Chapter 1

Introduction

1.1 General

The continued demands of high productivity have made resistance spot welding an interesting alternative to ordinary arc welding for applications in transport industry, i.e., for cars, trains and buses. The primary advantage of resistance spot welding over other joining methods is that it is fast, easy to operate, and adaptable to automation, and, as a consequence it is ideal for mass production. Another major advantage of spot welding is that it does not require considerable skill on the part of the operator. This merit is specifically significant when one deals with thinner sheets. With the advent of more sophisticated spot welding machines of higher capacity, the range of applications for spot welding is likely to expand. These excellent techno-economic benefits have made spot welding as one of the most important joining methods for sheet metals in the automotive industry. In an automotive, more than 5,000 spot-welds are used. The major automotive components where spot-welds are used are front cabin, back deck, side door panels, hoods and chassis. Apart from the numerous applications of resistance spot welding in automotive industry, its other applications are in domestic appliances, furniture, building products, enclosures and to a limited extent for aircraft components and so on.

1.2 Motivation of the present work

The integrity of the spot welds governs the overall structural rigidity and soundness of a vehicle. Spot-welds are subjected to various kinds of forces, and environmental conditions during their service. In an automobile for example, rough roads, sudden braking and vehicle crash lead to fatigue, quasi-static and impact loading conditions, and spot-welds occasionally fail. The interfacial surface between the sheets at the joint acts as an effective external crack causing stress concentration which usually assists to failure of the joint. Therefore, understanding the nature of the integrity of spot-welds under varied loading conditions is important to avoid failure at these joints. As a consequence, one finds several investigations related to integrity of spot-welds being pursued over the last decade. For example, (i) Zuniga and Sheppard (1997), Lee et al. (1998), Barkey and Kang (1999), Wung and co-workers (Wung, 2001; Wung et al., 2001), and Lin et al. (2002) have studied the problem related to the failure of spot-welds under quasi-static loading conditions, (ii) Zhang et al. (2001) and Bayraktar et al. (2004) have examined the failure of spot-welds under impact loading conditions, whereas (iii) fatigue life of spot-welds have been examined by Lee and Kim (2004), Lee and Choi (2005), Long and Khanna (2007) and Choi et al. (2007). One of the important aspects of spot welding is to ensure that the strengths of individual welds do not vary in a highly random way. The designer has to over specify the number of welds if weld quality cannot be guaranteed and it is also not known whether an apparent over-supply of welds will be adequate. But the existing state of understanding related to the strength of spot-welds is yet to crystallize in order to establish any commonly accepted standard. It is, therefore, important to critically examine this aspect emphasizing only on the strength of spot-welds in quasi-static loading.

Earlier investigators (Zuniga and Sheppard, 1997; Barkey and Kang, 1999; Wung, 2001; Wung et al., 2001; Lin et al., 2002) have usually expressed the strength of spot-welds in terms of failure load and have extended different force based criteria to predict failure of spot-welds. The failure load of spot-welds depends on many factors like weld nugget diameter, sheet thickness, electrode-indentation, loading mode and material property (VandenBossche, 1977; Ewing et al., 1982; Zhou et at., 1999). Lee et al. (1998) have shown that the nugget diameter has the major contribution (more than 70%) to the total variation in the failure loads. Thus, for a given material, defining the strength of spot-welds which is independent of all the above-mentioned variables, is a necessity for industrial practice primarily for design purposes. Hence assessment of the strength of spot-welds in quasi-static loading would save cost and time by reducing the requirement of numerous tests to predict failure of spot-welds with different nugget diameters and sheet thicknesses under different loading modes.

In usual automotive applications, pressing and stamping of sheets prior to spot-welding are common manufacturing steps, which induce additional strain in the sheet metals. For example, Jeong (1998) has reported that the magnitude of work-hardening in a simple press-formed outer-door panel of automotives is nearly equivalent to an amount of pre-strain, induced by approximately 1.1 to 7.5% of uniaxial tensile strain. While the possible factors (nugget diameter, sheet thickness, material property, loading mode, etc.) which control the strength of spot welds have been studied to some extent, the estimated strength values remain shrouded with uncertainty of unknown magnitude due to the lack of understanding of the effect of pre-strain on the weld-strength. The possibility of the considerable effect of pre-strain on the strength of spot welds can be traced to the report of Han et al. (2006), who have demonstrated that pre-strain influences the strength and fatigue behaviour of self-piercing riveted aluminum alloy sheets. It is, therefore, necessary to acquire knowledge on the effect of pre-strain of sheet-metals on the quality of the spot-welded joints.

Application of thinner gauge steel sheets is increasing in the automotive industry for the purpose of weight reduction to enhance fuel efficiency and decrease environmental pollution. But, such use of thinner gauge deep-drawing quality steel in automotive outer-body panels, has occasionally led to in-service denting problems. The improvement in dent resistance by employing steels with higher yield strength is not a viable alternative because of their inherently lower levels of formability and shape fixability. This has led to an ever-increasing usage of bake hardening (BH) steels. Bake hardening refers to the increase in yield strength that occurs as a result of the paint baking treatment of the formed auto-body parts. The primary mechanism that causes the additional strengthening is the immobilization of dislocations by the segregation of interstitial atoms, known as classical static strain aging (Elsen and Hougardy, 1993; Kozeschnik and Buchmayer, 1997, and Kvackaj and Mamuzic, 2006). The BH steels have low yield strengths and exhibit a high degree of formability before baking treatment. The BH steels are press-formed, assembled through welding and finally paint baking is done. When the formed parts of BH steels are paint baked, the parts gain strength and dent resistance (Baker et al, 2002; De et al., 2000). This increase in strength due to bake hardening can be expected to affect the strength of spot-welds. Katayama et al. (2004), and Hirose and Kobayashi (2005) have studied the effect of bake hardening on the mechanical behaviour of laser beam weld joints. But there exists limited work related to the effect of bake hardening on the strength of spot-welds.

Spot-welds in the coastal region are subjected to corrosive environment of the marine atmosphere. The auto-body panels, especially the parts under the car body, easily suffer corrosive attacks by sodium chloride solution deposited on roads for melting snow (Tzeng, 2002). It is, therefore, required to gain knowledge regarding the effect of saline environment on the strength of spot-welds.

In an automobile, reduction of the vehicle mass for low fuel consumption can be detrimental to its crash resistance. Substituting thin gauge high strength steels for thicker hot-rolled mild steels has achieved significant weight reduction on suspension arms, engine mounting brackets, chassis sections, closures, supports, etc. The resistance of the vehicle in the case of collision is a major concern in car industry as it plays a key role in safety, reliability and integrity of welded structures. In the case of car collisions, high strain rates, ranging up to 10^3 s^{-1}, are experienced. The behaviour of spot-welds of thin sheets during impact loading, reproducing the conditions of collision, is of special importance. However, impact testing is not routinely performed for assessing weld quality because of its complexity, cost and relatively low reliability and repeatability; even the test procedure is in a developing stage.

Interstitial free (IF) steels find wide application for fabricating auto-body panels. The information and understanding related to the response of spot-welds on IF steel sheets to various service conditions are limited in the open literature. Various grades of IF steel sheets have thus been selected for assessing the integrity of spot-welds in this investigation.

1.3 Objectives of the work

The major objectives of this investigation are enumerated below:

(a) Assessment of strength and fracture behavior of spot-welded joints on interstitial free steel sheets and understanding their failure behaviour.

(b) Examination of the effect of pre-straining of steel sheets on the strength and fracture behaviour of spot-welds.

(c) Study of the effect of baking treatment on the strength of spot-welds made on pre-strained sheets.

(d) Examination of the role of aggressive environment on the strength behaviour of spot welds.

(e) Assessment of toughness of spot-welded joints on IF steel sheets under impact loading.

1.4 Layout of the work

An introduction related to the significance of spot-welding and the motivations behind the present work are presented in **Chapter 1.** A critical review with emphasis on mechanical behavior of spot-welds with attempts to unfold the unanswered questions in this field of research constitutes the content of **Chapter 2**. **Chapter 3** contains information generated from the characterization of the structure and properties of the base materials selected to fabricate the spot-welded samples for this investigation. The estimation of the load carrying capacity of spot-welds with varied nugget diameters under different loading modes and their pertinent analyses are the content of **Chapter 4**. Attempts have been made in **Chapter 4** to examine the appropriateness of the use of failure load vis-à-vis failure stress and to establish general relationships among the strength values estimated under different loading modes. The effect of pre-strain (in base metals) on the strength of spot-welds has been examined in detail in **Chapter 5**. The results and analyses from an investigation on the effect of baking treatment on the strengths of spot-welds made on pre-strained sheets are the content of **Chapter 6**. The influence of corrosive environment (3.5% NaCl solution) on the strength of spot-welds has been examined in **Chapter 7**. Estimation of impact tensile toughness of spot-welded joints and a comparative assessment of their quasi-static and impact toughness values has been presented in **Chapter 8.**

The major experiments involved in Chapter 3 to Chapter 8 are: (i) qualitative and quantitative microscopy using optical, SEM and TEM, (ii) measurement of micro-hardness of base metals and gradient microstructure around spot-welds, (iii) extensive studies on load-displacement plots of base metal (virgin and pre-strained) and weldments (under different loading modes), (iv) slow strain rate tests with or without in-situ hydrogen charging, (v) estimation of toughness under impact condition, and (vi) fractographic analyses.

The major conclusions drawn from the experimental results and the pertinent analyses are summarized in **Chapter 9**.