 18 cycles.
(Button diameter: 6.75 mm, I = 11.90 kA, failure mode: full button pullout)

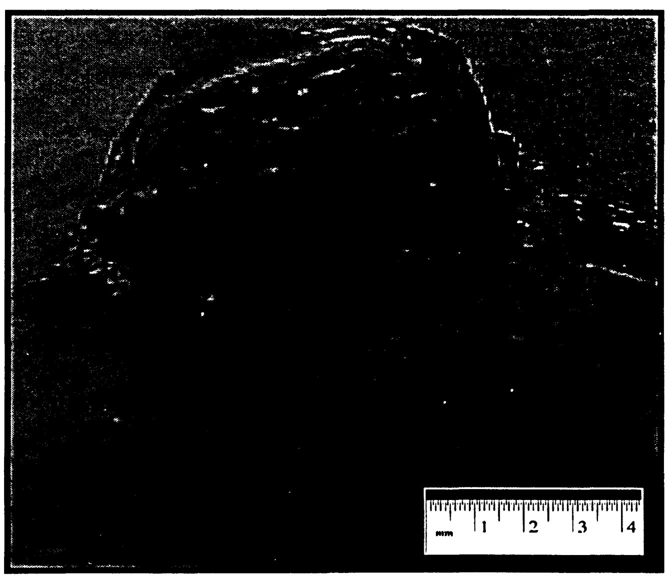


Figure 4.7 Expulsion nugget at 34 cycles.
(Button diameter: 8.17 mm, I = 10.70 kA, failure mode: full button pullout)

At higher welding current due to fast thermal expansion, the expulsion can occur before the nugget can grow to its maximum size. The average nugget diameters at expulsion for various weld times are shown in Table 4.2. The average nugget diameter at expulsion at all weld times should theoretically be equal to the electrode face diameter i.e. 8.0 mm. Therefore at lower welding time of 18 cycles, there is evidence of premature expulsion, which is expulsion before the nugget grows to the maximum size (8.0 mm). The micrograph in figure 4.6 shows expulsion button at 18 cycles. The button diameter was 6.75 mm, at the current of 11.90 kA. The failure mode observed during peel test was full button pullout. At the higher welding time (34 cycles), a minimum acceptable nugget diameter can be formed at comparatively lower welding currents. The nugget grows very slowly with respect to the current increase until expulsion. At higher welding time (34 cycles), lower welding current is passed for a considerably longer time. This facilitates gradual heating of the whole cross section between the two electrodes. The whole cross section between the two electrodes heats up to the melting temperature resulting in a bigger nugget diameter. The macrograph in figure 4.7 shows a nugget with 8.17 mm diameter. The convex shape of weld lobe at 30-34 cycles (Figure 4.4) may be the result of severe electrode tip wear at longer weld times.

Figure 4.8 summarizes the lobe widths and weld times for DP600. It can be observed that lobe width increases almost linearly with respect to the welding time beyond 22 cycles. The acceptable lobe width for mild steel is 2000 amperes. The A/SP recommended welding time for welding same thickness mild steel (2.0 mm to 2.0 mm) is 22 cycles. If weld time of 22 cycles is used for welding DP600 steels, lobe width of 767 amperes can be achieved. This lobe width is less as compared to acceptable 2000 amperes. For DP600 steels, welding at higher weld time of 30 to 34 cycles can result in lobe width of 1800 to 2300 amperes. Significant lobe widths for DP600 can be achieved at higher welding times. If mild steel in a car body structure is replaced by DP600 then higher weld time has to be used for spot welding DP600. Higher welding time means more time for conducting one spot weld. Typically 2000 to 5000 spot welds are necessary for assembling one vehicle. Therefore increasing spot welding time will increase total assembling time for a vehicle. The automobile manufacturers are reluctant to use schedules with higher welding times since it has a negative effect on the production rate.

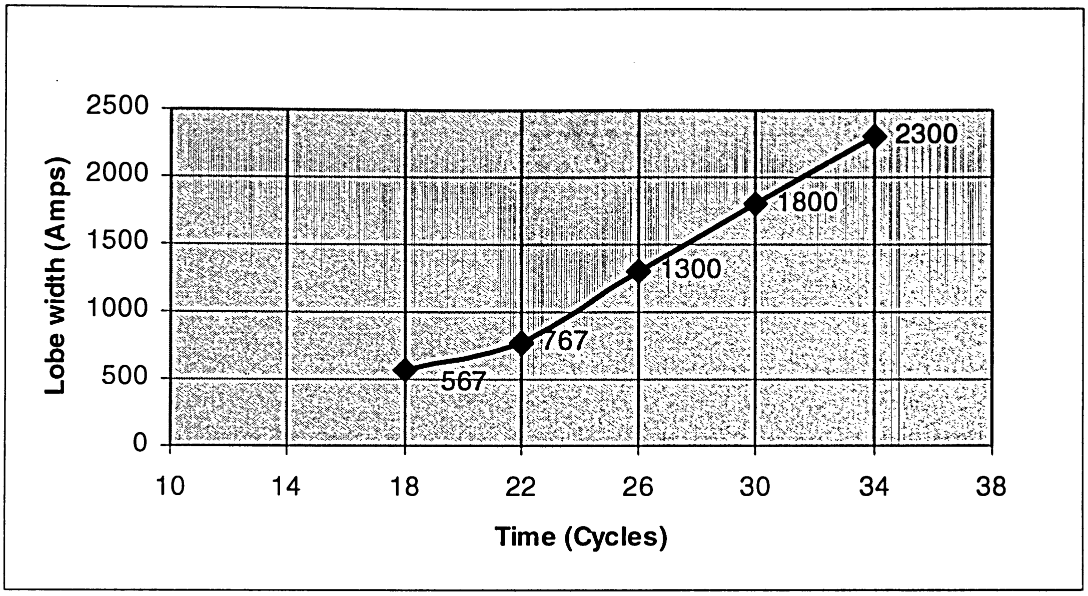


Figure 4.8 Lobe widths at various weld times for DP600

4.2 WELD LOBE FOR DP600 WITH UPSLOPING PULSE WELD SCHEDULE

Gedeon[7] showed that upsloping current when used with truncated cone electrodes can increase the lobe widths for hot dip galvanized mild steels which have free zinc in the coating. He proposed that by gradually increasing the current during upsloping, zinc in the coating gradually heats up with a little melting. This develops a favorable heat generation pattern by allowing the entire cross section to increase the temperature before the zinc coating completely melts. They showed that wide lobe widths can be observed with proper upsloping weld pulse design. His study involved use of truncated cone electrodes and all materials were hot dip galvanized, which means that free zinc is available in the coating[40]. Therefore upsloping weld schedule was designed for the given material combination. Spot welding trials with upsloping welding schedule were conducted for welding 2.0 mm DP600 to itself. An upsloping weld pulse designed for this combination is shown in Figure 4.9. The welding current was raised from 20% of Imax to 50% of Imax for the first 6 cycles. The weld lobe was plotted with 6 upsloping cycles at various welding times of 22, 26 and 30 cycles (6+16, 6+20, 6+24). All other welding parameters were selected as per Table 4.1. Figure 4.10 shows lobes with upsloping and single pulse welding schedules.

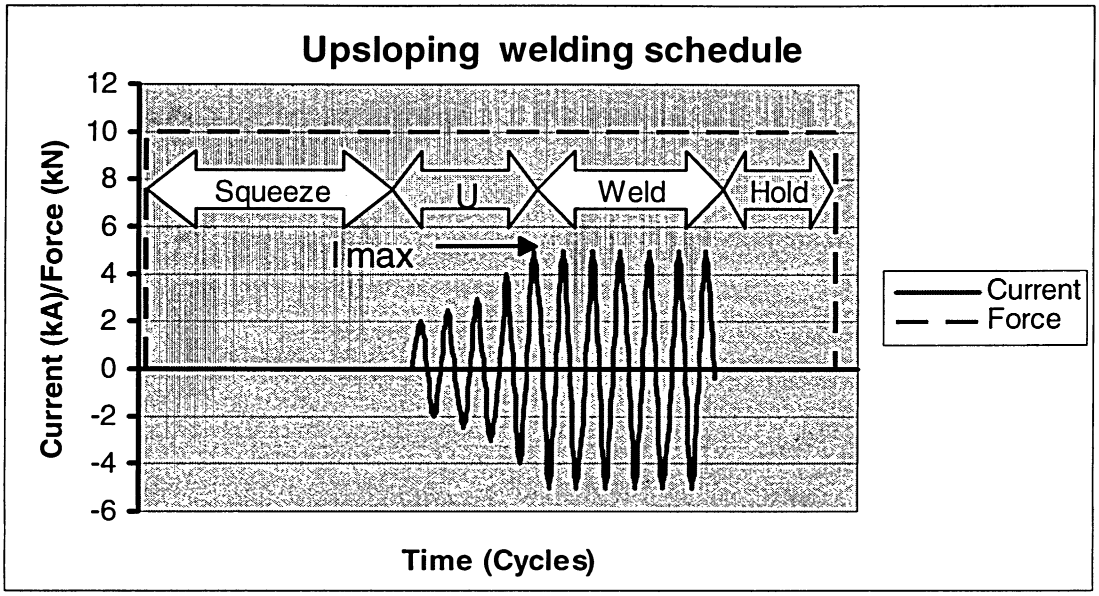


Figure 4.9 Upsloping welding schedule (Note: U = upsloping)

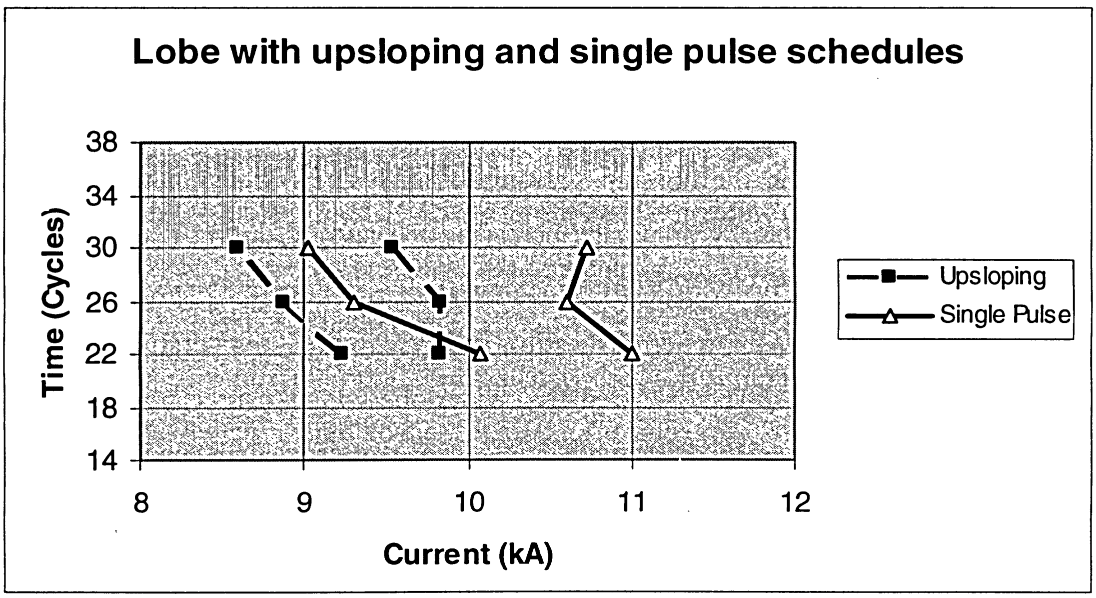


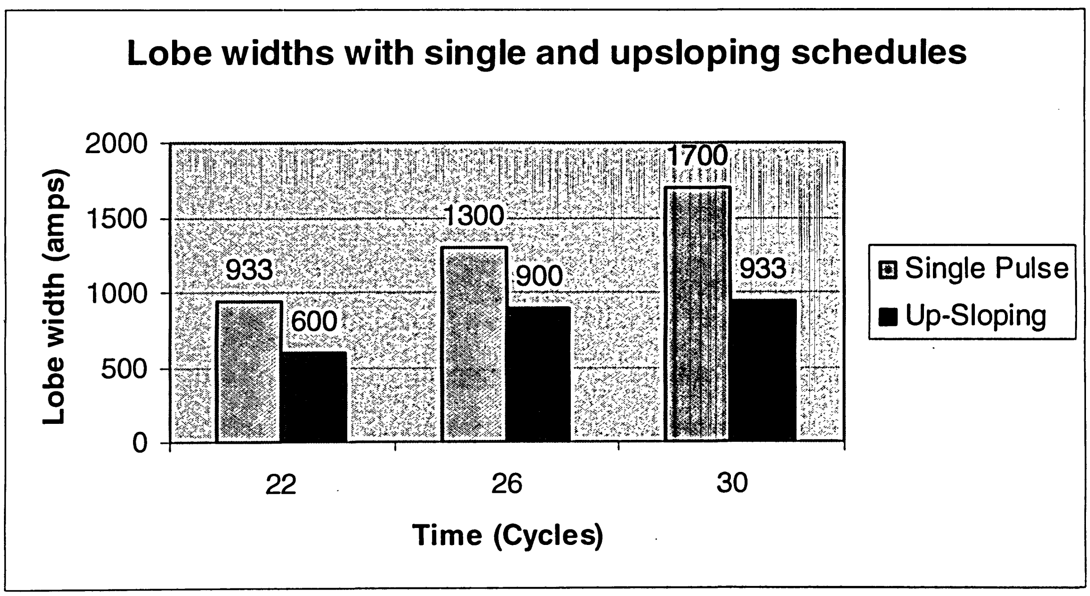
Figure 4.10 Weld lobes for DP600 with single pulse and upsloping schedules

Table 4.3 shows average expulsion diameters at various weld times. Figure 4.11 compares lobe widths with single pulse and upsloping weld schedule. The weld lobe data of this experiment can be found in appendix B.

Table 4.3 Average expulsion nugget diameters with upsloping pulse

Single pulse		Upsloping pulse	
Weld time (Cycles)	Average*expulsion diameter (mm)	Welding time (Cycles)	Average*expulsion diameter (mm)
22	7.39	6 upsloping +16	6.58
26	7.46	6 upsloping +20	7.05
30	7.58	6 upsloping +24	7.24

*Average expulsion diameter calculated from minimum three different observations.



4.11 Lobe widths and weld time for DP600 (2.0/2.0 mm)

Observations and discussion

Figure 4.10 shows that, for the given welding time, the lobe with upsloping schedule is located at lower currents than that with the single pulse. The upsloping schedule results in expulsion at lower welding current than that in the single pulse schedule. Schedules with upsloping current could not achieve maximum nugget diameters (Table 4.3). At a particular weld time, nugget diameter with single pulse current was bigger than that with the upsloping pulse. As seen in figure 4.11, the width of the lobe with upsloping schedule is much less than that with the single pulse.

This shows that, weld pulse design has a significant effect on the lobe width. Therefore designing of proper welding pulse is necessary for achieving wide current ranges. Gedeon and Eagar[19] showed that upsloping schedules result in increased lobe widths for mild steel. The present results show that upsloping schedules for DP600 resulted in narrow lobe widths. There was need to understand the reasons which contribute to these differences in the result.

The differences in the results may be due to the difference in the nugget growth mechanism in dual phase steel than in mild steel. The nugget growth mechanism for a particular steel depends upon the variation of contact and dynamic resistance during a weld pulse[5]. Gedeon[19] explained the mechanism of weld nugget formation for the zinc coated steels with respect to the dynamic resistance behavior of mild steel (explained in section 2.5.3). He proposed that a welding pulse compatible with the stages of nugget growth can be developed after studying the nugget growth mechanism for a given steel. Various types of schedules including prepulsing, postpulsing, up and downsloping as well as multiple pulsing can be used for spot welding galvanized steels [12]. These schedules are set with the aim of increasing the width of the lobe and of improving the electrode tip life. Many researchers [33, 19, 12]proved the fact that optimum weld pulse design can be achieved with the help of detailed nugget growth studies. Therefore to design an optimum weld pulse, nugget growth study for a given material combination was necessary. Following section discussed the experiments designed to understand the nugget growth mechanism in 2.0 mm DP600 combinations.

4.3 NUGGET GROWTH STUDIES FOR DP600

Spot welding was carried out at the welding current just prior to the expulsion. To design a welding schedule with a proper weld pulse, involving upsloping, prepulsing, downsloping and postpulsing, it was necessary to understand how nugget forms and grows during a welding pulse near the expulsion current. In this section, the developing nugget and condition of zinc at the faying interface were examined by stopping the weld sequence after each cycle and pulling the two sheets apart (peel test). Thus, for a 26 cycle weld, 26 different samples (one sample after each cycle) were welded and inspected. The procedure of weld-break-study was continued till expulsion occurred at the faying interface.

4.3.1 Nugget growth in single pulse weld schedule

Single pulse welding is the simplest schedule used for spot welding. In the present experiment nugget growth in single pulse was understood. The knowledge of these observations was used to design complex weld schedule. Table 4.4 shows the welding parameters used for conducting nugget growth studies in a single pulse. Figure 4.12 shows nugget growth in a single pulse. Nugget growth and weld current are superimposed on the same graph to understand the nugget growth with respect to the weld pulse. Figure 4.12 only shows weld stage, for simplicity squeeze and hold stages are not shown. The macrographs (Figure 4.13) show faying surfaces after 9, 13, 21 and 26 cycles.

Table 4.4 Welding parameters used for nugget growth studies in single pulse

Sheet Thickness (mm)	Electrode			Weld Time (cy)	Hold Time (cy)	Welding Rate (welds/Min)
	Dressed face Dia. (mm)	Force (kN)	Cooling (l/mm)			
2.0	8.0	6.6	6.0	26	10	15

Welding current just prior to expulsion i.e. 11.4 kA (figure 4.12) was used. Each point showing the nugget diameter is the average of three different readings.

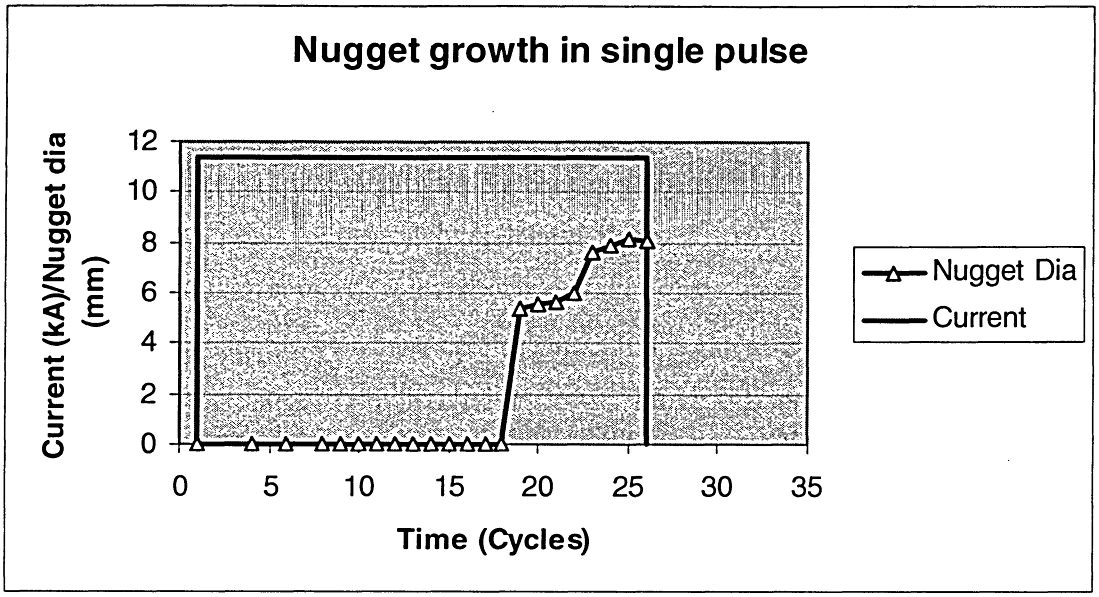


Figure 4.12 Nugget growth in the single pulse

Observations and discussion

At 9 cycles (figure 4.13) zinc is present at the faying interface. From cycle 1 to 13, zinc gradually melts and is pushed away from the centre towards the periphery of the electrodes. The zinc that is pushed away from the centre forms a zinc 'halo' (liquid zinc seal) along the periphery of the electrodes. This observation was in accordance with that of many researchers [42, 43, 46].

During the single pulse welding of 2.0 mm DP600, the substrate starts melting at 13 cycles (figure 4.13). Dickinson[44] suggested that the contact resistance plays an important role before substrate melting and bulk resistance plays an important role after substrate melting. He also suggested that for hot dip galvanized materials, zinc should start melting after 5 to 6 cycles. In the present work zinc started melting after 8 to 9 cycles. Bulk resistance of DP steels is different from that of mild steel. This might be one of the reasons for the prolonged time taken for the zinc removal. The length of the incubation period before weld formation is dependent on the total stack thickness[38]. Longer time is required for welding a thick stack than that for a thin stack because of greater mass of steel involved.

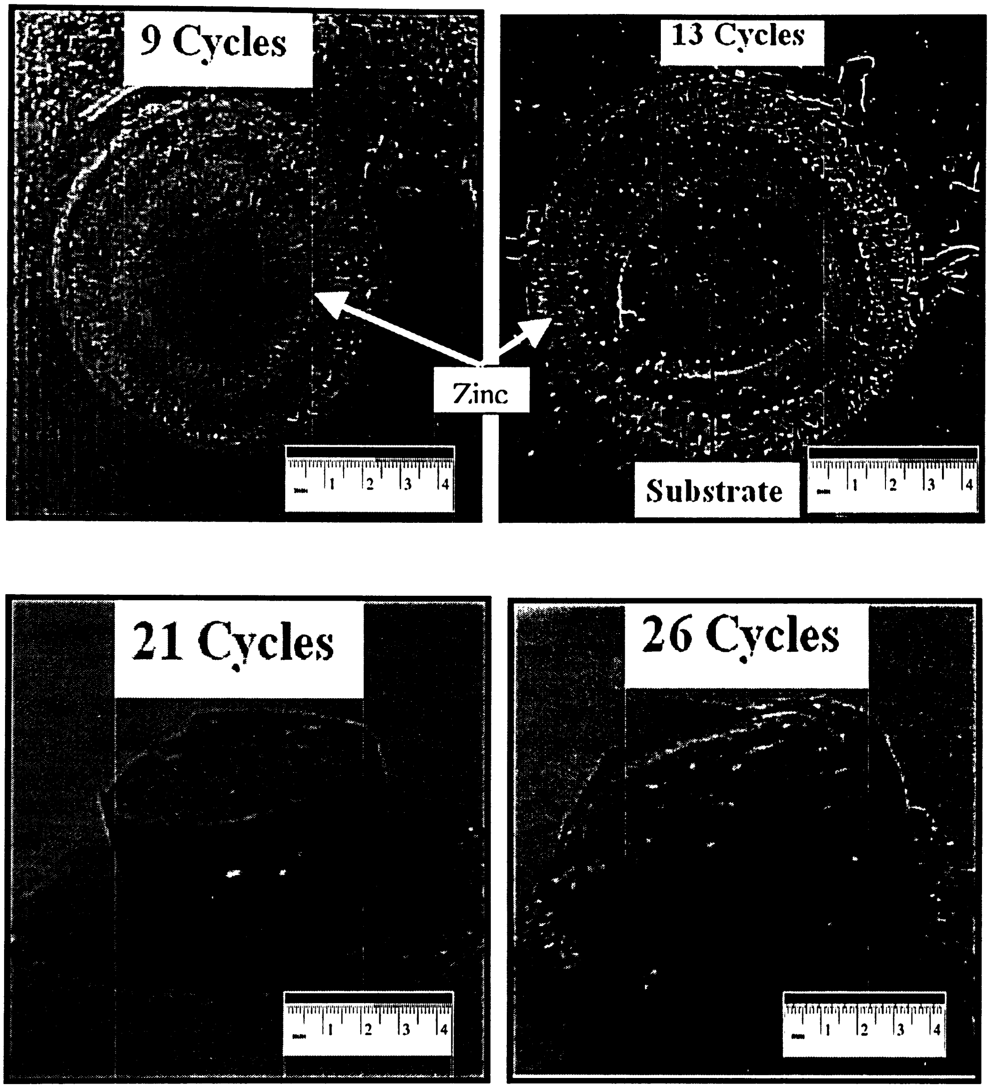


Figure 4.13 Macrographs at 9, 13, 21 and 26 cycles during single pulse welding of DP600

Various interacting phenomena observed during this experiment were zinc removal, start of substrate melting and nugget growth. Once a nugget is formed it grows very quickly (23 to 26 cycles) with time and leads to expulsion. The fast nugget growth and excessive heating during a later stage result in early expulsion, smaller expulsion nugget diameter, and push the expulsion line to the left. This results in lower lobe width. Therefore it was necessary to investigate the possible reasons for fast nugget growth. Lee[16] divided the nugget growth phenomenon based on the dynamic resistance curve during spot welding of mild steel. He suggested following three stages

a) Electrical contact formation

b) Heating and faying interface fusion

c) Nugget growth

His work showed that the first stage in nugget growth (1 to 17 cycles) is contact resistance dominated and the last stage (23 to 26 cycles) is bulk resistance dominated. This is because, after 23 cycles the contact phenomenon at the faying interface no longer exists (due to melting of contact interface). The heat generation is governed by the resistance offered by the melted steel mass at the interface. Thus bulk resistance dominates after 23 cycles. Therefore, it was necessary to investigate the bulk resistivity of dual phase 600 steels. Recently, Jiang[8] investigated the bulk electrical resistivity of Dual Phase steels. Table 4.5 gives the bulk resistivity of various steels. DP600 has higher bulk resistance than conventional high strength or mild steels. The difference in resistivity values of individual steels is due to differences in chemistry and microstructure. The higher bulk resistivity of DP steel is due to its higher carbon and alloying content[8].

Table 4.5 Bulk electrical resistivity of various steels[8]

Material (1.5mm)	Resistivity (m x Ω)
Mild Steel	1.25×10^{-7}
HSLA	1.46×10^{-7}
DP600	2.44×10^{-7}

Therefore the higher bulk resistivity of DP600, and the fact that, the bulk resistance dominates the later stage of nugget growth, leads to extremely fast nugget growth during the spot welding of DP600 steel. Control over this nugget growth is necessary to avoid premature expulsion, i.e. expulsion before the nugget grows to its maximum size. Thus the nugget growth control can be achieved by reducing the heat input when the nugget is growing fast.

4.3.2 Nugget growth in double pulse weld schedule

Attempts were made to control the heat input of the rapidly growing nugget using double pulse schedule. Two hold time cycles during a welding pulse were introduced. Thus a single pulse of 26 cycles was divided into two pulses. Table 4.6 shows welding parameters used for conducting nugget growth studies in a double pulse. A welding current just below expulsion i.e. 11.4 kA was used. Figure 4.14 shows the weld nugget growth in double pulse welding. Figure 4.15 shows the macrograph of developing nuggets.

Table 4.6 Welding parameters used for nugget growth studies in single pulse

Sheet Thickness (mm)	Electrode			Hold Time (cy)	Welding Rate (welds/Min)
	Dressed face Dia. (mm)	Force (kN)	Cooling (l/mm)		
2.0	8.0	6.6	6.0	10	15

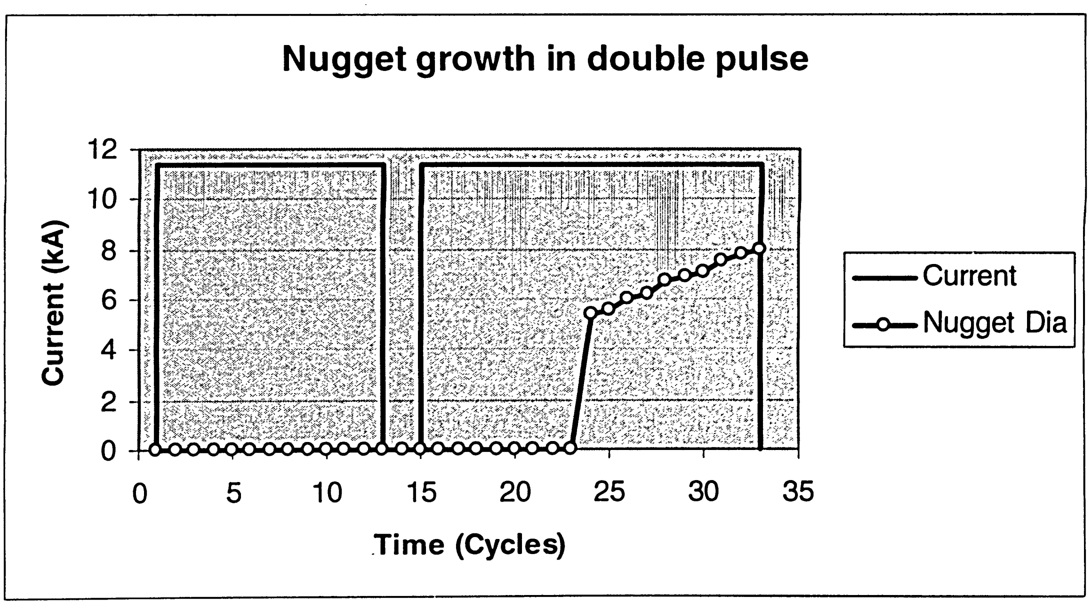


Figure 4.14 Nugget growth in double pulse for DP600 (2.0/2.0 mm)

Observations and Discussion

Observations of the faying surface (figure 4.15) showed that after 13 cycles, all the zinc was removed. The nugget growth in double pulse was slower than that in single pulse. Minimum nugget (i.e. $4\sqrt{t}$) was formed after 26 cycles and expulsion occurred at 33 cycles. Therefore, slower nugget growth is possible if heat input is interrupted by using two hold time cycle. It should be noted that the double pulse schedules leads to longer weld times.

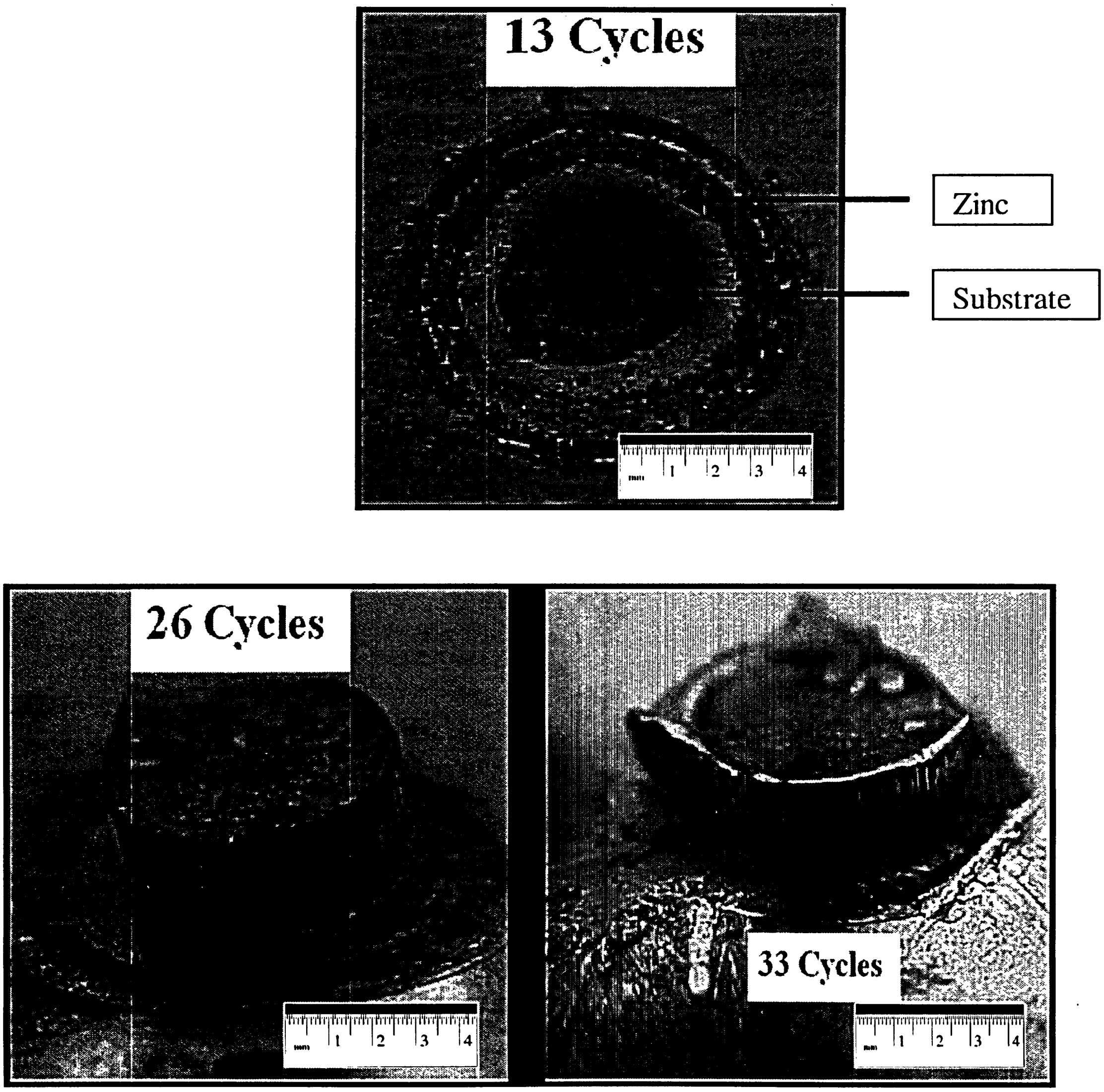


Figure 4.15 Macrograph at 13, 26 and 33 cycles during double pulse welding of DP600

The weld pulse of 13 cycles was selected because it was observed that after 13 cycles all the zinc from the faying interface was removed and the substrate started melting at the faying interface. Thus, it was possible to separate the two stages namely, zinc removal and substrate melting. Therefore the galvanized steel was finally welded after zinc removal, as if there was no zinc at the faying interface.

Multiple pulse welding schedules have received more attention in recent years for welding AHSS. Milititsky et al.[9] showed that acceptable welding ranges can be achieved with single, double and triple pulse welding schedules with higher electrode force. In fact, triple pulsing can increase weld lobes for DP600. Previous studies[9] have shown that multiple pulsing can enhance the current ranges but the mechanism was not examined in detail. The present work was initiated to understand the mechanisms involved in nugget growth in single and multiple pulse welding. This was followed by the design of an enhanced welding schedule to improve the spot welding performance of DP600 steel.

4.3.3 Designing of enhanced pulse weld schedule for DP600

Table 4.7 shows welding parameters used for conducting nugget growth studies in the enhanced pulse. An enhanced pulse was designing from a double pulse by reducing current on the second pulse. Hold time of 2 cycles was maintained after first 13 cycles. Once conductive layer of zinc was removed, current on the second pulse was reduced to decrease heat input and slow down nugget growth. A welding current just prior to expulsion i.e. 11.4 kA was used. Figure 4.16 shows the enhanced welding pulse. The reduced current on the second pulse was adjusted to take care of the extremely fast nugget growth. Figure 4.17 shows the nugget growth for two different designs of enhanced welding pulse.

Table 4.7 Welding parameters used for nugget growth studies in enhanced pulse

Sheet Thickness (mm)	Electrode			Hold Time (cy)	Welding Rate (welds/Min)
	Dressed face Dia. (mm)	Force (kN)	Cooling (l/mm)		
2.0	8.0	6.6	6.0	10	15

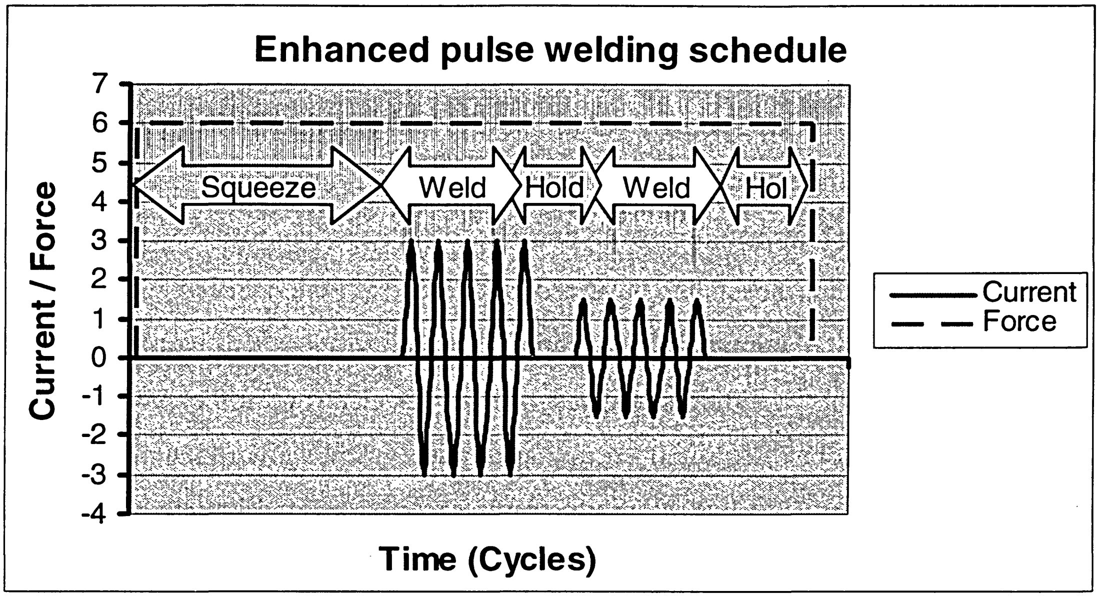


Figure 4.16 Enhanced welding pulse graphical presentation

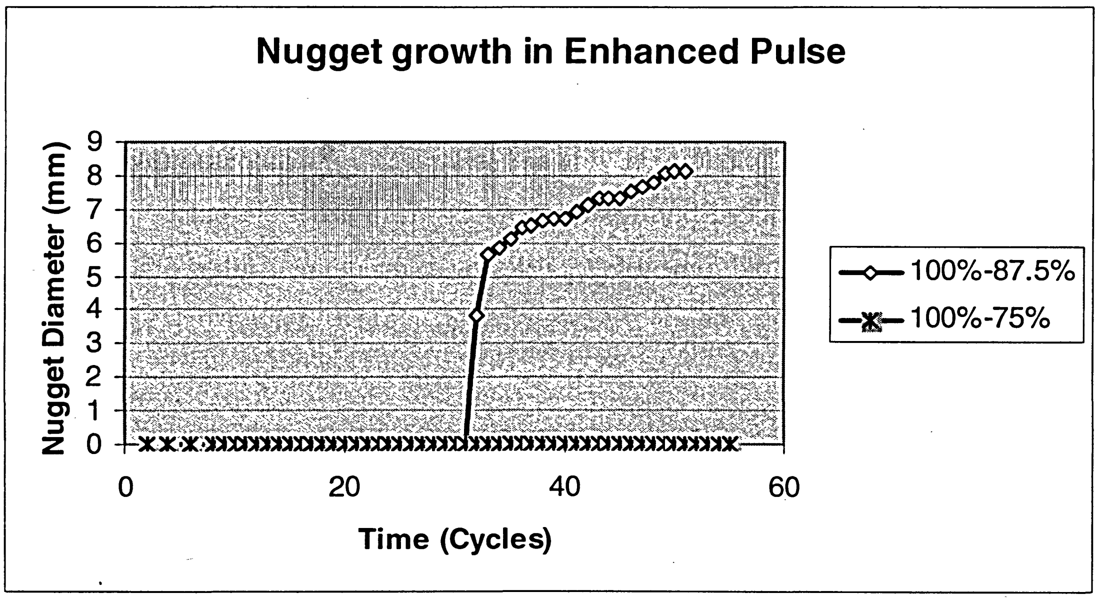


Figure 4.17 Nugget growth in Enhanced Pulse Design

Observations and discussion

It was crucial to find the amount of current on the second pulse with respect to the first pulse. A series of experiments were conducted with different current values for the second pulse (with respect to the first pulse). Figure 4.17 shows the nugget growth for two different designs of enhanced welding pulse. The first series shows enhanced pulse with the second pulse current at 87.5% of the first pulse (Referred to as 100%-87.5%). The second series shows current pattern of 100%-75%. Once the conductive zinc layer is removed and substrate starts melting (13 cycles), the current can be reduced to avoid expulsion. This will shift the maximum nugget line farther to the right on the weld lobe diagram. Thus a wide current range can be achieved for AHSS. The enhanced pulse is designed to generate a favorable heat generation pattern for materials like DP600 which have higher electrical bulk resistivity. Figure 4.18 shows the comparison of nugget growths in single, double and enhanced pulse design. The 100%-87.5% weld pulse design was found to give better results than the single pulse. Nugget growth was slowest and nugget diameters were well above maximum nugget diameters (i.e. 8.0 mm). The 100%-75% weld pulse did not form nugget even after 50 cycles. It was found that 75% current on the second pulse could not generate sufficient heat to melt the substrate to form a nugget. The 100%-87.5% enhanced pulse showed slower nugget growth and results in bigger nugget diameter, although higher amounts of current are necessary with the enhanced pulse to achieve weld in shorter welding time.

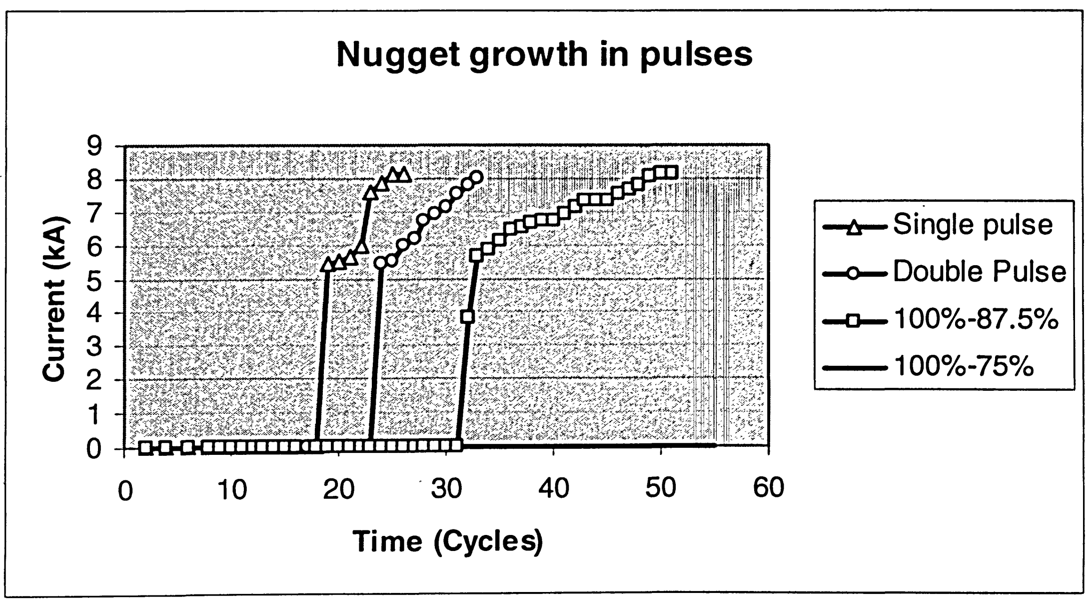


Figure 4.18 Nugget growth curves for single, double and enhanced pulse

4.4 WELD LOBES FOR DP600 WITH ENHANCED PULSE WELD SCHEDULE

Figure 4.19 shows lobes at 26 cycles for DP600. Figure 4.20 compares the lobe width with single and enhanced pulse.

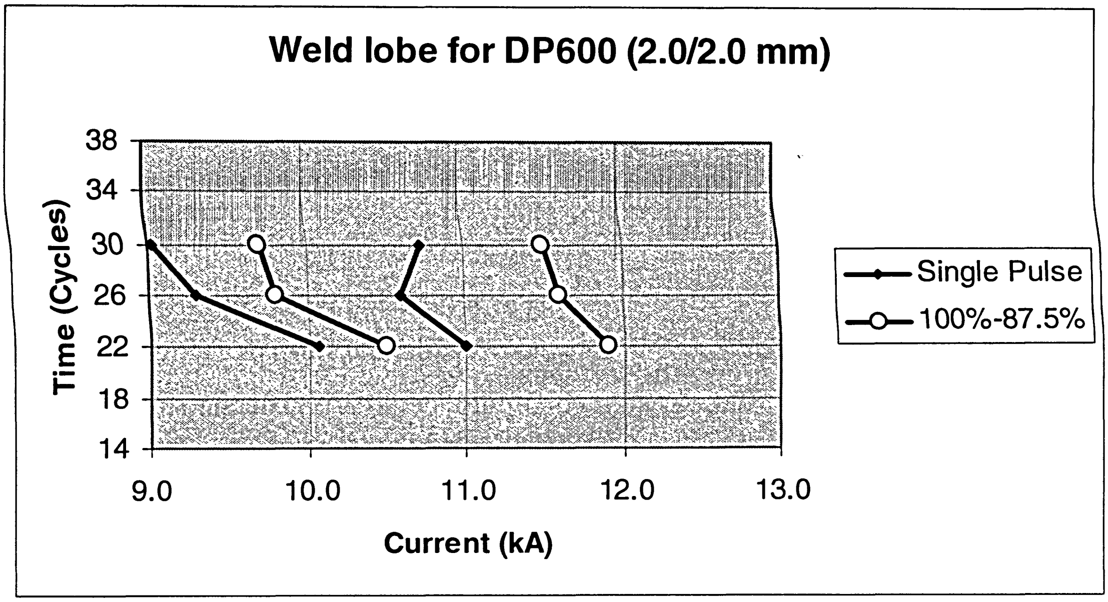


Figure 4.19 Weld lobe width with single pulse and enhanced schedule for DP600

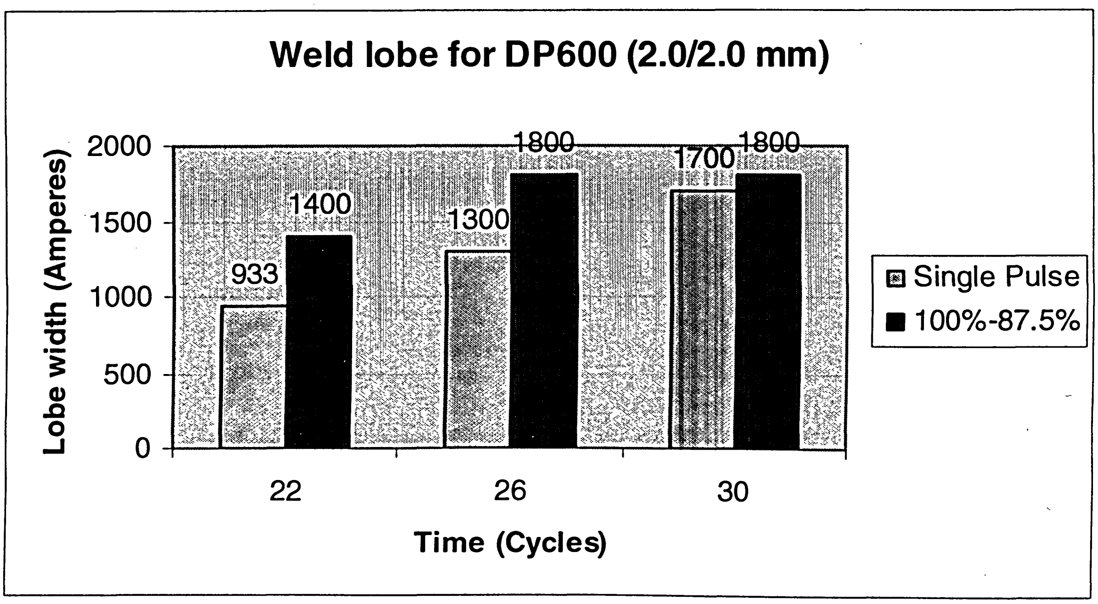


Figure 4.20 Lobe widths with single and enhanced schedule for DP600

Observations and discussion:

Welding trials on DP steel showed that there was a significant increase in the width of the lobe with the enhanced welding pulse. It can be seen that lobes with the enhanced schedules lie at higher current than lobes with single pulse. Expulsion line is shifted more towards the higher current than the minimum nugget line. In the enhanced pulse the current on the second pulse was reduced. This reduced current may have been contributed for the shift of maximum nugget line to the right. The overall result of the enhanced pulse was increased lobe width, which can be seen in figure 4.20. Considerable increase in the lobe widths was achieved at 22 cycles and 26 cycles. At 26 cycles, the enhanced pulse showed a 38% increase in the lobe width over the single pulse. Peterson[37] suggested complex welding schedule for spot welding AHSS (section 2.6.1 and figure 2.22). These schedules involve complex integration of weld and force actions during a spot welding operation. Welding machine with microcontroller and servo controlled electrode force application systems are necessary to implement these schedules. Servo controlled force application system (Servo gun) is the force application system which can vary force in each individual weld cycle (1 cycle = 1/60 second for 60 Hz frequency). Lalam and Agashe[29] suggested use of DC power source to weld DP600 steels. The enhanced schedule proposed here is simpler than complex welding schedules. These schedules can be implemented with the simple, single phase AC welding machine with pneumatic force application system which is less expensive and popular among the steel fabricators.

4.5 WELD LOBES FOR DP600 AND 350 HSLA JOINTS

Spot welding trials on the first material combination (i..e 2.0 mm DP600 welded to itself) showed that enhanced pulse resulted in the increased lobe widths. The enhanced weld schedule, with 87.5% lower current on the second pulse showed the best results. The enhanced weld schedule was used for spot welding second material combination i.e. 2.0 mm DP600 welded to same thickness 350 HSLA.

4.5.1 Weld lobes for DP600 and 350 HSLA joints with enhanced pulse weld schedule

Table 4.8 shows welding parameters used for plotting lobes. Figure 4.21 shows lobes with the single and enhanced welding pulse for the DP600 to 350 HSLA joints.

Table 4.8 Welding parameters used for DP to HSLA welds

Sheet Thickness (mm)	Electrode			Weld Time (cy)	Hold Time (cy)	Welding Rate (welds/Min)
	Dressed face Dia. (mm)	Force (kN)	Cooling (l/mm)			
2.0	8.0	5.5	6.0	22 & 26	10	15

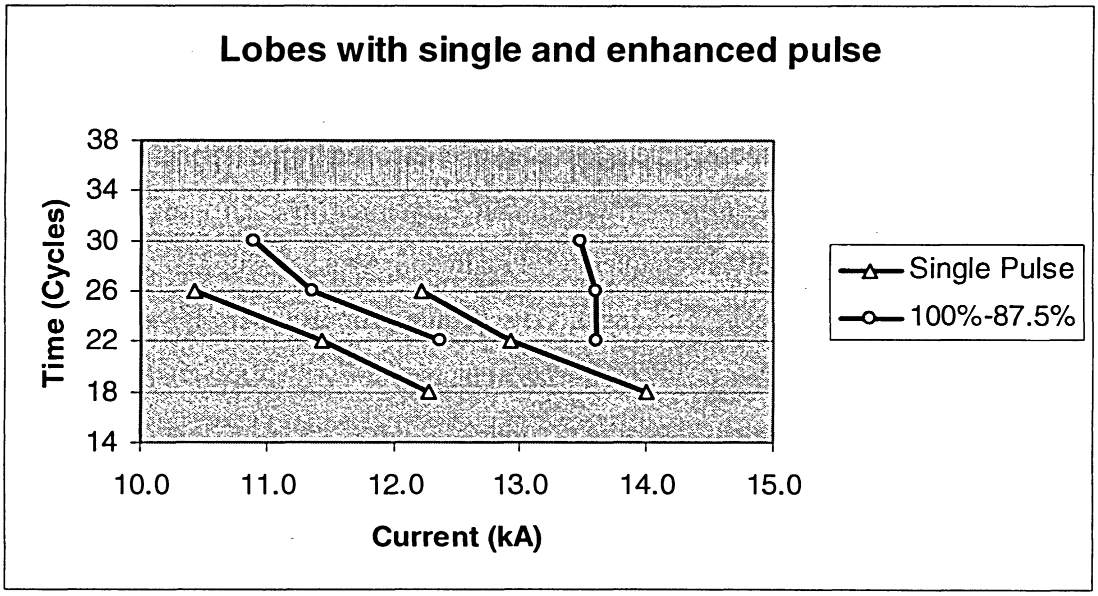


Figure 4.21 Lobes for 2.0 mm DP600 welded to 2.0 mm grade 350 HSLA

Figure 4.22 shows comparison of lobe widths with single and enhanced pulses. Table 4.9 show nugget diameters and lobe widths for these combinations.

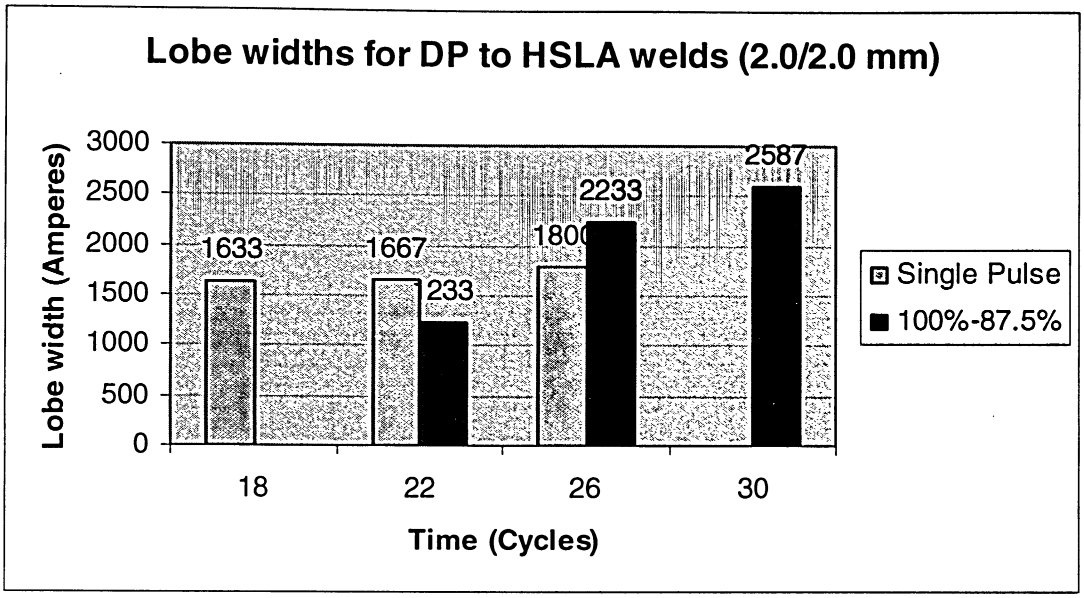


Figure 4.22 Lobe widths (2.0 mm DP600 welded to 2.0 mm 350 HSLA)

Table 4.9 Lobe widths and nugget diameters with enhanced and single pulse schedule for DP600 and 350 HSLA joints (2.0/2.0 mm)

Time (cycles)	Enhanced Pulse		Single Pulse	
	Nugget Dia.	Lobe width	Nugget Dia.	Lobe width
18	---	------	7.22	1633
22	7.08	1233	7.80	1667
26	7.90	2233	8.01	1800
30	8.32	2587	----	------

Observation and discussions

The enhanced pulse schedule resulted in larger lobe widths than the single pulse schedule. The enhanced pulse is located at higher currents than that with single pulse (figure 4.21). For enhanced welding pulse lobe width increases with the welding time. A comparison of weld lobes with single and enhanced pulses can be seen in figure 4.22. Acceptable lobe widths (>2000 amps) can be achieved with the enhanced welding pulse at higher welding times.

Enhanced welding pulse works better at higher welding times. For example at a welding time of 26 cycles, the enhanced welding pulse showed a 24% increase in the lobe width over the single pulse. However at the welding time of 22 cycles, enhanced pulse showed lower lobe widths than single pulse. This might be due to the higher weld currents used on comparatively shorter weld pulses of 11 cycles in the enhanced pulse (11/2/11).

4.6 SPOT WELDING OF UNEQUAL THICKNESS JOINTS

Resistance welder manufacturer's Association (RWMA) and many other standards suggest welding schedules for welding equal thickness sheets. There is less data available on schedules for spot welding unequal thickness and chemistry sheet combinations. An attempt was done by Agashe and Zhang[36]. They suggested selection of welding schedules based on heat balance. Their theory takes into account the heat input into the fusion zone, HAZ and indentation. They used basic proportionality equations to reflect their contributions in welding and predicted the welding parameters. This approach is difficult to implement in a production environment as knowledge of all thermodynamic constants of the sheets is necessary for finalizing the weld schedule. Milititsky et al.[9] suggested a more practical approach with the modification in the electrode tip design. The present work involved welding trials using Milititsky's tip design approach.

4.6.1 Selection of electrode tip design

Figure 4.23 (A) shows the tip design concept suggested by Milititsky et al.[9]. With this tip design concept, heat can be concentrated at the faying interface where maximum heat should be generated. With the approach showed in Figure B, heat is concentrated in the thicker sheet rather than at the interface. Howe[10] showed that design 4.23 (B) results in shifting of nugget towards the thicker sheet. In the present work lobes were established with the design (A) approach. Table 4.10 Shows electrode tip design used for establishing lobes.

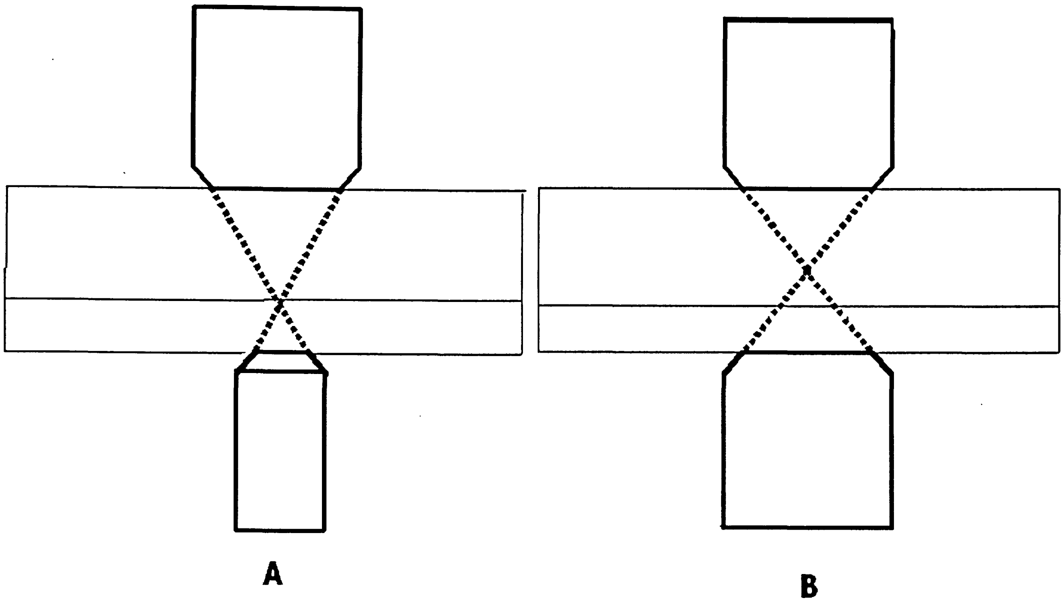


Figure 4.23 Schematic of weld tip design

Table 4.10: Electrode face for spot welding DP600 and EDDQ joints (2.0/0.7 mm)

Material-A	Tip Diameter on side A	Material-B	Tip diameter on side B
DP600	8.0 mm	0.7 mm EDDQ	5.0 mm

4.6.2 Selection of welding parameters

When thick sheet is spot welded to thin sheet, it is recommended that weld schedules and button failure criterion recommend for thinner sheet should be followed. Table 4.11 shows the welding parameters used for establishing the lobes.

Table 4.11 Welding parameters for DP600 and EDDQ joints (2.0/0.7 mm)

Sheet Thicknes s (mm)	Electrode			Weld Time (cycles)	Short Hold Time (cycles)	Welding Rate (w/Min)
	Dressed face Dia. (mm)	Force (kN)	Cooling (l/mm)			
2.0 to 0.7	8.0 & 5.0	2.0	4.0	16,18	5	15

4.6.3 Weld lobes for DP and EDDQ joints (2.0 /0.7 mm)

Preliminary experiments were conducted with the double and enhanced weld schedule. The results were not encouraging. Earlier work[9] suggested that triple pulsing can result in increased lobe widths for spot welding unequal thickness DP steel to itself. No data was available for the DP to EDDQ unequal thickness joints. Triple pulse was designed for the given material combination. The suggested weld time for 0.7 mm mild steels was 11 cycles. Results of the first two combinations of the present work showed that higher weld time give better weld lobes. Therefore weld lobes were plotted at 16 cycles. In an attempt to get increased lobe width weld pulse with three pulses were designed. Weld time of 15 cycles was divided into 3 weld pulses of 5 cycles with 2 cycles hold time between pulses. In the present report this pulse is abbreviated as 5/2/5/2/5 i.e. 2 cool time cycles between three pulses of 5 cycles. Figure 4.24 shows representation of triple pulse. Table 4.12 shows weld schedule for triple pulse. Figure 4.25 shows weld lobes with single and triple pulse.

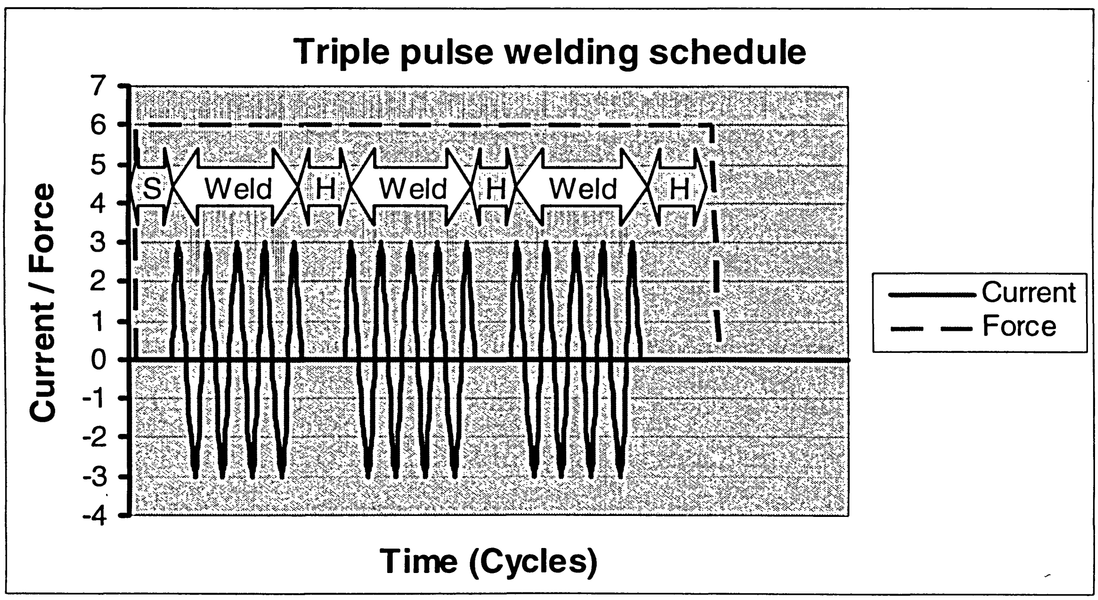


Figure 4.24 Triple pulse graphical presentations (S = squeeze, H= Hold)

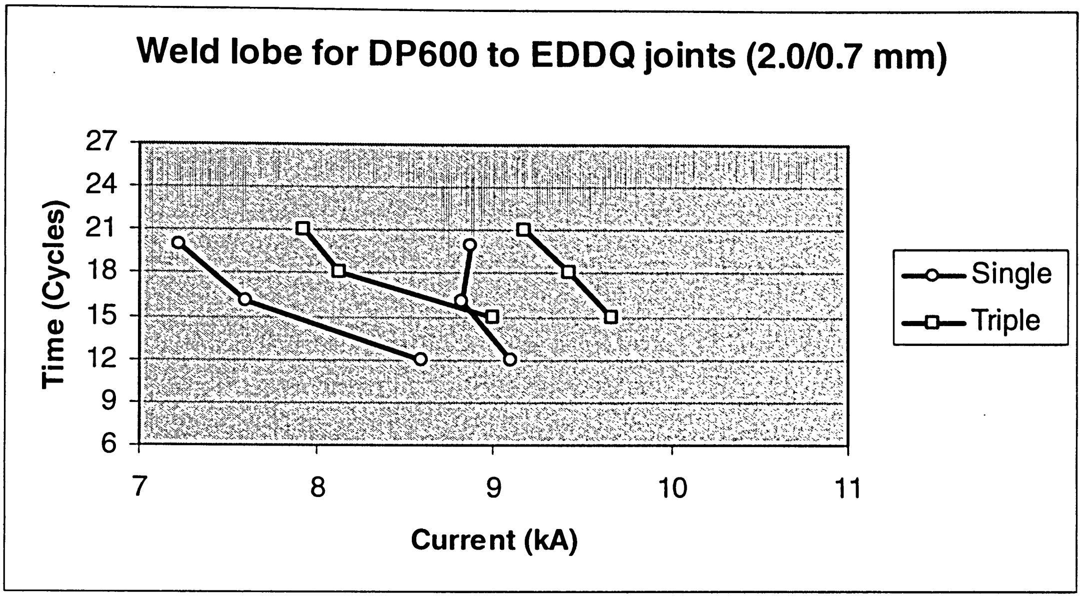


Figure 4.25 Lobes for DP600 to EDDQ joints (2.0/0.7 mm)

Table 4.12 Welding parameters for DP600 and EDDQ joints (2.0/0.7 mm)

Total Weld Time (Cycles)	Triple Pulse Schedule
15	5/2/5/2/5
18	6/2/6/2/6
21	7/2/7/2/7

Observation and discussion

It was found that lobe width increases with the weld time (Figure 4.26) for both single and triple pulse. Lobes with single pulse show wide current ranges than that with the triple pulse. Triple pulse weld schedules result in irregular nugget shapes as shown in Figure 4.27. The short welding pulse and more interruptions among the weld pulse resulted in the irregular shape nuggets. Measurement of irregular shape nugget is explained in Figure 3.16. Due to irregularity in shape the average diameter of nuggets were smaller. This affected maximum and minimum nugget line on the lobe diagram. The maximum and minimum nugget lines on the lobe shifted towards left and right respectively due to the irregularity of the nugget shape.

The interrupted heat input in triple pulse might not be able to generate the required heat to form a solid round button as in single pulse. The peel test showed button pull out failure for both single and triple pulse.

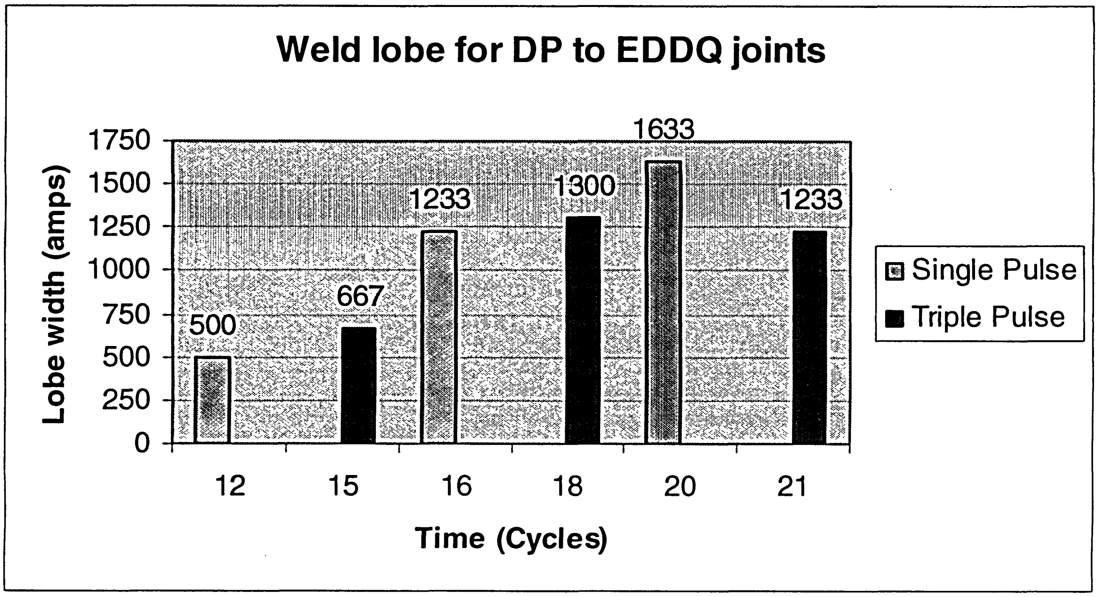


Figure 4.26 Comparison of lobe widths for DP and EDDQ joints

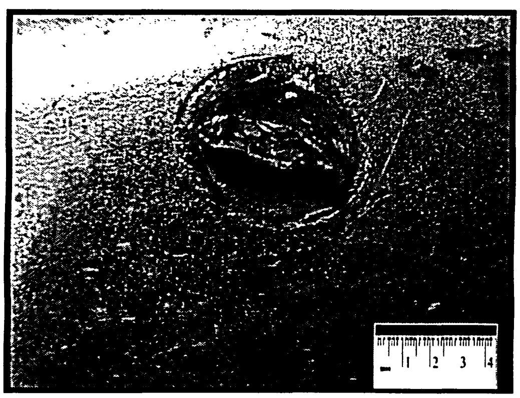


Figure 4.27 Macrograph of irregular nugget with triple pulse

CHAPTER 5

CONCLUSIONS

Large weld lobes for given material combinations were achieved. The nugget growth study carried out in this work resulted in designing an enhanced weld schedule. Lobes plotted with this enhanced weld schedule resulted in robust (large) weld lobes. The enhanced schedule proposed here is less complex, and can be implemented with single phase AC spot welding machines. Conclusions for each material combination are discussed below

A) 2.0 MM DP 600 SPOT-WELDED TO 2.0 MM DP600

Among various welding parameters, weld time had a significant effect on the nugget diameter and lobe width. Higher weld times show bigger nugget diameters and larger lobe widths. A maximum lobe width of 2300 Amperes was observed (at 34 cycles) with the single pulse schedule. At a higher weld time, a larger nugget was formed due to heating and melting of entire cross sectional area (of sheets) between the two electrodes. At a lower welding time, due to the restricted time and higher current, the nugget could not grow to the maximum size, showing premature failure.

Lobes established with the single pulse schedule were larger than those established with the upsloping schedule. The maximum lobe width with the upsloping schedule was 750 Amperes while for the single pulse it was 2300 Amperes. Upsloping weld schedules could not achieve maximum nugget diameter. Upsloping weld schedules lie to the left of the single pulse weld schedule because single pulse schedules need more current to form acceptable welds than the upsloping schedule.

In the case of this combination, the single pulse weld schedule showed faster nugget growth after nugget formation. One of the reasons for faster nugget growth might be higher bulk resistivity of DP600. Higher bulk resistivity leads to higher heat generation, and control over this heat is necessary to avoid expulsion. Excessive heat input in DP600 was controlled by interrupting the weld pulse with two hold time cycles. Thus, the single pulse was divided into two pulses. In the double pulse weld schedule, the first pulse removed the zinc and the second pulse slowed down the nugget growth. Further, an effective control over the heat input was achieved with the help of an enhanced weld schedule. In this enhanced weld schedule (100%-87.5%) the first pulse removed zinc and the second pulse controlled the nugget growth. The lobes plotted with this enhanced weld schedule showed considerable increase in the lobe width over the single pulse schedule (e.g. 38% at 26 cycles, considering the mean values of I_{min} and I_{max}).

B) 2.0 MM DP600 SPOT WELDED TO 2.0 MM HSLA

Weld lobes with enhanced schedules and single pulse schedules were compared. The enhanced weld schedule (100%-87.5%) resulted in larger (>2000 amps) lobes for this combination. A considerable increase in the lobe width was achieved with the enhanced weld schedule over the single pulse schedule (e.g. 24% at 26 cycles, considering the mean values of I_{min} and I_{max}).

C) 2.0 MM DP600 SPOT WELDED TO 0.7 MM EDDQ

Unequal thickness steel sheets were spot welded with the tip design based on heat balance. Enhanced pulse (100%-87.5%) showed irregular nugget failure for this combination, therefore it is not recommended. Larger lobe widths were achieved with the single pulse than those with the triple pulse. The triple pulse was not beneficial for spot welding DP to EDDQ combinations. This is because the triple pulse could not generate the necessary heat due to short weld pulses and interruptions between the two pulses. As a result irregular shape nugget diameters were observed with the triple pulse. Therefore triple pulse weld schedules are not recommended for spot welding the present combination.

5.1 RECOMMENDATIONS AND FUTURE WORK

Some possible areas for future work include:

- Comparison of the mechanical properties (tensile shear, cross tension) of nuggets welded with enhanced pulse and single pulse schedules.
- Comparison of the fatigue performance of spot welds with various pulses (single, double and enhanced)
- Metallography of weld nuggets with various weld pulses to evaluate the microstructure present with various pulses.
- Determination of the optimum level of the second pulse in the enhanced pulse schedule, rather than the 87.5% current on the second pulse used in the present work.

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APPENDIX-A

Table A.1 Welding parameters [18]

Sheet Thickness (mm)	Electrode				Weld Time cycles	Short Hold Time cycles	Long Hold Time cycles	Welding Rate (w/Min)
	Type no	Dressed face Diameter. (mm)	Force (kN)	Cooling (l/mm)				
0.60-0.69	1	4.5	1.6	4.0	10	5	90	25
0.70-0.79	2	5.0	2.0	4.0	11	5	90	25
0.80-0.89	2	5.0	2.2	4.0	12	5	90	25
0.90-1.09	3	6.0	2.8	4.0	13	5	90	20
1.10-1.29	3	6.0	3.1	4.0	14	5	90	20
1.30-1.49	4	7.0	3.8	6.0	16	10	90	15
1.50-1.69	4	7.0	4.2	6.0	18	10	90	15
1.70-1.89	5	8.0	5.0	6.0	20	10	90	15
1.90-2.09	5	8.0	5.5	6.0	22	10	90	15
2.10-2.49	6	9.0	6.4	6.0	30	10	90	15
2.50-3.00	6	9.0	7.0	6.0	40	10	90	15

APPENDIX-B

Table B.1 Weld lobe data for DP600 to DP600 joints (2.0/2.0 mm) at 22 cycles with single pulse weld schedules.

Time	Minimum Current (kA)			Expulsion Current (kA)			Avg. Min	Avg. Exp	Range
(Cycles)	L1	L2	L3	L1	L2	L3	(kA)	(kA)	(A)
26	10.00	10.10	10.40	11.20	11.00	11.10	10.17	11.10	933
22	10.80	10.70	10.50	11.20	11.30	11.30	10.67	11.27	600
18	11.30	11.60	11.60	12.00	12.30	11.90	11.50	12.07	567

Lobe #	Time Cycles	Diameter (mm)			Current (kA)	Weld Order
		Min	Max	Mean		
1	26	0.00	0.00	0.00	7.60	2
1	26	0.00	0.00	0.00	8.60	4
1	26	0.00	0.00	0.00	8.90	6
1	26	3.25	4.21	3.73	9.20	8
1	26	3.37	3.70	3.54	9.30	10
1	26	0.00	0.00	0.00	9.70	12
1	26	3.02	4.15	3.59	9.80	14
1	26	4.03	5.24	4.64	9.90	16
1	26	5.62	5.74	5.68	9.80	18
1	26	4.91	5.53	5.22	10.00	20
1	26	5.71	6.33	6.02	10.00	22
1	26	6.00	6.30	6.15	10.40	24
1	22	0.00	0.00	0.00	10.40	26
1	26	5.71	6.23	5.97	10.50	28
1	22	0.00	0.00	0.00	10.60	30
1	22	0.00	0.00	0.00	10.70	32
1	26	5.70	6.45	6.08	10.60	34
1	26	6.75	7.47	7.11	10.80	36
1	22	4.94	6.80	5.87	10.90	38
1	22	6.39	7.26	6.83	10.80	40
1	26	7.43	7.62	7.53	10.80	42
1	18	0.00	0.00	0.00	11.00	44
1	26	7.59	7.88	7.74	10.90	46
1	22	6.05	7.72	6.89	10.80	48
1	18	0.00	0.00	0.00	10.90	50
1	26	7.71	7.87	7.79	11.10	52
1	22	7.10	7.56	7.33	11.20	54
1	18	0.00	0.00	0.00	11.00	56
1	18	0.00	0.00	0.00	11.30	58
1	26	7.01	7.52	7.27	11.10	60
1	22	7.29	7.53	7.41	11.10	62
1	26	7.76	8.05	7.91	11.20	64
1	22	7.45	7.83	7.64	11.20	66

Lobe #	Time Cycles	Diameter (mm)			Current (kA)	Weld Order
		Min	Max	Mean		
1	18	4.85	6.51	5.68	11.20	68
1	18	4.45	4.63	4.54	11.60	70
1	18	6.52	7.75	7.14	11.30	72
1	18	6.27	7.94	7.11	11.60	74
1	18	6.80	7.75	7.28	11.90	76
1	18	7.60	8.24	7.92	11.90	78
1	18	7.71	8.25	7.98	12.00	80
2	26	0.00	0.00	0.00	8.90	82
2	26	0.00	0.00	0.00	9.10	84
2	26	1.56	2.59	2.08	9.20	86
2	26	4.56	4.72	4.64	9.40	88
2	26	4.39	7.25	5.82	9.50	90
2	26	4.30	4.90	4.60	9.70	92
2	26	4.52	5.28	4.90	9.80	94
2	26	5.07	5.91	5.49	9.90	96
2	26	5.37	5.69	5.53	10.00	98
2	26	5.66	6.42	6.04	10.10	100
2	26	6.97	7.75	7.36	10.20	102
2	22	4.41	4.75	4.58	10.20	104
2	26	6.98	7.63	7.31	10.30	106
2	22	4.07	7.33	5.70	10.40	108
2	26	5.83	6.34	6.09	10.60	110
2	18	0.00	0.00	0.00	10.60	112
2	22	4.87	5.79	5.33	10.60	114
2	22	6.23	7.59	6.91	10.70	116
2	18	0.00	0.00	0.00	10.80	118
2	26	6.93	7.86	7.40	10.70	120
2	22	6.85	7.88	7.37	10.90	122
2	26	6.53	7.81	7.17	10.80	124
2	18	4.17	5.14	4.66	10.70	126
2	26	7.05	7.82	7.44	10.90	128
2	22	5.67	6.38	6.03	11.00	130
2	18	0.00	0.00	0.00	11.00	132
2	18	0.00	0.00	0.00	11.20	134
2	22	5.22	6.34	5.78	11.10	136
2	26	7.34	8.38	7.86	11.00	138
2	22	7.35	8.12	7.74	11.20	140
2	18	4.54	4.92	4.73	11.30	142
2	22	7.49	8.63	8.06	11.30	144
2	18	6.45	7.18	6.82	11.30	146
2	18	4.60	6.21	5.41	11.40	148
2	18	5.12	6.14	5.63	11.60	150
2	18	6.06	6.93	6.50	11.60	152
2	18	6.35	7.99	7.17	11.80	154
2	18	6.46	6.60	6.53	11.80	156

Lobe #	Time Cycles	Diameter (mm)			Current (kA)	Weld Order
		Min	Max	Mean		
2	18	6.64	7.82	7.23	12.00	158
2	18	6.56	8.48	7.52	12.20	160
2	18	5.88	7.33	6.61	12.30	162
3	26	4.51	5.26	4.89	9.70	164
3	26	4.78	7.85	6.32	9.70	166
3	26	3.74	4.36	4.05	10.10	168
3	26	4.61	5.54	5.08	10.20	170
3	26	4.63	5.25	4.94	10.30	172
3	26	5.23	5.99	5.61	10.30	174
3	26	5.43	6.84	6.14	10.50	176
3	26	6.60	6.68	6.64	10.40	178
3	26	6.78	7.95	7.37	10.60	180
3	22	5.11	6.22	5.67	10.50	182
3	18	0.00	0.00	0.00	10.80	184
3	26	7.45	7.80	7.63	10.70	186
3	22	5.78	6.43	6.11	10.60	188
3	18	0.00	0.00	0.00	10.80	190
3	26	6.38	7.86	7.12	10.80	192
3	22	5.42	6.41	5.92	10.90	194
3	22	7.06	7.54	7.30	10.90	196
3	18	4.27	5.29	4.78	10.80	198
3	26	7.19	7.33	7.26	10.80	200
3	22	6.83	8.09	7.46	11.00	202
3	18	0.00	0.00	0.00	11.10	204
3	26	7.29	7.62	7.46	11.10	206
3	22	7.43	8.45	7.94	11.10	208
3	18	4.12	4.97	4.55	11.20	210
3	18	4.50	5.04	4.77	11.40	212
3	22	6.76	7.92	7.34	11.30	214
3	18	5.30	6.79	6.05	11.20	216
3	18	4.66	6.14	5.40	11.40	218
3	18	4.52	6.30	5.41	11.30	220
3	18	6.10	7.12	6.61	11.60	222
3	18	5.90	7.62	6.76	11.70	224
3	18	5.78	6.58	6.18	11.90	226
3	18	6.57	6.93	6.75	11.90	228

Table B.2 Weld lobe data for DP600 to DP600 joints (2.0/2.0 mm) at 26 cycles with single pulse weld schedule.

Time (Cycles)	Minimum Current (kA)			Expulsion Current (kA)			Min. Avg (kA)	Exp. Avg (kA)	Range (A)
	L1	L2	L3	L1	L2	L3			
30	9.50	9.10	8.50	11.30	10.70	10.20	9.03	10.73	1700
26	9.80	9.40	8.70	11.30	10.60	9.90	9.30	10.60	1300
22	10.40	9.80	10.00	11.20	10.80	11.00	10.07	11.00	933

Lobe #	Time Cycles	Diameter (mm)			Current (kA)	Weld Order
		Min	Max	Mean		
1	30	0.00	0.00	0.00	8.50	2
1	30	3.32	3.72	3.52	8.80	4
1	30	0.00	0.00	0.00	8.80	6
1	30	0.00	0.00	0.00	9.10	8
1	30	4.69	4.90	4.80	9.10	10
1	30	4.47	5.04	4.76	9.20	12
1	30	4.47	5.06	4.77	9.40	14
1	30	5.27	6.24	5.76	9.50	16
1	30	5.79	6.35	6.07	9.60	18
1	30	6.02	6.57	6.30	9.70	20
1	26	0.00	0.00	0.00	9.70	22
1	30	6.48	6.55	6.52	9.80	24
1	26	5.90	5.60	5.75	9.80	26
1	26	5.78	6.47	6.13	10.00	28
1	30	6.26	6.90	6.58	10.00	30
1	22	2.82	4.06	3.44	10.00	32
1	26	4.55	6.08	5.32	10.10	34
1	22	3.54	6.14	4.84	10.00	36
1	30	5.20	6.05	5.63	10.20	38
1	22	5.88	4.15	5.02	10.20	40
1	26	5.64	5.97	5.81	10.20	42
1	30	6.46	6.85	6.66	10.20	44
1	30	6.71	7.06	6.89	10.40	46
1	26	6.50	7.33	6.92	10.30	48
1	22	5.07	5.30	5.19	10.30	50
1	30	6.51	7.20	6.86	10.50	52
1	26	6.42	6.85	6.64	10.50	54
1	22	6.06	6.71	6.39	10.40	56
1	26	6.49	6.52	6.51	10.50	58
1	30	7.21	7.50	7.36	10.50	60
1	22	6.11	6.87	6.49	10.50	62
1	26	6.79	7.10	6.95	10.60	64
1	30	6.80	7.17	6.99	10.60	66
1	22	5.77	6.48	6.13	10.60	68
1	22	6.41	6.90	6.66	10.80	70
1	30	6.86	7.13	7.00	10.80	72

Lobe #	Time Cycles	Diameter (mm)			Current (kA)	Weld Order
		Min	Max	Mean		
1	26	6.90	6.88	6.89	10.90	74
1	30	7.03	7.11	7.07	10.90	76
1	22	6.68	6.77	6.73	11.00	78
1	26	6.78	7.06	6.92	11.00	80
1	26	6.83	7.44	7.14	11.10	82
1	22	6.87	7.54	7.21	11.10	84
1	30	7.10	7.24	7.17	11.10	86
1	22	7.14	7.25	7.20	11.20	88
1	26	7.38	7.65	7.52	11.30	90
1	30	7.62	7.81	7.72	11.30	92
2	30	0.00	0.00	0.00	8.50	94
2	30	0.00	0.00	0.00	8.50	96
2	30	3.79	5.12	4.46	8.70	98
2	30	5.04	5.32	5.18	8.80	100
2	30	5.04	5.16	5.10	8.90	102
2	30	5.41	5.73	5.57	8.90	106
2	30	5.94	6.77	6.36	9.10	108
2	30	6.09	6.76	6.43	9.30	110
2	26	5.20	5.26	5.23	9.40	112
2	30	6.34	6.85	6.60	9.20	114
2	26	5.66	6.56	6.11	9.40	116
2	30	6.01	6.81	6.41	9.40	118
2	30	6.54	6.81	6.68	9.50	119
2	26	5.87	6.62	6.25	9.60	120
2	22	5.45	5.48	5.47	9.70	122
2	30	6.47	6.85	6.66	9.70	124
2	26	5.89	6.65	6.27	9.70	126
2	30	6.09	6.62	6.36	9.80	128
2	22	5.18	5.41	5.30	9.80	130
2	26	6.72	5.88	6.30	9.70	132
2	22	6.02	6.57	6.30	9.80	134
2	30	6.22	6.71	6.47	9.90	136
2	26	5.96	6.73	6.35	9.90	138
2	26	6.34	7.06	6.70	10.00	140
2	30	6.26	6.98	6.62	10.00	142
2	22	6.09	6.62	6.36	10.00	144
2	30	7.06	7.45	7.26	10.10	146
2	26	6.05	6.91	6.48	10.10	148
2	22	6.03	6.60	6.32	10.10	150
2	30	6.81	7.15	6.98	10.30	152
2	22	6.11	6.88	6.50	10.20	154
2	26	6.95	7.04	7.00	10.30	156
2	22	6.23	6.39	6.31	10.40	158
2	26	6.92	7.03	6.98	10.50	160
2	30	6.84	7.06	6.95	10.40	162

Lobe #	Time Cycles	Diameter (mm)			Current (kA)	Weld Order
		Min	Max	Mean		
2	26	6.78	7.05	6.92	10.60	164
2	30	6.61	6.95	6.78	10.70	166
2	22	6.63	6.74	6.69	10.50	168
2	22	6.96	7.03	7.00	10.80	170
3	30	0.00	0.00	0.00	7.70	172
3	30	0.00	0.00	0.00	8.00	174
3	30	0.00	0.00	0.00	7.90	176
3	30	3.38	3.53	3.46	8.00	178
3	30	4.30	4.34	4.32	8.20	180
3	30	4.64	4.87	4.76	8.30	182
3	30	5.94	6.93	6.44	8.40	184
3	30	5.48	5.74	5.61	8.50	186
3	26	4.54	4.94	4.74	8.50	188
3	30	6.08	6.39	6.24	8.50	190
3	26	5.24	6.03	5.64	8.60	192
3	26	6.18	6.22	6.20	8.70	194
3	30	6.09	6.48	6.29	8.70	196
3	26	5.88	6.06	5.97	8.80	198
3	30	6.09	6.46	6.28	8.80	200
3	22	0.00	0.00	0.00	8.90	202
3	22	3.84	4.52	4.18	9.10	204
3	26	6.30	5.73	6.02	9.00	206
3	30	6.18	6.20	6.19	9.00	208
3	22	4.08	4.58	4.33	9.20	210
3	26	6.21	6.69	6.45	9.00	212
3	30	6.34	6.63	6.49	9.20	214
3	30	6.48	6.87	6.68	9.20	216
3	26	5.72	5.96	5.84	9.30	218
3	22	4.27	4.60	4.44	9.40	220
3	30	6.27	6.68	6.48	9.50	222
3	26	5.76	5.83	5.80	9.50	224
3	22	0.00	0.00	0.00	9.60	226
3	22	4.92	4.95	4.94	9.50	228
3	30	6.84	6.87	6.86	9.60	230
3	26	5.53	6.21	5.87	9.60	232
3	26	6.44	6.57	6.51	9.70	234
3	22	4.68	5.09	4.89	9.80	236
3	30	6.74	6.88	6.81	9.70	238
3	22	4.59	5.11	4.85	9.90	240
3	26	6.29	6.56	6.43	9.80	242
3	30	6.87	6.91	6.89	9.80	244
3	22	5.61	5.73	5.67	10.00	246
3	26	6.32	6.59	6.46	9.90	248
3	30	6.52	6.98	6.75	9.80	250
3	22	6.08	6.35	6.22	10.10	252

Lobe #	Time Cycles	Diameter (mm)			Current (kA)	Weld Order
		Min	Max	Mean		
3	30	6.87	7.13	7.00	10.00	254
3	22	6.48	6.50	6.49	10.20	256
3	30	7.17	7.25	7.21	10.20	258
3	22	6.60	6.96	6.78	10.30	260
3	22	6.88	7.04	6.96	10.40	262
3	22	6.69	6.82	6.76	10.60	264
3	22	6.86	7.56	7.21	10.70	266
3	22	6.80	6.94	6.87	10.80	268
3	22	7.06	7.18	7.12	11.00	270

Table B.3 Weld lobe data for DP600 to DP600 joints (2.0/2.0 mm) at 30 cycles with single pulse weld schedule.

Time (Cycles)	Minimum Current (kA)			Expulsion Current (kA)			Min. Avg (kA)	Exp. Avg (kA)	Range (A)
	L1	L2	L3	L1	L2	L3			
34	8.80	8.60	8.80	11.10	11.10	11.30	8.72	11.20	2300
30	9.70	9.30	9.00	11.20	10.80	11.10	9.33	11.03	1700
26	9.50	9.30	9.10	10.70	10.90	11.20	9.30	10.93	1633

Lobe #	Time Cycles	Diameter (mm)			Current (kA)	Weld Order
		Min	Max	Mean		
1	34	0.00	0.00	0.00	8.30	2
1	34	0.00	0.00	0.00	8.50	4
1	34	4.71	4.97	4.84	8.60	6
1	34	5.00	5.04	5.02	8.80	8
1	34	5.13	5.27	5.20	8.90	10
1	34	5.38	5.54	5.46	8.90	12
1	34	5.87	6.19	6.03	8.80	14
1	30	4.41	4.90	4.66	9.20	16
1	30	5.28	5.32	5.30	9.30	18
1	34	5.96	7.39	6.68	9.10	20
1	30	5.80	5.92	5.86	9.30	22
1	34	5.97	6.73	6.35	9.30	24
1	26	0.00	0.00	0.00	9.50	26
1	26	4.75	7.17	5.96	9.50	28
1	34	6.19	7.00	6.60	9.50	30
1	30	5.45	5.57	5.51	9.50	32
1	26	5.22	7.07	6.15	9.80	34
1	34	6.77	7.37	7.07	9.60	36
1	30	5.55	6.06	5.81	9.70	38
1	30	5.69	6.08	5.89	9.70	40
1	26	5.01	7.48	6.25	9.90	42
1	34	7.33	8.19	7.76	9.80	44
1	26	5.32	7.04	6.18	10.10	46
1	34	6.62	6.72	6.67	9.90	48
1	30	5.74	6.03	5.89	10.00	50
1	30	5.88	6.43	6.16	10.10	52
1	26	5.40	7.14	6.27	10.20	54
1	34	7.65	7.78	7.72	10.10	56
1	30	6.75	7.64	7.20	10.10	58
1	26	5.63	6.09	5.86	10.10	60
1	34	7.44	7.78	7.61	10.20	62
1	34	7.51	7.55	7.53	10.20	64
1	26	5.31	6.11	5.71	10.40	66
1	30	7.65	7.69	7.67	10.40	68
1	30	6.56	7.22	6.89	10.30	70
1	26	6.08	6.19	6.14	10.40	72

Lobe #	Time Cycles	Diameter (mm)			Current (kA)	Weld Order
		Min	Max	Mean		
1	34	6.74	6.85	6.80	10.50	74
1	30	7.93	8.03	7.98	10.60	76
1	34	7.22	7.35	7.29	10.60	78
1	26	6.12	7.09	6.61	10.60	80
1	26	7.74	7.64	7.69	10.70	82
1	30	7.16	7.06	7.11	10.70	84
1	34	8.18	8.39	8.29	11.10	86
1	30	6.76	7.02	6.89	10.80	88
1	26	6.90	7.14	7.02	10.70	90
1	30	6.86	7.63	7.25	11.00	92
1	30	8.13	8.22	8.18	11.00	94
1	30	7.83	7.99	7.91	11.20	96
2	34	0.00	0.00	0.00	8.50	98
2	34	0.00	0.00	0.00	8.50	100
2	34	0.00	0.00	0.00	8.70	102
2	34	0.00	0.00	0.00	8.70	104
2	34	4.89	5.20	5.05	8.70	106
2	34	4.97	5.12	5.05	8.80	108
2	34	6.56	6.78	6.67	8.60	110
2	30	4.83	4.94	4.89	8.90	112
2	34	6.11	6.16	6.14	9.10	114
2	30	5.37	5.61	5.49	9.00	116
2	34	6.46	6.63	6.55	9.20	118
2	30	5.29	5.55	5.42	9.20	120
2	30	7.06	7.51	7.29	9.30	122
2	34	7.11	7.23	7.17	9.20	124
2	34	7.12	7.63	7.38	9.40	126
2	30	6.90	7.23	7.07	9.40	128
2	26	6.22	6.88	6.55	9.30	130
2	34	7.73	7.89	7.81	9.40	132
2	26	6.95	7.21	7.08	9.40	134
2	30	6.83	7.21	7.02	9.40	136
2	34	7.36	7.65	7.51	9.50	138
2	26	6.72	7.31	7.02	9.60	140
2	30	6.90	7.25	7.08	9.50	142
2	26	6.79	7.09	6.94	9.70	144
2	30	6.95	7.26	7.11	9.70	146
2	34	7.94	7.99	7.97	9.70	148
2	26	6.88	7.47	7.18	9.80	150
2	34	7.94	8.01	7.98	9.80	152
2	30	7.79	7.85	7.82	9.80	154
2	30	7.61	8.26	7.94	9.90	156
2	26	7.64	7.84	7.74	9.90	158
2	34	7.88	8.10	7.99	10.00	160
2	26	7.32	7.81	7.57	10.10	162

Lobe #	Time Cycles	Diameter (mm)			Current (kA)	Weld Order
		Min	Max	Mean		
2	34	7.93	8.51	8.22	10.10	164
2	30	7.92	8.08	8.00	10.00	166
2	30	7.68	7.87	7.78	10.20	168
2	26	7.57	7.89	7.73	10.20	170
2	34	8.08	8.21	8.15	10.30	172
2	26	7.70	7.96	7.83	10.40	174
2	34	7.95	8.11	8.03	10.40	176
2	30	7.79	8.03	7.91	10.40	178
2	30	7.99	8.41	8.20	10.50	180
2	26	7.05	7.25	7.15	10.50	182
2	34	7.88	8.07	7.98	10.50	184
2	26	7.59	7.85	7.72	10.60	186
2	30	7.96	8.11	8.04	10.80	188
2	34	8.07	8.26	8.17	11.10	190
2	26	8.02	8.15	8.09	10.70	192
2	26	7.98	8.27	8.13	10.90	194
3	34	3.62	4.84	4.23	8.30	196
3	34	0.00	0.00	0.00	8.50	198
3	34	5.65	6.18	5.92	8.60	200
3	30	0.00	0.00	0.00	8.70	202
3	34	4.28	4.41	4.35	8.70	204
3	30	0.00	0.00	0.00	8.80	206
3	30	5.44	6.65	6.05	8.70	208
3	34	5.35	5.82	5.59	8.80	210
3	26	0.00	0.00	0.00	9.10	212
3	30	4.92	5.25	5.09	8.80	214
3	34	6.04	6.24	6.14	8.90	216
3	34	6.70	6.95	6.83	9.00	218
3	30	5.75	6.79	6.27	9.00	220
3	26	0.00	0.00	0.00	9.10	222
3	30	6.28	6.39	6.34	9.10	224
3	34	7.03	7.15	7.09	9.20	226
3	26	5.16	6.23	5.70	9.10	228
3	30	6.05	6.38	6.22	9.30	230
3	34	6.77	7.07	6.92	9.20	232
3	26	5.46	6.38	5.92	9.30	234
3	26	5.47	5.86	5.67	9.50	236
3	34	6.66	7.31	6.99	9.40	238
3	30	6.70	6.97	6.84	9.40	240
3	26	5.94	6.71	6.33	9.60	242
3	30	6.62	6.66	6.64	9.50	244
3	34	7.15	7.37	7.26	9.50	246
3	30	6.56	7.01	6.79	9.70	248
3	34	6.82	7.56	7.19	9.70	250
3	26	6.20	6.71	6.46	9.80	252

Lobe #	Time Cycles	Diameter (mm)			Current (kA)	Weld Order
		Min	Max	Mean		
3	30	6.63	6.74	6.69	9.70	254
3	26	5.69	5.91	5.80	9.90	256
3	34	6.74	6.87	6.81	9.80	258
3	30	6.87	7.60	7.24	9.90	260
3	26	6.78	7.14	6.96	9.80	262
3	34	7.42	7.44	7.43	9.90	264
3	34	7.14	7.51	7.33	10.10	266
3	26	5.28	6.05	5.67	10.20	268
3	30	6.45	6.98	6.72	10.20	270
3	26	5.85	6.31	6.08	10.30	272
3	30	7.48	7.83	7.66	10.30	274
3	34	7.49	7.91	7.70	10.20	276
3	30	7.45	7.80	7.63	10.30	278
3	34	7.39	7.75	7.57	10.30	280
3	26	7.57	7.98	7.78	10.40	282
3	30	7.42	7.66	7.54	10.40	284
3	26	6.61	7.86	7.24	10.60	286
3	34	7.76	7.85	7.81	10.50	288
3	26	7.02	7.85	7.44	10.60	290
3	34	7.80	7.91	7.86	10.60	292
3	30	8.17	8.43	8.30	10.70	294
3	30	7.81	7.93	7.87	10.80	296
3	34	8.19	8.57	8.38	10.80	298
3	26	7.76	7.97	7.87	10.80	300
3	30	7.48	8.31	7.90	10.90	302
3	26	7.25	8.43	7.84	10.90	304
3	34	7.53	8.23	7.88	10.90	306
3	26	7.78	7.87	7.83	10.90	308
3	30	7.68	7.79	7.74	11.10	310
3	34	7.72	8.37	8.05	11.00	312
3	26	7.01	8.20	7.61	11.20	314
3	34	7.20	8.23	7.72	11.30	316

Table B.4 Weld Lobe for DP600 to DP600 joints (2.0/2.0 mm) at 26 cycles with Upsloping schedules.

Time (Cycles)	Minimum Current (kA)			Expulsion Current (kA)			Min. Avg (kA)	Exp. Avg (kA)	Range (A)
	L1	L2	L3	L1	L2	L3			
6+16=22	9.30	8.90	9.50	9.70	9.40	10.40	9.23	9.83	600
6+20=26	8.80	8.90	8.90	9.80	9.40	10.30	8.87	9.97	900
6+26=30	8.90	8.50	8.40	9.50	9.20	9.90	8.60	9.53	933

Note: 6+ 16 represents 6 upsloping weld cycles and 16 weld cycles.

Lobe #	Time Cycles	Diameter (mm)			Current (kA)	Weld Order
		Min	Max	Mean		
1	6+26	0.00	0.00	0.00	7.80	2
1	6+26	0.00	0.00	0.00	8.40	4
1	6+26	4.00	4.36	4.18	8.70	6
1	6+26	4.18	5.05	4.62	8.70	8
1	6+26	5.20	5.64	5.42	8.80	10
1	6+20	0.00	0.00	0.00	8.70	12
1	6+26	5.61	6.30	5.96	8.90	14
1	6+20	3.93	3.99	3.96	8.90	16
1	6+16	3.25	4.22	3.74	8.80	18
1	6+20	5.55	5.95	5.75	8.80	20
1	6+26	6.53	6.86	6.70	9.00	22
1	6+20	5.60	5.78	5.69	9.00	24
1	6+26	7.28	8.29	7.79	9.00	26
1	6+16	0.00	0.00	0.00	9.00	28
1	6+26	6.04	6.33	6.19	9.40	30
1	6+16	4.35	4.82	4.59	9.00	32
1	6+20	5.88	6.41	6.15	9.10	34
1	6+26	7.06	7.80	7.43	9.40	36
1	6+20	6.11	6.26	6.19	9.30	38
1	6+16	4.79	5.43	5.11	9.20	40
1	6+16	4.96	5.66	5.31	9.20	42
1	6+20	6.18	6.22	6.20	9.40	44
1	6+26	6.72	6.91	6.82	9.50	46
1	6+20	6.45	6.77	6.61	9.50	48
1	6+16	6.40	6.42	6.41	9.30	50
1	6+20	7.21	7.77	7.49	9.50	52
1	6+16	6.50	6.62	6.56	9.50	54
1	6+20	6.85	7.10	6.98	9.80	56
1	6+16	7.41	8.13	7.77	9.60	58
1	6+16	6.17	7.20	6.69	9.70	60
2	6+26	0.00	0.00	0.00	8.00	62
2	6+26	5.27	5.55	5.41	8.30	64
2	6+20	0.00	0.00	0.00	8.30	66
2	6+26	4.75	5.32	5.04	8.40	68

Lobe #	Time cycles	Diameter (mm)			Current (kA)	Weld Order
		Min	Max	Mean		
2	6+20	3.77	4.55	4.16	8.30	70
2	6+26	5.90	6.03	5.97	8.50	72
2	6+20	4.14	4.70	4.42	8.40	74
2	6+26	5.56	6.06	5.81	8.50	76
2	6+20	0.00	0.00	0.00	8.60	78
2	6+20	4.68	5.13	4.91	8.70	80
2	6+26	5.78	6.28	6.03	8.70	82
2	6+26	6.21	7.14	6.68	8.80	84
2	6+20	5.25	5.98	5.62	8.70	86
2	6+20	5.51	5.85	5.68	8.90	88
2	6+16	4.30	4.45	4.38	8.80	90
2	6+26	6.22	7.10	6.66	8.90	92
2	6+26	7.46	6.47	6.97	9.10	94
2	6+20	5.97	6.40	6.19	8.90	96
2	6+16	0.00	0.00	0.00	8.90	98
2	6+26	7.23	6.97	7.10	9.20	100
2	6+16	5.61	5.77	5.69	8.90	102
2	6+20	6.13	6.75	6.44	9.10	104
2	6+20	5.96	6.82	6.39	9.20	106
2	6+16	5.84	6.16	6.00	9.00	108
2	6+16	6.39	7.42	6.91	9.10	110
2	6+20	6.67	7.04	6.86	9.40	112
2	6+16	5.10	6.55	5.83	9.40	114
3	6+26	4.88	4.96	4.92	7.90	116
3	6+26	5.24	5.47	5.36	8.00	118
3	6+26	5.64	5.96	5.80	8.20	120
3	6+20	4.76	4.95	4.86	8.00	122
3	6+20	0.00	0.00	0.00	8.30	124
3	6+26	5.40	5.85	5.63	8.20	126
3	6+26	5.72	6.33	6.03	8.40	128
3	6+20	4.59	5.44	5.02	8.30	130
3	6+20	4.59	5.30	4.95	8.40	132
3	6+26	6.04	6.95	6.50	8.50	134
3	6+20	5.92	6.13	6.03	8.50	136
3	6+26	5.86	6.48	6.17	8.70	138
3	6+26	6.54	6.89	6.72	8.70	140
3	6+16	3.82	4.46	4.14	8.60	142
3	6+20	5.27	5.86	5.57	8.70	144
3	6+26	6.12	7.23	6.68	8.90	146
3	6+16	4.24	5.05	4.65	8.70	148
3	6+20	5.67	6.26	5.97	8.90	150
3	6+20	6.02	6.59	6.31	8.80	152
3	6+16	4.47	5.14	4.81	8.90	154
3	6+26	6.67	7.61	7.14	9.10	156
3	6+20	6.24	6.57	6.41	9.20	158

Lobe #	Time cycles	Diameter (mm)			Current (kA)	Weld Order
		Min	Max	Mean		
3	6+26	7.22	7.88	7.55	9.00	160
3	6+16	4.84	5.57	5.21	9.00	162
3	6+16	5.01	5.66	5.34	9.10	164
3	6+26	6.76	7.72	7.24	9.20	166
3	6+20	6.05	6.73	6.39	9.20	168
3	6+16	4.99	6.02	5.51	9.20	170
3	6+20	6.03	7.08	6.56	9.30	172
3	6+26	7.68	7.97	7.83	9.40	174
3	6+20	6.30	7.08	6.69	9.50	176
3	6+16	5.14	5.68	5.41	9.40	178
3	6+26	6.98	8.12	7.55	9.60	180
3	6+16	5.52	6.06	5.79	9.50	182
3	6+20	6.33	6.85	6.59	9.60	184
3	6+26	7.59	8.06	7.83	9.70	186
3	6+26	7.80	7.99	7.90	9.90	188
3	6+16	6.47	5.63	6.05	9.60	190
3	6+20	6.73	7.55	7.14	9.80	192
3	6+26	7.64	7.98	7.81	9.90	194
3	6+16	7.25	7.28	7.27	9.60	196
3	6+20	7.45	8.18	7.82	9.80	198
3	6+20	7.61	7.71	7.66	9.90	200
3	6+16	6.38	6.82	6.60	9.80	202
3	6+16	8.19	8.37	8.28	9.80	204
3	6+20	8.08	8.40	8.24	10.00	206
3	6+20	7.31	7.32	7.32	10.30	207
3	6+16	6.25	7.33	6.79	10.10	208
3	6+16	7.33	7.91	7.62	10.00	210
3	6+16	7.39	8.00	7.70	10.20	212
3	6+16	6.93	7.50	7.22	10.40	214

Table B.5 Weld Lobe for DP600 to 350 HSLA joints (2.0/2.0 mm) at 22 cycles with single pulse schedules.

Weld	Minimum Current (kA)			Expulsion Current (kA)			Min. Avg	Exp. Avg	Range
cycles	L1	L2	L3	L1	L2	L3	(kA)	(kA)	(A)
26	10.50	10.40	10.40	12.60	12.20	11.90	10.43	12.23	1800
22	11.50	11.60	11.20	13.10	12.60	13.10	11.43	12.93	1500
18	12.40	12.10	12.30	14.10	13.30	14.60	12.27	14.00	1733

Lobe #	Time cycles	Diameter (mm)			Current (kA)	Weld Order
		Min	Max	Mean		
1	26	3.43	3.85	3.64	10.30	2
1	26	4.33	4.79	4.56	10.30	4
1	26	4.80	5.68	5.24	10.30	6
1	26	5.43	6.20	5.82	10.50	8
1	22	3.60	4.06	3.83	10.60	10
1	26	5.07	6.24	5.66	10.70	12
1	22	4.46	5.17	4.82	10.50	14
1	22	4.37	5.07	4.72	10.80	16
1	26	6.40	6.52	6.46	10.70	18
1	26	5.99	6.44	6.22	10.80	20
1	22	4.12	5.25	4.69	11.00	22
1	22	3.61	4.65	4.13	11.10	24
1	26	6.65	6.77	6.71	10.90	26
1	26	6.72	7.00	6.86	11.10	28
1	22	4.83	5.35	5.09	11.20	30
1	26	7.13	7.42	7.28	11.20	32
1	22	5.16	5.93	5.55	11.20	34
1	26	7.56	7.66	7.61	11.40	36
1	22	5.57	5.77	5.67	11.50	38
1	22	5.76	6.21	5.99	11.50	40
1	26	7.33	8.11	7.72	11.30	42
1	26	7.22	7.90	7.56	11.50	44
1	22	6.05	6.29	6.17	11.50	46
1	26	7.20	8.03	7.62	11.60	48
1	22	5.88	6.11	6.00	11.70	50
1	18	3.18	3.29	3.24	11.70	52
1	22	6.74	6.75	6.75	11.90	54
1	26	7.55	7.95	7.75	11.90	56
1	22	6.85	6.98	6.92	12.00	58
1	26	8.29	8.32	8.31	12.00	60
1	18	4.72	5.13	4.93	11.90	62
1	26	7.90	8.41	8.16	12.10	64
1	22	6.98	7.20	7.09	12.10	66
1	18	5.33	5.55	5.44	12.00	68
1	18	4.96	5.88	5.42	12.20	70
1	26	8.06	8.58	8.32	12.20	72

Lobe #	Time cycles	Diameter (mm)			Current (kA)	Weld Order
		Min	Max	Mean		
1	22	6.96	7.69	7.32	12.30	74
1	18	5.05	6.54	5.80	12.40	76
1	22	7.48	8.54	8.01	12.40	78
1	26	8.38	8.51	8.45	12.50	80
1	22	7.31	7.94	7.63	12.60	82
1	18	5.38	5.96	5.67	12.60	84
1	26	8.56	5.67	7.12	12.60	86
1	22	7.53	7.77	7.65	12.80	88
1	18	5.65	6.39	6.02	12.80	90
1	18	6.37	6.44	6.41	13.00	92
1	22	7.44	8.11	7.78	12.90	94
1	22	7.73	8.02	7.88	13.10	96
1	18	6.25	6.54	6.40	13.10	98
1	18	5.99	5.56	5.78	13.20	100
1	18	6.39	6.74	6.57	13.30	102
1	18	6.65	6.98	6.82	13.50	104
1	18	6.23	6.35	6.29	13.60	106
1	18	7.00	8.06	7.53	13.80	108
1	18	7.02	7.07	7.05	14.00	110
1	18	6.28	6.77	6.53	14.10	112
2	26	2.64	2.66	2.65	9.80	114
2	26	3.10	3.63	3.37	9.80	116
2	26	3.95	4.43	4.19	9.90	118
2	26	4.23	4.77	4.50	9.90	120
2	26	4.26	5.21	4.74	10.10	122
2	26	4.81	4.00	4.41	10.20	124
2	26	5.77	5.95	5.86	10.40	126
2	26	5.82	5.90	5.86	10.50	128
2	26	6.36	6.57	6.47	10.70	130
2	26	6.85	6.98	6.92	10.80	132
2	26	6.48	6.79	6.64	11.00	134
2	26	6.37	6.38	6.38	11.10	136
2	22	5.25	5.79	5.52	11.30	138
2	26	6.45	6.73	6.59	11.20	140
2	26	7.04	7.53	7.29	11.30	142
2	22	4.39	5.72	5.06	11.40	144
2	26	7.17	7.24	7.21	11.50	146
2	22	5.32	5.34	5.33	11.60	148
2	26	7.37	8.31	7.84	11.60	150
2	22	5.49	5.84	5.67	11.60	152
2	22	6.39	6.67	6.53	11.70	154
2	26	7.38	7.90	7.64	11.70	156
2	26	7.77	7.90	7.84	11.80	158
2	22	6.57	6.80	6.69	11.90	160
2	22	7.20	7.33	7.27	12.00	162

Lobe #	Time cycles	Diameter (mm)			Current (kA)	Weld Order
		Min	Max	Mean		
2	26	8.07	8.53	8.30	12.00	164
2	26	7.29	7.70	7.50	12.20	166
2	18	5.07	5.54	5.31	12.10	168
2	22	6.82	8.44	7.63	11.90	170
2	22	7.11	7.55	7.33	12.20	172
2	18	5.64	6.12	5.88	12.10	174
2	22	7.02	8.61	7.82	12.30	176
2	18	5.72	6.23	5.98	12.30	178
2	22	7.43	7.98	7.71	12.50	180
2	18	6.39	6.99	6.69	12.40	182
2	18	6.38	6.31	6.35	12.60	184
2	22	7.42	8.26	7.84	12.60	186
2	18	5.86	6.39	6.13	12.80	188
2	18	6.54	7.02	6.78	12.90	190
2	18	6.38	6.87	6.63	12.90	192
2	18	5.66	6.69	6.18	13.20	194
2	18	5.26	6.11	5.69	13.30	196
3	26	5.15	5.42	5.29	10.20	198
3	26	5.05	5.19	5.12	10.20	200
3	26	5.65	5.82	5.74	10.40	202
3	26	5.98	6.21	6.10	10.40	204
3	26	5.74	5.95	5.85	10.60	206
3	26	6.33	6.49	6.41	10.60	208
3	26	6.69	7.25	6.97	10.70	210
3	26	6.86	6.90	6.88	10.80	212
3	26	6.73	7.22	6.98	11.00	214
3	22	5.17	5.68	5.43	11.00	216
3	26	7.74	7.79	7.77	11.30	218
3	22	5.75	5.93	5.84	11.20	220
3	26	7.60	7.92	7.76	11.30	222
3	22	6.08	6.39	6.24	11.30	224
3	22	6.45	6.54	6.50	11.40	226
3	26	7.38	7.63	7.51	11.50	228
3	18	3.39	4.73	4.06	11.80	230
3	22	6.18	6.39	6.29	11.70	232
3	26	7.75	7.76	7.76	11.70	234
3	22	6.51	6.54	6.53	11.80	236
3	18	4.49	4.86	4.68	11.80	238
3	26	7.51	7.67	7.59	11.90	240
3	18	4.52	5.06	4.79	12.00	242
3	22	6.36	7.04	6.70	12.00	244
3	22	6.74	7.32	7.03	12.10	246
3	18	5.05	5.81	5.43	12.00	248
3	22	7.66	8.11	7.89	12.10	250
3	18	4.96	5.17	5.07	12.30	252

Lobe #	Time cycles	Diameter (mm)			Current (kA)	Weld Order
		Min	Max	Mean		
2	26	8.07	8.53	8.30	12.00	164
3	22	7.61	7.68	7.65	12.20	254
3	18	5.22	5.65	5.44	12.30	256
3	18	5.98	7.26	6.62	12.30	258
3	22	7.69	8.02	7.86	12.40	260
3	22	7.94	8.22	8.08	12.40	262
3	18	5.30	6.26	5.78	12.50	264
3	18	5.52	6.11	5.82	12.60	266
3	22	7.56	8.11	7.84	12.60	268
3	22	7.28	7.74	7.51	12.70	270
3	18	5.68	5.72	5.70	12.90	272
3	18	5.92	5.46	5.69	13.00	274
3	22	7.75	7.84	7.80	13.10	276
3	18	6.72	7.10	6.91	13.10	278
3	18	6.93	8.15	7.54	13.30	280
3	18	7.11	7.81	7.46	13.60	282
3	18	6.85	8.46	7.66	13.70	284
3	18	7.66	8.40	8.03	13.70	286
3	18	6.83	7.59	7.21	13.90	288
3	18	6.92	8.41	7.67	14.10	290
3	18	7.51	8.49	8.00	14.30	292
3	18	7.64	8.11	7.88	14.60	294

Table B.6 Weld Lobe for DP600 to 350 HSLA joints (2.0/2.0 mm) at 26 (13/2/13) cycles with enhanced pulse schedules.

Weld Time	Minimum current (kA)			Expulsion current (kA)			Min. Avg (kA)	Exp. Avg (kA)	Range (A)
	L1	L2	L3	L1	L2	L3			
15/2/15	10.80	10.80	11.10	13.50	13.70	13.20	10.90	13.47	2567
13/2/13	11.20	11.30	11.60	13.40	13.80	13.60	11.37	13.60	2233
11/2/11	12.10	12.40	12.60	13.50	13.80	13.50	12.37	13.60	1233

Lobe #	Time Cycles	Current kA	Hold Time	Time cycles	Current kA	Diameter (mm)			Weld Order
						Min	Max	Mean	
1	15	10.30	2	15	8.70	3.03	3.42	3.23	2
1	15	10.40	2	15	9.00	4.84	4.85	4.85	4
1	15	10.60	2	15	9.20	5.51	5.59	5.55	6
1	15	10.80	2	15	9.40	6.06	6.10	6.08	8
1	13	10.90	2	13	9.40	5.08	5.52	5.30	10
1	15	11.00	2	15	9.60	6.65	6.78	6.72	12
1	13	11.10	2	13	9.60	4.81	5.30	5.06	14
1	15	11.10	2	15	9.80	6.62	6.80	6.71	16
1	13	11.20	2	13	9.80	5.81	5.82	5.82	18
1	13	11.40	2	13	10.00	6.20	6.39	6.30	20
1	15	11.30	2	15	10.00	6.86	7.00	6.93	22
1	15	11.50	2	15	10.20	6.78	7.76	7.27	24
1	13	11.60	2	13	10.20	6.05	6.44	6.25	26
1	11	11.70	2	11	10.20	4.16	4.60	4.38	28
1	13	11.80	2	13	10.40	6.56	6.96	6.76	30
1	15	11.70	2	15	10.40	7.60	7.60	7.60	32
1	11	11.80	2	11	10.40	4.80	4.49	4.65	34
1	15	11.90	2	15	10.60	6.79	7.93	7.36	36
1	11	11.90	2	11	10.60	4.97	5.19	5.08	38
1	13	11.90	2	13	10.60	6.85	6.97	6.91	40
1	15	12.10	2	15	10.70	6.77	8.10	7.44	42
1	13	12.10	2	13	10.70	7.16	7.38	7.27	44
1	11	12.1	2	11	10.70	5.89	5.7	5.795	46
1	13	12.40	2	13	11.00	7.41	7.54	7.48	48
1	15	12.30	2	15	11.00	8.08	8.16	8.12	50
1	11	12.40	2	11	11.00	6.27	6.72	6.50	54
1	11	12.50	2	11	11.10	6.83	6.95	6.89	56
1	13	12.50	2	13	11.10	7.50	7.60	7.55	58
1	15	12.70	2	15	11.10	7.39	7.80	7.60	60
1	11	12.80	2	11	11.20	6.75	7.22	6.99	62
1	15	12.60	2	15	11.20	7.85	7.99	7.92	64
1	13	12.70	2	13	11.20	7.48	8.04	7.76	66
1	15	12.90	2	15	11.40	6.80	8.13	7.47	68
1	13	12.90	2	13	11.40	6.70	7.82	7.26	70
1	11	13.00	2	11	11.40	6.79	7.01	6.90	72
1	15	12.90	2	15	11.50	7.63	8.17	7.90	74

Lobe #	Time Cycles	Current kA	Hold Time	Time cycles	Current kA	Diameter (mm)			Weld Order
						Min	Max	Mean	
1	13	12.90	2	13	11.50	7.78	7.80	7.79	78
1	15	13.10	2	15	11.60	7.11	8.54	7.83	80
1	13	13.30	2	13	11.60	7.50	7.91	7.71	82
1	11	13.20	2	11	11.60	6.75	7.00	6.88	84
1	15	13.50	2	15	11.80	7.50	8.05	7.78	86
1	11	13.50	2	11	11.80	7.31	7.32	7.32	88
1	13	13.40	2	13	11.80	5.24	6.46	5.85	90
1	11	13.50	2	11	11.90	5.53	6.20	5.87	92
1	15	13.50	2	15	11.90	7.90	7.96	7.93	94
2	15	10.50	2	15	9.00	4.24	5.17	4.71	96
2	15	10.50	2	15	9.20	4.42	5.36	4.89	98
2	15	10.80	2	15	9.40	5.19	6.44	5.82	100
2	15	11.00	2	15	9.60	5.62	7.02	6.32	102
2	13	11.00	2	13	9.60	4.08	5.38	4.73	104
2	15	11.10	2	15	9.80	5.74	7.15	6.45	106
2	13	11.20	2	13	9.80	4.20	6.23	5.22	108
2	13	11.30	2	13	10.00	5.25	6.81	6.03	110
2	15	11.30	2	15	10.00	6.06	7.23	6.65	112
2	13	11.50	2	13	10.20	5.43	7.08	6.26	114
2	15	11.50	2	15	10.20	6.61	7.95	7.28	116
2	15	11.70	2	15	10.50	7.66	8.07	7.87	118
2	13	11.70	2	13	10.50	6.22	7.24	6.73	120
2	13	11.80	2	13	10.50	6.23	7.44	6.84	122
2	15	11.90	2	15	10.50	6.74	8.01	7.38	124
2	13	12.10	2	13	10.60	6.04	7.61	6.83	128
2	11	12.20	2	11	10.60	4.01	6.03	5.02	130
2	11	12.40	2	11	10.70	5.19	6.96	6.08	132
2	15	12.40	2	15	10.70	6.70	8.55	7.63	134
2	13	12.40	2	13	10.70	6.81	8.14	7.48	136
2	15	12.50	2	15	11.00	6.63	8.47	7.55	138
2	11	12.70	2	11	11.00	4.85	6.53	5.69	140
2	13	12.60	2	13	11.00	6.45	7.89	7.17	142
2	11	12.80	2	11	11.20	5.44	7.17	6.31	144
2	13	12.80	2	13	11.20	7.04	8.32	7.68	146
2	15	12.60	2	15	11.20	7.08	8.62	7.85	148
2	13	12.90	2	13	11.30	6.85	8.34	7.60	150
2	15	12.90	2	15	11.30	7.85	9.08	8.47	152
2	11	13.10	2	11	11.30	5.29	7.29	6.29	154
2	15	13.00	2	15	11.40	7.02	8.67	7.85	156
2	11	13.20	2	11	11.40	6.35	7.32	6.84	158
2	13	13.00	2	13	11.40	6.57	8.69	7.63	160
2	15	13.10	2	15	11.50	8.69	8.80	8.75	162
2	11	13.30	2	11	11.50	6.35	7.81	7.08	164
2	13	13.10	2	13	11.50	7.05	8.78	7.92	166

Lobe #	Time Cycles	Current kA	Hold Time	Time cycles	Current kA	Diameter (mm)			Weld Order
						Min	Max	Mean	
2	15	13.40	2	15	11.70	7.31	8.93	8.12	168
2	13	13.50	2	13	11.70	7.21	8.73	7.97	170
2	11	13.50	2	11	11.70	5.32	7.46	6.39	172
2	15	13.70	2	15	11.90	7.16	8.45	7.81	174
2	11	13.70	2	11	11.90	6.88	8.36	7.62	176
2	13	13.60	2	13	11.90	7.35	8.81	8.08	178
2	11	13.80	2	11	12.00	7.00	8.58	7.79	180
2	13	13.80	2	13	12.00	5.65	6.83	6.24	182
2	11	12.80	2	11	12.10	6.73	8.91	7.82	184
3	15	10.50	2	15	9.00	3.34	5.13	4.24	186
3	15	10.60	2	15	9.20	3.05	5.28	4.17	188
3	15	10.80	2	15	9.40	4.14	6.24	5.19	190
3	15	11.10	2	15	9.60	4.77	6.92	5.85	192
3	15	11.20	2	15	9.80	4.98	7.28	6.13	194
3	13	11.20	2	13	9.80	3.10	5.38	4.24	196
3	13	11.30	2	13	10.00	4.02	6.01	5.02	200
3	15	11.70	2	15	10.20	6.27	8.16	7.22	202
3	13	11.60	2	13	10.20	4.41	6.99	5.70	204
3	13	11.70	2	13	10.50	5.23	7.83	6.53	206
3	15	11.70	2	15	10.50	6.64	8.08	7.36	208
3	15	11.90	2	15	10.60	6.43	8.22	7.33	210
3	13	11.90	2	13	10.60	5.32	7.99	6.66	212
3	13	12.10	2	13	10.70	5.57	7.61	6.59	214
3	15	12.10	2	15	10.70	6.77	8.35	7.56	216
3	13	12.40	2	13	11.00	5.86	8.08	6.97	218
3	15	12.40	2	15	11.00	7.01	8.59	7.80	220
3	11	12.50	2	11	11.00	3.93	6.25	5.09	222
3	15	12.50	2	15	11.10	7.03	8.56	7.80	224
3	11	12.60	2	11	11.10	4.50	6.85	5.68	226
3	13	12.50	2	13	11.10	6.63	8.71	7.67	228
3	13	12.90	2	13	11.20	6.65	8.30	7.48	230
3	15	12.70	2	15	11.20	8.15	9.21	8.68	232
3	11	12.90	2	11	11.20	5.20	7.13	6.17	234
3	13	12.90	2	13	11.40	4.50	7.16	5.83	236
3	11	12.80	2	11	11.40	5.06	7.88	6.47	238
3	15	12.90	2	15	11.40	6.72	8.32	7.52	240
3	11	13.00	2	11	11.50	5.58	7.99	6.79	242
3	13	12.90	2	13	11.50	7.12	8.82	7.97	244
3	15	12.90	2	15	11.50	7.43	9.34	8.39	246
3	11	13.10	2	11	11.70	5.33	7.59	6.46	248
3	15	13.20	2	15	11.70	6.88	8.61	7.75	250
3	13	13.10	2	13	11.70	6.96	8.86	7.91	252
3	11	13.40	2	11	11.70	5.22	6.92	6.07	254
3	13	13.60	2	13	11.70	5.76	7.36	6.56	256
3	11	13.50	2	11	11.90	5.26	6.95	6.11	258

Table B.7 **Weld lobe for DP600 to EDDQ joints (2.0/0.7 mm) at 16 cycles with single pulse schedules.**

Time cycles	Minimum current (kA)			Expulsion current (kA)			Min. Avg (kA)	Max. Avg (kA)	Range (A)
	L1	L2	L3	L1	L2	L3			
20	7.10	7.40	7.20	9.20	8.70	8.70	7.23	8.87	1633
16	7.60	7.70	7.50	9.00	9.00	8.50	7.60	8.83	1233
12	8.80	8.50	8.50	9.30	9.10	8.90	8.60	9.10	500

Lobe #	Weld Time	Diameter (mm)			Current (kA)	Weld Order
		Min	Max	Mean		
1	20	0.00	0.00	0.00	7.00	2
1	20	3.30	4.03	3.67	7.10	4
1	20	3.83	5.00	4.42	7.30	6
1	16	2.90	3.85	3.38	7.20	8
1	20	3.27	4.48	3.88	7.30	10
1	16	0.00	0.00	0.00	7.30	12
1	20	3.61	4.66	4.14	7.60	14
1	16	3.05	4.73	3.89	7.60	16
1	12	0.00	0.00	0.00	7.60	18
1	16	3.61	5.61	4.61	7.70	20
1	20	4.41	5.85	5.13	7.70	22
1	12	0.00	0.00	0.00	7.80	24
1	20	4.12	6.10	5.11	7.80	26
1	16	2.77	4.77	3.77	7.90	28
1	20	4.30	6.18	5.24	8.00	30
1	16	3.68	5.67	4.68	7.90	32
1	20	4.42	5.63	5.03	8.10	36
1	16	3.11	5.39	4.25	8.00	38
1	20	5.42	5.73	5.58	8.10	40
1	16	3.90	6.50	5.20	8.10	42
1	12	2.47	4.74	3.61	8.20	44
1	12	3.37	5.28	4.33	8.30	46
1	16	3.83	6.07	4.95	8.40	48
1	20	4.04	6.02	5.03	8.20	50
1	12	2.55	4.35	3.45	8.40	52
1	20	5.53	5.67	5.60	8.50	54
1	16	4.08	5.03	4.56	8.40	56
1	16	5.48	5.63	5.56	8.60	58
1	20	5.55	6.17	5.86	8.60	60
1	12	0.99	1.50	1.25	8.50	62
1	12	3.17	4.53	3.85	8.80	64
1	16	5.35	5.55	5.45	8.70	66
1	20	5.09	5.14	5.12	8.70	68
1	16	5.22	5.65	5.44	8.70	70
1	12	5.08	5.11	5.10	8.80	72
1	20	5.51	6.03	5.77	8.70	74

Lobe #	Weld Time	Diameter (mm)			Current (kA)	Weld Order
		Min	Max	Mean		
1	20	5.78	5.95	5.87	9.10	76
1	12	5.06	5.51	5.29	8.90	78
1	16	5.71	5.80	5.76	8.90	80
1	16	5.49	5.61	5.55	9.00	82
1	20	5.67	5.71	5.69	9.20	84
1	12	5.30	5.49	5.40	9.10	86
1	12	5.35	5.53	5.44	9.00	88
1	12	5.24	5.20	5.22	9.10	90
1	12	5.73	5.76	5.75	9.30	92
2	20	0.00	0.00	0.00	7.20	94
2	20	0.00	0.00	0.00	7.40	96
2	20	3.03	4.42	3.73	7.40	98
2	20	3.28	5.15	4.22	7.50	100
2	20	3.80	4.55	4.18	7.50	102
2	20	4.22	5.15	4.69	7.70	104
2	16	3.61	4.45	4.03	7.70	106
2	20	3.79	5.12	4.46	7.70	108
2	16	3.13	4.78	3.96	7.70	110
2	16	3.88	5.62	4.75	7.90	112
2	20	4.78	5.68	5.23	8.00	114
2	20	4.93	5.34	5.14	7.90	116
2	12	0.00	0.00	0.00	7.90	118
2	16	4.04	5.31	4.68	7.90	120
2	20	4.73	5.54	5.14	8.20	122
2	16	4.11	5.60	4.86	8.10	124
2	16	5.14	5.74	5.44	8.40	126
2	20	5.75	6.35	6.05	8.10	128
2	20	5.57	5.72	5.65	8.30	130
2	16	5.13	5.70	5.42	8.30	132
2	20	5.22	5.87	5.55	8.40	134
2	16	4.66	5.39	5.03	8.40	136
2	12	3.28	3.58	3.43	8.40	138
2	12	4.31	5.40	4.86	8.50	140
2	16	5.37	5.77	5.57	8.60	142
2	20	5.57	6.09	5.83	8.70	144
2	16	5.42	5.49	5.46	8.60	146
2	12	4.49	4.87	4.68	8.70	148
2	12	4.18	4.83	4.51	8.90	150
2	16	5.20	5.61	5.41	8.70	152
2	16	5.21	5.64	5.43	8.90	154
2	12	4.48	4.85	4.67	8.90	156
2	16	5.69	5.77	5.73	9.00	158
2	12	4.67	4.71	4.69	8.90	160
2	12	5.27	5.39	5.33	9.10	162
3	20	0.00	0.00	0.00	7.10	164

Lobe #	Weld Time	Diameter (mm)			Current (kA)	Weld Order
		Min	Max	Mean		
3	20	4.28	4.29	4.29	7.20	166
3	20	3.53	4.35	3.94	7.30	168
3	20	3.80	4.28	4.04	7.50	170
3	16	0.00	0.00	0.00	7.30	172
3	16	3.93	4.26	4.10	7.50	174
3	20	4.61	4.77	4.69	7.50	176
3	20	4.66	4.84	4.75	7.60	178
3	16	3.77	4.11	3.94	7.60	180
3	20	4.75	5.54	5.15	7.80	182
3	16	3.93	4.31	4.12	7.80	184
3	16	3.84	3.93	3.89	7.90	186
3	20	4.86	4.90	4.88	7.90	188
3	16	4.39	4.67	4.53	8.00	190
3	20	4.99	5.67	5.33	8.00	192
3	16	5.04	5.52	5.28	8.20	194
3	20	5.25	5.70	5.48	8.10	196
3	20	5.34	5.78	5.56	8.30	198
3	12	3.32	3.69	3.51	8.30	200
3	16	6.69	5.32	6.01	8.20	202
3	12	0.00	0.00	0.00	8.30	204
3	16	4.99	5.54	5.27	8.40	206
3	20	5.20	5.97	5.59	8.30	208
3	20	5.21	5.81	5.51	8.40	210
3	12	3.64	5.59	4.62	8.50	212
3	16	5.18	5.84	5.51	8.30	214
3	12	3.99	5.34	4.67	8.60	216
3	16	5.11	6.00	5.56	8.50	218
3	20	5.48	5.92	5.70	8.70	220
3	12	4.20	5.25	4.73	8.70	222
3	12	4.28	5.73	5.01	8.80	224
3	12	4.57	5.82	5.20	8.90	226

Table B.8 **Weld lobe for DP600 to EDDQ joints (2.0/0.7 mm) at 16 cycles with triple pulse schedules.**

Time cycles	Minimum current (kA)			Expulsion current (kA)			Min. Avg (kA)	Exp. Avg (kA)	Range (kA)
	L1	L2	L3	L1	L2	L3			
7/2/7/2/7	8.00	7.80	8.00	9.30	9.20	9.00	7.93	9.17	1233
6/2/6/2/6	8.00	8.30	8.10	9.70	9.30	9.30	8.13	9.43	1300
5/2/5/2/5	9.10	9.00	8.90	9.70	9.50	9.80	9.00	9.67	667

Note: 7/2/7/2/7 represents three weld pulses with 7 cycles each and hold time of 2 cycles between them

Lobe #	Weld Time	Diameter (mm)			Current (kA)	Weld Order
		Min	Max	Mean		
1	7/2/7/2/7	0.00	0.00	0.00	7.00	2
1	7/2/7/2/7	0.00	0.00	0.00	7.10	4
1	7/2/7/2/7	1.10	2.60	1.85	7.40	6
1	7/2/7/2/7	1.44	3.44	2.44	7.60	8
1	6/2/6/2/6	0.00	0.00	0.00	7.60	10
1	7/2/7/2/7	1.37	2.95	2.16	7.80	12
1	6/2/6/2/6	0.00	0.00	0.00	7.70	14
1	7/2/7/2/7	2.03	3.92	2.98	7.80	16
1	7/2/7/2/7	3.32	5.17	4.25	8.00	18
1	6/2/6/2/6	2.07	3.24	2.66	8.00	20
1	7/2/7/2/7	3.90	5.00	4.45	8.00	22
1	6/2/6/2/6	3.21	4.64	3.93	8.00	24
1	6/2/6/2/6	3.18	4.73	3.96	8.10	26
1	7/2/7/2/7	4.12	5.51	4.82	8.10	28
1	5/2/5/2/5	0.00	0.00	0.00	8.30	30
1	7/2/7/2/7	4.30	5.75	5.03	8.10	32
1	5/2/5/2/5	1.06	3.02	2.04	8.40	34
1	6/2/6/2/6	2.57	3.79	3.18	8.30	36
1	5/2/5/2/5	2.75	4.21	3.48	8.30	38
1	6/2/6/2/6	2.01	4.19	3.10	8.40	40
1	7/2/7/2/7	3.65	5.15	4.40	8.50	42
1	6/2/6/2/6	2.76	4.39	3.58	8.60	44
1	5/2/5/2/5	2.35	3.88	3.12	8.60	46
1	7/2/7/2/7	3.83	5.90	4.87	8.50	48
1	6/2/6/2/6	3.75	4.21	3.98	8.80	50
1	7/2/7/2/7	3.23	5.96	4.60	8.70	52
1	5/2/5/2/5	1.35	3.29	2.32	8.90	54
1	5/2/5/2/5	2.20	4.58	3.39	8.70	56
1	7/2/7/2/7	3.48	5.50	4.49	8.70	58
1	6/2/6/2/6	2.77	5.24	4.01	8.80	60
1	5/2/5/2/5	2.84	5.29	4.07	8.90	62
1	7/2/7/2/7	4.67	6.14	5.41	8.90	64
1	6/2/6/2/6	4.41	6.00	5.21	9.00	66
1	6/2/6/2/6	4.06	5.73	4.90	9.00	68

Lobe #	Weld Time	Diameter (mm)			Current (kA)	Weld Order
		Min	Max	Mean		
1	5/2/5/2/5	2.30	5.42	3.86	9.10	70
1	7/2/7/2/7	5.29	6.16	5.73	9.10	72
1	6/2/6/2/6	2.86	6.15	4.51	9.20	74
1	7/2/7/2/7	5.10	6.04	5.57	9.10	76
1	5/2/5/2/5	2.97	5.05	4.01	9.20	78
1	6/2/6/2/6	4.42	6.08	5.25	9.20	80
1	5/2/5/2/5	3.21	5.59	4.40	9.20	82
1	7/2/7/2/7	5.78	6.23	6.01	9.10	84
1	5/2/5/2/5	2.97	5.58	4.28	9.20	86
1	7/2/7/2/7	5.63	5.96	5.80	9.30	88
1	6/2/6/2/6	5.75	5.77	5.76	9.40	90
1	5/2/5/2/5	2.79	5.68	4.24	9.40	92
1	6/2/6/2/6	5.92	5.99	5.96	9.30	94
1	6/2/6/2/6	5.64	5.88	5.76	9.30	96
1	5/2/5/2/5	4.82	5.06	4.94	9.60	98
1	6/2/6/2/6	5.70	5.84	5.77	9.60	100
1	5/2/5/2/5	4.68	5.57	5.13	9.60	102
1	6/2/6/2/6	5.54	5.62	5.58	9.70	104
1	5/2/5/2/5	5.34	5.69	5.52	9.60	106
1	5/2/5/2/5	5.84	5.88	5.86	9.70	108
2	7/2/7/2/7	1.48	1.00	1.24	7.30	110
2	6/2/6/2/6	0.00	0.00	0.00	7.50	112
2	6/2/6/2/6	1.32	1.55	1.44	7.60	114
2	7/2/7/2/7	1.70	2.22	1.96	7.70	116
2	7/2/7/2/7	2.60	5.83	4.22	7.80	118
2	6/2/6/2/6	2.12	2.49	2.31	7.80	120
2	7/2/7/2/7	3.09	5.73	4.41	7.90	122
2	6/2/6/2/6	2.51	2.74	2.63	8.00	124
2	6/2/6/2/6	1.69	2.29	1.99	8.10	126
2	7/2/7/2/7	2.75	5.64	4.20	7.90	128
2	6/2/6/2/6	2.35	3.12	2.74	8.20	130
2	7/2/7/2/7	2.87	5.73	4.30	8.20	132
2	7/2/7/2/7	3.31	5.84	4.58	8.20	134
2	6/2/6/2/6	3.03	5.80	4.42	8.30	136
2	6/2/6/2/6	2.50	6.09	4.30	8.30	138
2	7/2/7/2/7	3.29	5.77	4.53	8.30	140
2	6/2/6/2/6	2.83	5.25	4.04	8.50	142
2	7/2/7/2/7	3.82	5.88	4.85	8.90	144
2	6/2/6/2/6	3.49	5.58	4.54	8.60	146
2	7/2/7/2/7	3.76	5.86	4.81	8.50	148
2	7/2/7/2/7	3.87	5.78	4.83	8.70	150
2	6/2/6/2/6	3.99	5.67	4.83	8.80	152
2	6/2/6/2/6	4.38	5.67	5.03	9.10	154
2	7/2/7/2/7	5.93	4.41	5.17	9.20	156
2	5/2/5/2/5	4.16	5.93	5.05	9.00	158

Lobe #	Weld Time	Diameter (mm)			Current (kA)	Weld Order
		Min	Max	Mean		
1	5/2/5/2/5	2.30	5.42	3.86	9.10	70
2	6/2/6/2/6	4.27	5.86	5.07	9.10	160
2	5/2/5/2/5	3.69	5.69	4.69	9.30	162
2	5/2/5/2/5	4.16	5.78	4.97	9.30	164
2	6/2/6/2/6	4.73	6.00	5.37	9.30	166
2	5/2/5/2/5	4.18	5.70	4.94	9.30	168
2	5/2/5/2/5	4.60	5.86	5.23	9.50	170
2	5/2/5/2/5	4.23	5.99	5.11	9.50	172
3	7/2/7/2/7	1.16	1.45	1.31	7.80	174
3	7/2/7/2/7	3.20	1.88	2.54	8.00	176
3	6/2/6/2/6	0.00	0.00	0.00	8.00	178
3	7/2/7/2/7	2.74	5.83	4.29	8.00	180
3	6/2/6/2/6	1.87	5.35	3.61	8.10	182
3	6/2/6/2/6	2.27	5.36	3.82	8.10	184
3	7/2/7/2/7	3.86	5.97	4.92	8.10	186
3	7/2/7/2/7	2.93	5.95	4.44	8.20	188
3	6/2/6/2/6	3.45	5.81	4.63	8.30	190
3	6/2/6/2/6	2.39	5.79	4.09	8.50	192
3	7/2/7/2/7	3.11	6.17	4.64	8.40	194
3	6/2/6/2/6	2.85	5.97	4.41	8.60	196
3	7/2/7/2/7	3.11	5.97	4.54	8.50	198
3	6/2/6/2/6	2.94	5.88	4.41	8.70	200
3	7/2/7/2/7	3.64	5.84	4.74	8.70	202
3	7/2/7/2/7	6.15	3.48	4.82	8.70	204
3	6/2/6/2/6	2.80	5.96	4.38	8.70	206
3	6/2/6/2/6	2.79	6.11	4.45	8.80	208
3	7/2/7/2/7	3.58	5.83	4.71	8.80	210
3	7/2/7/2/7	4.05	5.58	4.82	9.00	212
3	6/2/6/2/6	4.42	6.17	5.30	9.00	214
3	5/2/5/2/5	2.00	5.76	3.88	8.90	216
3	6/2/6/2/6	4.67	6.06	5.37	9.00	218
3	5/2/5/2/5	2.07	5.57	3.82	9.00	220
3	6/2/6/2/6	4.05	6.10	5.08	9.20	222
3	5/2/5/2/5	2.63	5.75	4.19	9.20	224
3	6/2/6/2/6	4.04	6.17	5.11	9.30	226
3	5/2/5/2/5	2.87	5.85	4.36	9.30	228
3	5/2/5/2/5	3.06	5.99	4.53	9.40	230
3	5/2/5/2/5	3.64	6.32	4.98	9.60	232
3	5/2/5/2/5	4.22	5.92	5.07	9.70	234
3	5/2/5/2/5	3.51	6.04	4.78	9.70	236
3	5/2/5/2/5	4.18	5.82	5.00	9.80	238

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PUBLICATIONS

Tawade G., Lee A., Boudreau G., Bhole S., "Robust schedules for spot welding zinc coated advanced high strength steels for automotive applications" Sheet Metal Welding Conference-XI, Detroit, Michigan, 11-14 May 2004.

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