MATERIALS ENGINEERING | RESEARCH ARTICLE

A microstructure evaluation of different areas of resistance spot welding on ultra-high strength TRIP1100 steel

Iman Hajiannia1*, Morteza Shamanian1, Masoud Atapour1, Ehsan Ghassemali2 and Rouholah Ashiri3

Abstract: In this study, the microstructure of resistance spot welds of advanced ultra-high strength TRIP1100 steel was investigated. For this purpose, welding was performed after determining the best welding parameters. Four sections of the heat-affected zone (HAZ) regions were selected in the regions where the heat exchange was used to control the microstructure. Then, they were used with EBSD by scanning electron microscopy (SEM). The results showed that the TRIP1100 steel microstructure consisted of polygonal ferrites, bainites, residual austenite (RA) and martensite/austenitic islands (M/A). They also showed that the melting zone (FZ) has a lath martensite structure, and the grains are larger in packets. The structure of the martensite and different orientation grains are located in the Upper-critical area (UCHAZ). In the Inter-critical region (ICHAZ), the high carbon martensitic content is higher due to the presence and the structure of ferrite and martensite. In the sub-critical region (SCHAZ), due to the tempering of martensite at a temperature below $A_{C1}$, the structure is similar to the base metal (BM), with the difference that the RA degradation reduces its structure by 50%. It was found that the RA in...
the BM had completely transformed. The results showed that with the movement of the BM to the weld metal, the boundaries with a low angle were increased.

**Subjects:** Automotive Design; Materials Processing; Metals & Alloys

**Keywords:** resistance spot weld; TRIP1100; EBSD and microstructure

### 1. Introduction

Transformation-induced plasticity (TRIP) steel is an AHSS (Pouranvari & Marashi, 2011). The popularity of AHSSs has been increasing recently because of their strength and ductility synergy. They have been widely applied in automotive industries to a decrease in weight simultaneous with improvements in vehicle safety (Hajiannia, Shamanian, Atapour Ghasemali, & Soeidi, 2018). Usually, the microstructure of the steel consists of bainite, martensite, and retained austenite in a matrix of soft ferrite (Bhadeshia, 2001). Resistance spot welding (RSW) is a reliable welding method wherein a molten zone is formed between steel sheets (Moosalu, Noori Teymorlu, Parvini Ahmadi, Yazdani, 2012). Meanwhile, it is the most widely used method to join sheet metals in automotive industry. These steels are known as TRIP steels because the retained austenite transforms to martensite at high strains resulting in an excellent work hardenability persisting over a large amount of strain. However, the weldability of these steels has been an ongoing concern due to the high amounts of carbon and other austenite stabilizers, which can produce hard microstructures in the weld zone since high cooling rates are experienced in RSW (Sajjadi-Nikoo, Pouranvari, Abedi, & Ghaderi, 2018). When performing RSW, microstructural changes in the fusion zone (FZ) and surrounding heat-affected zone (HAZ) affect the weld mechanical properties, which need to be specified so that optimized welding procedures can be developed for these steels (Park & Kang, 2007).

Thousands of resistance spot welds are usually executed to join the doors, body-in-white and other components in a vehicle auto-body (Brauser et al., 2010). Moreover, the quality and good mechanical performances of RSW joints are crucial to provide the safety and durable design of a vehicle. Actually, many of the joints used in vehicle’s frame could act as fold initiation parts to manage impact energy in order to transfer impact loads through the vehicle’s frame in a car crash event. Some studies have been performed regarding the RSW of TRIP steels. Nayak, Baltazar Hernandez, Okita, and Zhou (2012) studied the microstructure of FZ in resistance spot welded (RSWed) TRIP steels. They found that the microstructure of FZ depend on chemistry and varied from martensite with interlath austenite to ferrite surrounded by bainite and artensite. In another study, Vargas, Mejia, Baltazar-Hernández, and Maldonado (2018) characterized the RSWed TRIP steels with different silicon and carbon contents. They reported that the volume fraction of retained austenite within the HAZ increased with increasing Si content. The available literature on the RSW of TRIP steels mainly focused on the effect of chemical composition on the microstructure of welded samples and the microstructure of ultrahigh strength TRIP steels after RSW has not been studied.

The aim of this work is to study the RSW metallurgy of the newly developed TRIP steel, which to the our best of knowledge, has not been evaluated yet. In spot weld at TRIP1100 steel, the HAZ is divided into three zones from a metallurgical viewpoint: upper-critical (UCHAZ), inter-critical (ICHAZ), and sub-critical (SCHAZ). The phase fraction and grain boundary distribution in these areas of weld was investigated, which is necessary to conduct to assess the possibility of its application in the auto-body. Microstructural investigation using SEM and EBSD techniques were conducted in order to evaluate the weld behavior.

### 2. Experimental method

In the present study, cold rolled uncoated TRIP1100 steel plates with a thickness of 1 mm as the base metal (BM) were used. The chemical composition and mechanical properties of the used plates are presented in Tables 1 and 2 respectively. The critical temperature $\text{Ac}_{3}$ in this steel was 858°C with the corresponding calculations, and that of $\text{Ac}_{1}$ was calculated as 720°C. The plates
were mechanically categorized in four classes based on ANSI/AWS/SAE/D8.9-13 standard (AWS standard). Samples with dimensions of 5 cm × 5 cm were cut from the initial steel and resistance spot welded using single phase alternating current of 50 Hz/100 kVA. Electrodes for welding group A, according to class 2, were selected with copper-cream-zirconium RWMA alloys. The shape of the chosen electrode was an inverted cone with a contact diameter of 6 mm. After studying the weldability with various parameters of spot resistance welding of the TRIP steel, suitable parameters for welding were selected. The welding parameters are presented in Table 3. Mechanical properties of welded samples were determined by tensile-shear and cross-tensile tests, according to AWS D8.9 standard (Baltazar Hernandez, Okita, & Zhou, 2012), To evaluate the reproducibility of experimental result, according to the standard for each test, the required number of test (three) specimens was prepared and then the average results were used. To determine and observe the microstructure and measure of the weld, the nugget diameter was created from a shear weld center at the cross section; and then, it was analyzed stereographically by macroscopic the cross-sectional area. In Table 3, the failure force and the weld nugget diameter for the specimen are provided. A scanning electron microscope (SEM) was employed to investigate the microstructure of weldments. The specimens for microstructural investigations were prepared by mounting, grounding to 1200 grit finish following by polishing with 0.3 μm alumina suspension. The specimens were then etched with 2% Nital solution to reveal the microstructure. Moreover, electron backscatter diffraction (EBSD) on a field emission SEM (JSM7001F) equipped with an EBSD detector combined with the TSL (OIMA) analysis software was used to characterize the crystallographic orientations, and phases of the TRIP steel. The specimens were mechanically prepared for EBSD with a colloidal silica base (OPS).

3. Results and discussion

3.1. Microstructure of the base metal

Phase stability and different temperatures in the iron–carbon phase diagram are illustrated in Figure 1a. In Figure 1b, the TRIP steel spot welding macrostructure is illustrated by dividing different regions including: (1) BM, (2) HAZ, and (3) melting or welding metal (FZ).

As shown in Figure 2a, the TRIP1100 steel microstructure consists of ferrite and bainite, RA and martensite/austenitic island (M/A). Regarding the microstructure, retained austenite can be obtained

| Table 1. Chemical composition of experimental TRIP steel (in wt %) |
|-------------------------|----------------|----------------|----------------|---------------|----------------|----------------|---------------|
| C  | Si  | Mn  | S   | P   | Al  | Cr  | Ni  | Fe  |
| 0.18 | 1.03 | 2.45 | 0.009 | 0.003 | 0.01 | 0.02 | 0.3 | 余数 |

| Table 2. Mechanical properties of TRIP1100 steel |
|----------------|---------|----------------|---------------|---------------|
| Steel grade | Yield strength (MPa) | Tensile strength (MPa) | Elongation (%) |
| TRIP1100 | 616 ± 9 | 1150 ± 13 | 25 ± 1 |

| Table 3. Welding parameters and results of shear tensile strength and cross tension strength tests of the spot TRIP1100 weld |
|----------------|----------------|----------------|----------------|----------------|---------------|---------------|
| Weld Current (kA) | Electrode Force (kN) | Weld time (Cycles) | Hold time (Cycles) | shear tensile strength (N) | cross tension strength (N) | weld nugget size (mm) |
| 10 | 3.5 | 11 | 8 | 7750 ± 15 | 1315 ± 5 | 5.7 ± 0.2 |
in the bainite areas formed during the isothermal transformation at 350°C. A small amount of block RA is also observed in polygonal ferrite grains (Tang, Ding, Du, & Long, 2007). Although microscopic images and microstructural similarities can partly identify the RA phase, it is necessary to make calculations and accurate analyses to prove the presence of RA. It is also essential to know the properties of the microstructure and the existing phases. For this purpose, electron diffraction analysis from EBSD return electrons was used to study phase fractions. Figure 2b and 2c illustrate the crystallographic directions along with inverse pole figure (IPF) with image quality map (IQ), and phase fraction for TRIP1100 steel derived from EBSD analysis. With respect to Figure 2a, the size of ferrite grains of polygons ranges from 0.5 to 4 µm, and phases islands of M/A are between 1 and 2 µm.

The presence of austenite in the microstructure was determined to be about 6.5% at a level of 50 µm by a phase map in the boundary of Figure 2c. The images obtained from the phase map represent the uniform distribution of RA in the microstructure. It can be argued that RA has two block morphologies and very small grains (Thierry et al., 2016). The RA of the block forms inside the M/A, while it appears between the bony masses in the form of very fine grains (Petrov, Kestens, Wasiłkowska, & Houbaert, 2007). In Figure 2b, a series of black and dark areas whose IQ are lower than the field are martensite areas. Martensite regions have a darker than ferrites (Zaefferer, Romano, & Friedel, 2008). Because the structure of ferrite and martensite is both BCC, it is not possible to detect it with IPF monoliths; however, after image analysis with the amount of darkness in the IQ image, separation of the two phases is possible.

4. Different regions of HAZ
In spot weld at TRIP1100 steel, the HAZ is divided into three zones from a metallurgical viewpoint: upper-critical (UCHAZ), inter-critical (ICHAZ), and sub-critical (SCHAZ).

4.1. Microstructure of the subcritical region
The region affected by low heat experiences a temperature below the transformation start-up temperature, and the heat reaches below Ac₃. The illustration of the SEM microscope structure of the sub-critical zone of the TRIP steel is presented in Figure 3a characterized by the fact that martensitic tempering is carried out at 200°C to 500°C (Moghanizadeh, Honarvar, & Choreishi et al., 2011). In sub-critical zone, some of the base metal martensite is tempered, and some of the remaining austenite is converted to ferrite and cementite. In addition, discontinuous martensite and bainite islands in the base metal have been converted to martensitic layers. Laminar martensite has been observed in low carbon steels. With respect to Figure 3a, the remainder of the
retained austenite in the microstructure can be transformed completely, but the RA remains between the masses of fine grains, and is present around the boundaries (Gould, Peterson, & Cruz, 2013). Figure 3b, illustrates the IPF of the sub-critical region, the grains in this area have different orientations. Figure 3c shows the phase map of the structure. It was found that 50% of the retained austenite in the structure was decomposed into ferrite and cementite due to heat. As shown in Figure 3d, larger-angle boundaries have a greater fraction (approximately 3.5 times) than low-angle boundaries.

4.2. **Microstructure of the inter-critical region**

In this area, the temperature is between \(\text{Ac}_3-\text{Ac}_1\), which is much more limited due to the temperature range. The temperature difference of 138°C for inter-critical areas confirms this
limitation. In this temperature range in the two-phase zone, the transformation of ferrite and austenite occurs (Timokhina, Hodgson, & Pereloma, 2003). Figure 4a shows the SEM image of the inter-critical region in the TRIP steel. Figure 4b shows the IPF image of the inter-critical region. The EBSD studies in Figure 4c show that in this region, the fraction of the boundary of the large angle to the low angle is greater than that of the SCHAZ (2.54), which indicates an increase in the boundary with a low angle in this region. Austenite is expected to result in carbon dissolution in excess of ferrite to produce more carbon-rich martensite at a low rate (Eftekharimilani, Van Der Aa, Hermans, & Richardson, 2017). Khan, Kuntz, Biro and Zhou (2008), reported the presence of ferrite, martensite and a small amount of retained austenite in the intercritical HAZ of resistance spot welded TRIP780 steel. The results from the previous work of by using the X-ray analysis showed which did not have sufficient accuracy for a small area of HAZ and only it is show the decrease in the retained austenite of HAZ (Ertek Emre & Kaçar, 2016). Microstructure of the ICHAZ in TRIP780 in study of Khan et al (2008), showed contained ferrite and a white banded structure. They showed this related to intensities of chemical attack by etchants. So to clarify the metallographic results, the TRIP samples were analyzed using XRD to clarify the phases present in all of the weld zones. Base metal analysis showed peaks for austenite and ferrite, which are the main constituents observed using metallographic examinations. Within the HAZ a reduction in intensity for the austenite peaks. This transition can pertain to a combination of austenite and martensite in the

Figure 3. (a) SEM image of the sub-critical region of TRIP steel (TM: tempered martensitic, F: ferrite) (b) inverse pole figure (IPF) image of the sub-critical region of point resistance of steel TRIP, (c) phase fraction, (d) the grain boundaries in the SCHAZ.
HAZ, suggesting the coexistence of both phases within this region. XRD readings of the FZ produced no evidence of austenite peaks, hence the structure was predominately martensitic as observed by SEM. The results in the present study show the use of EBSD analysis for each areas of HAZ can accurately reflect the phase details.

4.3. The microstructure of the upper-critical region

As shown in Figure 1b, this region starts from a melting point with an approximate temperature less than melting, and reaches the critical temperature of $A_{c3}$. Like other welding processes in the
RSW, the HAZ region is not melting, but placed in the full austenite region. Figure 5a shows the martensitic structure in UCHAZ, which was also observed by Khan et al. (2008), in the RSW of TRIP 780 steel. The higher the temperature and that of the melting temperature, the better conditions for the growth of the grain during the cooling down are. Moreover, according to the IPF, it is determined that the lath martensite is less than that of FZ (Figure 5b) (Khan et al., 2008). This area is very important for high-strength steels because it lies within the melting edge and also the location of the connection of solidification cracks. The IPF image in Figure 5b is a different
orientation of the martensitic packets. In this area, the fraction of retained austenite significantly reduced due to the high temperature. In the UCHAZ region, the fraction of the grains was higher at different angles than FZ, indicating that the UCHAZ beads are smaller than those in the other two regions. According to Figure 5c, a high-angle boundary fraction can be expressed in low angle 1.88. Investigations showed that moving up to the FZ of boundaries at a low angle would increase.

4.4. The microstructure of the nugget
Figure 6a shows the SEM image of the fusion zone in the spot weld of TRIP1100 steel. FZ has a fast solidification and columnar structure, drawn from the weld boundary to the center of the button.
Cooling the resistance welding points is much faster than arc welding and even laser beam welds, the microstructure is also fully martensite.

During the cooling process, solidification often occurs as a cell or a group of dendrites, and the welding metal consists of a combination of different groups or packages with different directions of growth and orientations. Figure 6b shows the image of the microstructure (IPF) of the melting area. From the EBSD analysis of the weld metal, the coarseness of the beads in the FZ region can be compared with the base metal and HAZ detection. The results of EBSD Chen (Zhang, Qiu, Xing, Bai, & Chen, 2014), showed that in the melting region, the ferrites of the first Delta, then austenite, and Figure 6c determined that the number and length of the field angles between 2° and 15° are approximately 20% below the boundaries at an angle higher than 15° (Kitahara, Ueji, Tsuji, & Minamino, 2006). In the primary austenite, the boundaries of the grain and those of the martensite packets can be seen in the IPF images. This change in the angle between the different packets is not greater than 10°. Figure 6c shows the primary austenite grain in the center of the shape, separated by a large angle and specific orientations of neighboring structures. The analysis of the austenitic grain of the early specimens has shown that the primary austenite grain consists of several packages, each of which is divided into parallel blocks, and one block is further divided into rags with heterogeneous widths. Therefore, the lath martensite is a martensitic crystal containing network defects like high density disorientation.

To investigate different fusion regions, the austenite fraction analysis by EBSD was used. Figure 7 shows various points of the TRIP steel spot welding. As shown in Figure 7, passing through different regions from the metal-to-metal side to the weld, the reduced austenite fraction has decreased. By increasing the input heat to the sample, various phases that affect the microstructure are formed, with a sudden increase in the cooling rate of the metal structure and HAZ. With this in mind, it is easy to predict hardness in different areas. Investigations on the fraction of grain boundary at high angles over low boundaries showed that the fraction of this ratio is reduced by moving from the base metal to the fusion zone. Figure 8 shows the ratio of large angle to low angles of motion from the base metal to the FZ. In other words, the percentage of low-angle boundaries has increased with exposure to heat, which can be due to the unevenness of the structure.

5. Conclusions
(1) The TRIP1100 has a multi-phase structure consisting of ferrites, martensite bainite and retained austenite, which was identified by the EBSD analysis. In SCHAZ area, marten-
The site was placed in the temperature range of the tempering and reduced 50% of the retained austenite in its structure. The results in the present study show the use of EBSD analysis for each area of HAZ can accurately reflect the phase details.

(2) In ICHAZ area, the main micro-structure was ferrite and martensite, and the martensitic phase fraction was more than ferrite, the area was at a critical temperature of $\text{Ac}_1$ and $\text{Ac}_3$. In the UCHAZ area, due to the high cooling rate, the solidification of the lath martensite structure, which was similar to the structure of the fusion zone, was achieved. Martensitic packets in the FZ were larger than the UCHAZ grains.

(3) The EBSD results showed that with increasing heat input, the type and orientation of the grains changed, and the fraction of the high angles boundary reduced and increased the low angle by moving toward the fusion zone. Moreover, by going toward the FZ, RA decreases, which is attributed to the degradation of the RA due to heat and tempering.

**Funding**
The authors received no direct funding for this research.

**Author details**
Iman Hajiannia$^1$
E-mail: i.hajiannia@ma.iut.ac.ir
ORCID ID: http://orcid.org/0000-0001-9572-9002
Morteza Shamanian$^1$
E-mail: shamanian@cc.iut.ac.ir
Masoud Atapour$^1$
E-mail: m.atapour@cc.iut.ac.ir
Ehsan Ghassemali$^2$
E-mail: ehsan.ghassemali@gmail.com
Rouholah Ashiri$^3$
E-mail: ro_ashiri@yahoo.com

1 Department of Materials Engineering, Isfahan University of Technology, Isfahan 84156-83111, Iran.
2 School of Engineering, Jönköping University, Box 1026, 551 11 Jönköping, Sweden.
3 Department of Materials Science and Engineering, Dezful Branch, Islamic Azad University, P.O. Box 313, Dezful, Iran.

**Citation information**
Cite this article as: A microstructure evaluation of different areas of resistance spot welding on ultra-high strength TRIP1100 steel, Iman Hajiannia, Morteza Shamanian, Masoud Atapour, Ehsan Ghassemali & Rouholah Ashiri, Cogent Engineering (2018), 5: 1512939.

**References**
AWS standard D8-9 1997.PDF.
Baltazar Hernandez, V. H., Okita, Y., & Zhou, Y. (2012). Second pulse current in resistance spot welded TRIP steel - Effects on the microstructure and mechanical behavior. Welding Journal [Internet], 91, 278S–285S. Retrieved from https://app.aws.org/wj/supplement/WJ_2012_10_s278.pdf
Bhadeshia, H. K. D. H. (2001). Tempering of bainite. Bainite in Steels, 91–116.
Brauser, S., Pepke, L. A., Weber, G., & Rethmeier, M. (2010). Deformation behaviour of spot-welded high strength steels for automotive applications. Materials Science and Engineering A [Internet], 527, 7099–7108. doi:10.1016/j.msea.2010.07.091
EftekhariMilani, P., Van Der Aa, E. M., Hermans, M. J. M., & Richardson, I. M. (2017). The microstructural evolution and elemental distribution of a 3rd generation 1 GPa advanced high strength steel during double pulse resistance spot welding. Welding in the World, 61, 691–701. doi:10.1007/s40194-017-0459-4
Ertek Emre, H., & Koçar, R. (2016). Resistance spot weldability of deformed TRIP800 steel: Various parameters were investigated for obtaining optimum tensile shear strength, weld button geometry, and electrode indentation, Metals, 6(12), 299.

Gould, J., Peterson, W., & Cruz, J. (2013). An examination of electronic servo-guns for the resistance spot welding of complex stack-ups. Welding in the World, 57, 243–256. doi:10.1007/s40194-012-0019-x

Hajiannia, I., Shaminian, M., Atapour, M., Ghassemoli, E., & Soeidi, N. (2016). Development of ultrahigh strength TRIP steel containing high volume fraction of martensite and study of the microstructure and tensile behavior. Transactions of the Indian Institute of Metals [Internet], 1–8. doi:10.1007/s12666-017-1271-y

Khan, M. I., Kunz, M. L., Biro, E., & Zhou, Y. (2008). Microstructure and mechanical properties of resistance spot welded advanced high strength steels. Materials Transactions [Internet], 69, 1629–1637. Retrieved from https://www.jstage.jst.go.jp/article/matertrans/49/7/49_MRA2008031/_article

Kitahara, H., Ueji, R., Tsuji, N., & Minamino, Y. (2006). Crystallographic features of lath martensite in low-carbon steel. Acta Materialia, 54, 1279–1288. doi:10.1016/j.actamat.2005.11.001

Moghanizadeh, A., Honarvar, F., Ghoreshi, M.Š., Ghajar, R. (2011). An investigation of the parameters affecting the quality of resistance spot welds in low carbon steel sheets. Aerospace Mechanics Journal, 7(24), 1–9.

Moosalu, H., Noori Teymorlu, A., Parvini Ahmadi, N., & Yazdani, S. (2012). Investigation of transformation induced plasticity in High Al-Low Si TRIP steel. International Journal of Iron & Steel Society of Iran, 9, 11–14.

Nayak, S. S., Baltazar Hernandez, V. H., Okita, Y., & Zhou, Y. (2012). Microstructure-hardness relationship in the fusion zone of TRIP steel welds. Materials Science and Engineering A [Internet], 551, 73–81. doi:10.1016/j.msea.2012.04.096

Park, J. M., & Kang, H. T. (2007). Prediction of fatigue life for spot welds using back-propagation neural networks. Materials and Design, 28, 2577–2584. doi:10.1016/j.matdes.2006.10.014

Petrov, R., Kestens, L., Wasilkowska, A., & Houbaert, Y. (2007). Microstructure and texture of a lightly deformed TRIP-assisted steel characterized by means of the EBSD technique. Materials Science and Engineering A, 447, 285–297. doi:10.1016/j.msea.2006.10.023

Pouranvari, M., & Marashi, S. P. H. (2011). Failure mode transition in AHSS resistance spot welds. Part I: Controlling Factors. Materials Science and Engineering A, 528, 8337–8343. doi:10.1016/j.msea.2011.08.017

Sajjadi-Nikoo, S., Pouranvari, M., Abedi, A., & Ghaderi, A. A. (2018). In situ postweld heat treatment of transformation induced plasticity steel resistance spot welds. Science and Technology of Welding and Joining [Internet], 23, 71–78. doi:10.1080/13621718.2017.1323174

Tang, Z., Ding, H., Du, L., & Long, L. (2007). Microstructures and mechanical properties of Si-Al-Mn TRIP steel with niobium. Journal of Materials Science and Technology, 23, 790–794.

Thierry, D., Vucko, F., Luckeneder, G., Weber, B., Dosdat, L., Bschorr, T., & Rother, K. (2016). Fatigue behavior of spot-welded joints in air and under corrosive environments: Part II: Fatigue under alternating and combined corrosion and fatigue load. Welding in the World [Internet], 60, 1231–1245. doi:10.1007/s40194-016-0367-z

Timokhina, I. B., Hodgson, P. D., & Pereloma, E. V. (2003). Effect of deformation schedule on the microstructure and mechanical properties of a thermomechanically processed C-Mn-Si transformation-induced plasticity steel. Metallurgical and Materials Transactions A, 34, 1599–1609. doi:10.1007/s11661-003-0305-8

Vargas, V. H., Mejia, I., Baltazar-Hernández, V. H., & Maldonado, C. (2018). Characterization of resistance spot welded transformation induced plasticity (TRIP) steels with different silicon and carbon contents. Journal of Manufacturing Processes. doi:10.1016/j.jmapro.2018.02.005

Zaeflerer, S., Romano, P., & Friedel, F. (2008). EBSD as a tool to identify and quantify bainite and ferrite in low-alloyed Al-TRIP steels. Journal of Microscopy, 230, 499–508. doi:10.1111/j.1365-2818.2008.01982.x

Zhang, H., Qiu, X., Xing, F., Bai, J., & Chen, J. (2016). Failure analysis of dissimilar thickness resistance spot welded joints in dual-phase steels during tensile shear test. Materials & Design [Internet], 55, 366–372. doi:10.1016/j.matdes.2013.09.040
