



# Shielding gas influences on laser weldability of tailored blanks of advanced automotive steels

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## ABSTRACT

The effects of shielding gas types and flow rates on CO<sub>2</sub> laser weldability of DP600/TRIP700 steel sheets were studied in this work. The evaluated shielding gases were helium (He), argon (Ar) and different mixtures of He and Ar. Weld penetration, tensile strength and formability (Erichsen test) of laser welds were found to be strongly dependent upon the shielding gas types. The ability of shielding gas in removing plasma plume and thus increasing weld penetration is believed to be closely related to ionization potential and atomic weight which determine the period of plasma formation and disappearance. It was found that the higher helium shielding gas flow rate, the deeper weld penetration and the lower weld width.

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## 1. Introduction

Tailor welded blanks (TWBs) are now extensively used in the automotive industry for fabrication of car body panels. TWBs were initially used at mass production level in Germany in the early 1980s. More recently, amid tougher environmental and safety regulations, TWBs have been used to accelerate weight reduction and stiffness improvement in the automotive industry [1].

The possibility of having different sheets of different thickness, strength and material properties enables the designer to distribute the material optimally. Optimal distribution of the material, indeed, means lighter structures, higher strengths and joining before forming results in lower production costs. Among other welding methods, laser beam welding (LBW) and mash seam welding (MSW) have received much more attention. Due to some reports, either CO<sub>2</sub> or Nd:YAG laser welding is used in approximately 99% of all TWBs application [2–4]. Laser welding is fast, precise, reliable and able to join a wide variety of materials, both varying in thickness and type.

During laser welding, the interaction of intense laser radiation with a workpiece leads to the formation of a long, thin and cylindrical cavity in a metal, called a keyhole. Generation of a keyhole enables the laser beam to penetrate the workpiece and is essential for deep welding. The keyhole contains ionized metal vapor and is surrounded by molten material called the weld pool. The metal

vapor which flows from the keyhole mixes with the shielding gas flowing from the opposite direction and forms a plasma plume over the keyhole mouth. The plasma plume has considerable influence on the processing conditions. Plasma strongly absorbs laser radiation and significantly changes energy transfer from the laser beam to a material [5].

The interaction between beam and matter is a complex phenomenon and it deeply influences the manufacturing process both in terms of applicability on a specific material and in terms of productivity and cost effectiveness. A plasma plume is generated due to this interaction by the ionization of both the shielding gas surrounding the welding zone and the metal vapors coming from the base material. The plasma plume causes undesired effects on the laser beam, such as energy absorption and defocusing. The most used engineering materials are metals and many of them are very reactive at high temperatures with either oxygen or nitrogen or hydrogen. Both the base metal reactivity with respect to the welding atmosphere and the plasma plume formation are taken under control by implementing different strategies of applications of the shielding gases. According to this, the gas exploited with these purposes should undergo some specific characteristics such as high ionization potential, inertia with respect to high temperature and base material components, high kinetic energy of the gas flux which deviate the plume away from the beam path and high distribution area which shielded the welding zone from the environmental atmosphere [6]. Due to its relevance to the heat transfer efficiency and stability of the laser welding process, laser induced plasma has been studied and reported on by numerous researchers [7–13].

In this paper, two groups of CO<sub>2</sub> laser beam welding experiments were carried out on the tailored blanks of DP600/TRIP700

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**Table 1**  
Chemical compositions (wt% measured)<sup>a</sup> of DP and TRIP steel.

|         | C     | Mn    | Al    | Si    | P     | S      | Cr    | Ni    | Zn    |
|---------|-------|-------|-------|-------|-------|--------|-------|-------|-------|
| DP600   | 0.057 | 0.860 | 0.029 | 0.096 | 0.026 | <0.001 | 0.418 | 0.039 | 0.004 |
| TRIP700 | 0.182 | 1.560 | 1.040 | 0.368 | 0.071 | <0.001 | 0.016 | 0.029 | 0.015 |

<sup>a</sup>  $X_{wt\% \text{ actual}} = [X_{wt\% \text{ measured}}] \pm [(2-3 \text{ accuracy}) \times (X_{wt\% \text{ measured}})]$ .

sheets to investigate the effect of the shielding gas types and flow rates on the weld penetration, tensile strength and formability aspects.

## 2. Experimental work

### 2.1. Material selection

2.5 mm uncoated DP600 and 1.2 mm galvanized TRIP700 steel sheets were used in this study. The chemical compositions of the investigated steels were determined by the optical emission spectrometer (accuracy =  $\pm 2-3\%$  relative) and summarized in Table 1. DP steel is composed of ferrite as a matrix and 13% martensite which decorates the ferrite grains, while TRIP steel is composed of ferrite as a matrix, 16% bainite and 11% retained austenite. The microstructures of the studied steels, observed by optical microscopy, are shown in Fig. 1.

### 2.2. Laser beam welding

Butt welding was made using a continuous wave (10.6  $\mu\text{m}$ ) CO<sub>2</sub> laser with a maximum beam power of 6 kW. In the set of experiments, the power of the CO<sub>2</sub> laser beam was maintained at 4 kW, travel speed at 4.2 m/min (70 mm/s) and the focus was on the top surface of the specimen. The mode of the laser was TEM<sub>10</sub> (transversal electronic–magnetic) and the laser beam was passed through four reflectors before a 200 mm focal length focusing mirror providing a focused spot size of approximately 0.3 mm diameter. The shielding gas nozzle was inclined the 45° and positioned in front of the laser beam source. The shielding gas nozzle diameter was 6 mm. The experimental set-up was shown in Fig. 2 and the process parameters were varied according to Table 2. The experiments A–F were used to study the effect of shielding gas type while experiments A and G were used to study the effect of gas velocity.

### 2.3. Mechanical characterization of base metals and welded sheets

Two transverse samples were cut from representative welds for each macrosection observations (weld dimensions), microhardness

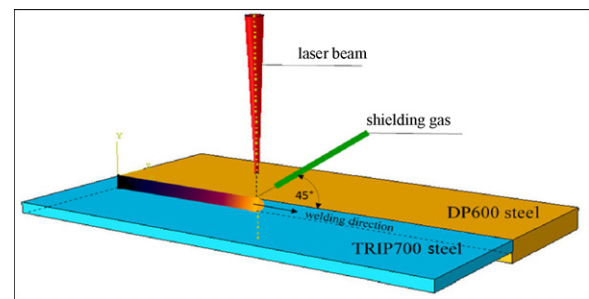


**Fig. 2.** A schematic set-up of laser beam welding process.

measurements, tensile properties determination and formability evaluations. The average of two values of weld penetration, ultimate strength, elongation and formability limit were recorded and used in this research.

Vickers microhardness testing using DIN EN 1043-2: 1996 (HV 0.1) was conducted on nital etched samples with load holding time of 10 s and measured by 0.1 mm intervals on a virtual line located in the half of the welds. The weld penetration was investigated by a penetration ratio (PR) which is the ratio of weld penetration depth to TRIP steel thickness ( $PR = D_{\text{weld}}/T_{\text{TRI steel}}$ ).

Uniaxial tensile testing was used to evaluate the tensile properties of the base metals using DIN EN 10002-1: 2001. Transverse samples were cut from representative welds by the electrical discharge machining technique for tensile properties evaluations of the welded sheets according to DIN EN 895: 1995. The crosshead speed was constant in all tensile tests and equal to 10 mm/min. The standard tensile properties (yield stress, ultimate tensile strength and elongation) were determined. In the tensile test, the strength ratio (SR) and elongation ratio (ER) were measured for the transverse welded specimen along tensile direction. The SR is defined as the ratio of the tensile strength of the weld to that of the base metal TRIP700 steel ( $SR = \sigma_{\text{weld}}/\sigma_{\text{TRI steel}}$ ). The elongation ratio (ER) is defined as the ratio of the elongation at ultimate strength of the weld to that of the base metal TRIP700 steel ( $ER = \text{elongation}_{\text{weld}}/\text{elongation}_{\text{TRI steel}}$ ).

The formability of both base metals and welded sheets was evaluated using the Erichsen test according to DIN EN ISO 20482. The welded specimens were carefully placed to locate the weld line at the centre of the dome punch. A 20 mm diameter hemispherical punch was used with a velocity of 10 mm/min. Draw-in of the specimens was resisted by 200 kN as sheet holder force to assure a pure stretching condition. The resulting stress state was nearly biaxial with strain in both transverse (perpendicular) and longitudinal (parallel) directions with respect to the weld line. Each coupon was stretched to failure and the limiting dome height was taken at the peak punch load. To minimize friction between the punch and sheet, specimens were cleaned and lightly coated with graphitized grease. The dies were thoroughly cleaned before each test. The welded samples were positioned with the bottom of the weld facing out so that the punch made contact with the front side.

**Table 2**  
Experimental procedure.

| Exp. code | Shielding gas |                |                   |
|-----------|---------------|----------------|-------------------|
|           | Type          | Speed (cm/min) | Flow rate (l/min) |
| A         | He            | 7.08           | 20                |
| B         | 75% He–25% Ar | 7.08           | 20                |
| C         | 50% He–50% Ar | 7.08           | 20                |
| D         | 25% He–75% Ar | 7.08           | 20                |
| E         | Ar            | 7.08           | 20                |
| F         | Atmosphere    | –              | –                 |
| G         | He            | 3.54           | 10                |

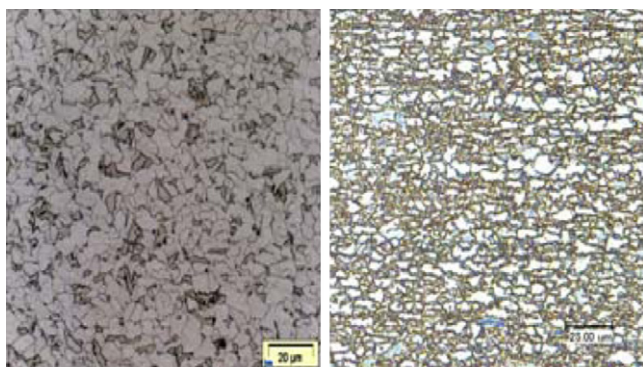


**Fig. 1.** Base metals microstructures.

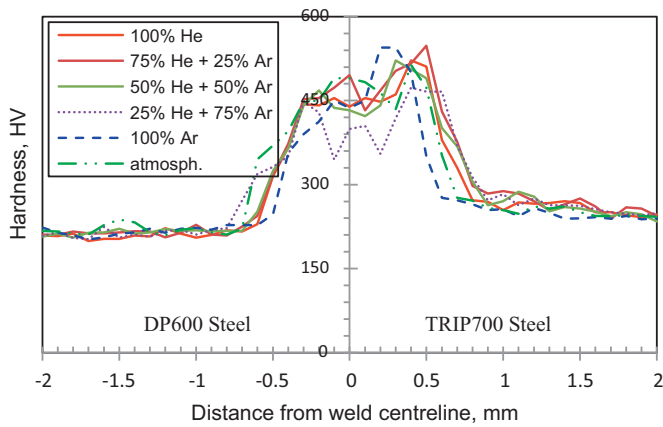


Fig. 3. Hardness distribution (DIN EN 1043-2: 1996, 100 g as a load and 10 s as a load holding time).

Fracture ratio ( $FR = LDH_{\text{weld}} / LDH_{\text{TRI steel}}$ ) is defined as the ratio of fracture height in the weld to that in the base metal TRIP700 steel. In addition, fracture position and morphology on each specimen were recorded.

### 3. Results and discussion

#### 3.1. Weld geometry profile and penetration ratio (PR)

Fig. 3 shows the characteristic weld hardness distributions under the tested shielding gases (group I) at 0.1 mm intervals along virtual line at a half of the welds. The hardness reached maximum value not only in the weld metal but also in the HAZ near the weld metal and decreased where approaching the base metal along the virtual line. The base metal hardness for DP600 and TRIP700 was 200 and 260 HV, respectively. Fig. 4 shows the surface and cross-section morphologies of weld using different shielding gases. The weld of E condition, shown in Fig. 4, had shallow penetration and this was due to the instability of the welding process as a result in the plume formation which consisted of the interaction between the material plasma and Ar shielding gas plasma. Ar (condition E) frequently produced lots of spatter, so it produced a bad surface

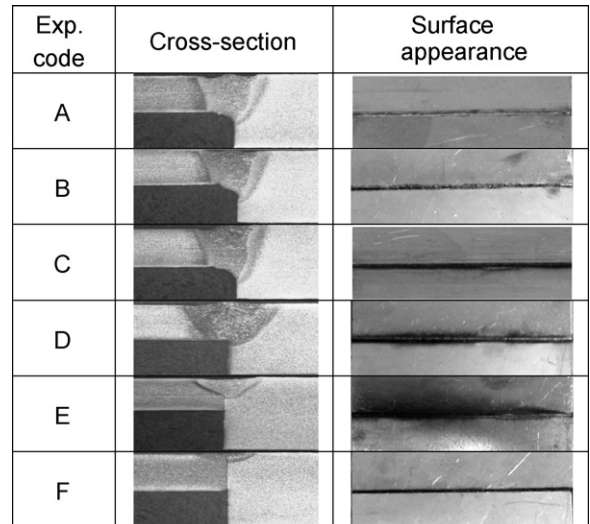


Fig. 4. Cross-sections and surface appearance of the welds.

appearance for a weld bead. However, the weld of 100% He had a continuous and uniform surface morphology together with a stable welding process and a full weld penetration. These indicate that the effects of shielding gas on the laser welding are strong. It was concluded that in high power CO<sub>2</sub> laser welding, the laser induced plasma resulting from the ionization of the shielding gas at the laser incident point could defocus the laser energy, decrease the weld penetration and even bring on the disappearance of laser keyhole.

#### 3.2. Uniaxial tensile testing

Fig. 5 shows the top and side views of a failed welded sheets specimen under uniaxial tension. In Fig. 5, the side view through the A–D samples width shows a shear failure mode where the fracture surfaces are inclined at 45° with respect to the loading direction, as seen in the left side of Fig. 5b. The deformation can be considered to be under a plane stress loading condition since the thickness of the specimen is much less than the width. This form of ductile fracture occurs in stages that initiate after necking begins, where small microvoids form in the interior of the material

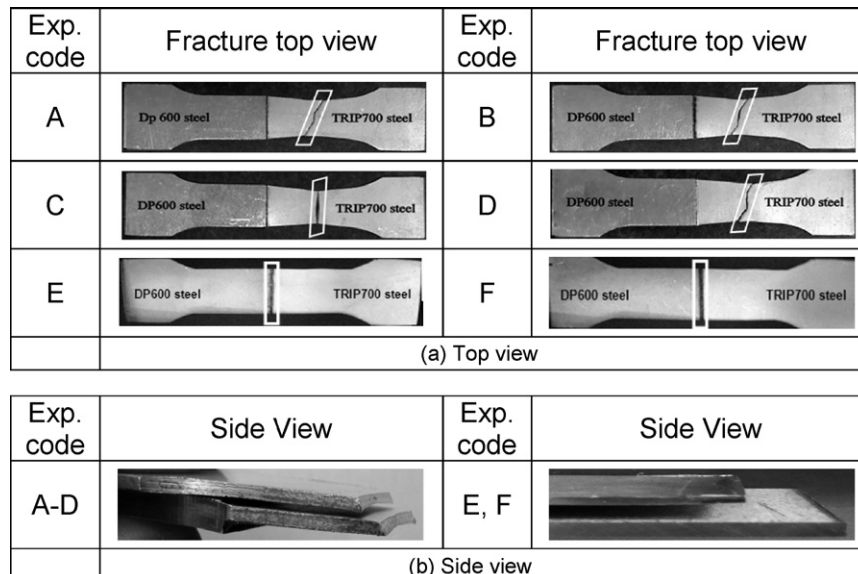


Fig. 5. Tensile test fractures.

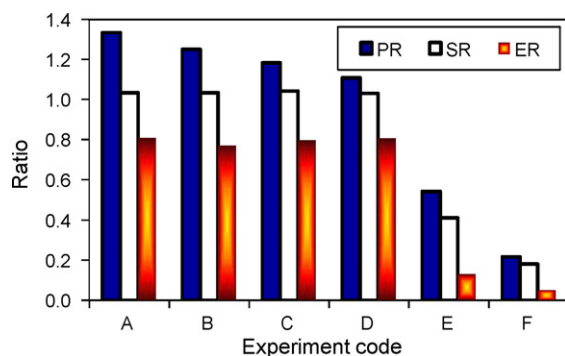


Fig. 6. Penetration, strength and elongation ratios related to the evaluated shielding gases.

and enlarge to form a crack. The crack continues to grow and spreads laterally towards the edges of the specimen. Finally, crack propagation is rapid along a surface that makes about a  $45^\circ$  angle with the tensile stress axis. In E and F experiments, the fracture is considered as a brittle fracture, where brittle fracture is a rapid run of cracks through a stressed material. The cracks run close to perpendicular to the applied stress. This perpendicular fracture leaves a relatively flat surface at the break, as given in the right side of Fig. 5b. Fig. 6 shows the relation among the penetration, strength and elongation ratios and evaluated shielding gases. It was found that the lower penetration ratio, the lower the strength ratio. The best strength ratio is achieved when 100% He is used as a shielding gas. The worst strength ratio was produced when shielding gas was not used (welding in atmosphere).

### 3.3. Formability test and formability ratio (FR)

Biaxial stretch formability testing for base metals and welded blanks was performed by standard Erichsen testing. Fig. 7 shows top views of formability fracture of the welded blanks and it shows that in A–D experiments, all fractures took place in the TRIP steel base material where the crack starts from fusion zone (the highest hardness region) and propagates in TRIP steel sheet (the thinner sheet) with a crescent shaped path at a different radial distance from the weld centerline.

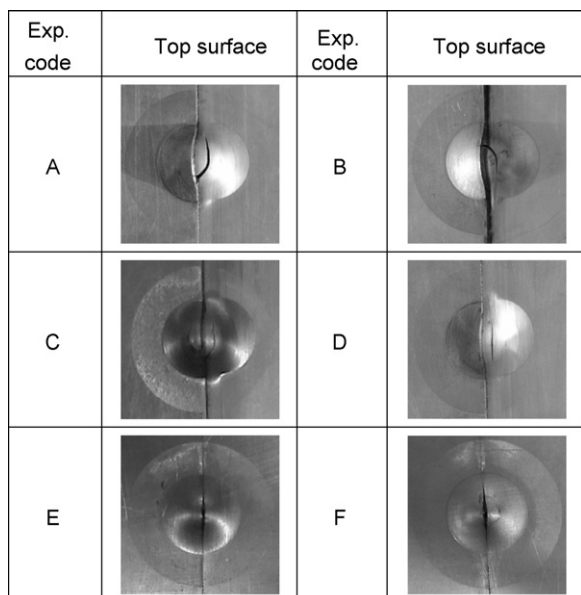


Fig. 7. Top views of Erichsen test specimen after fracture.

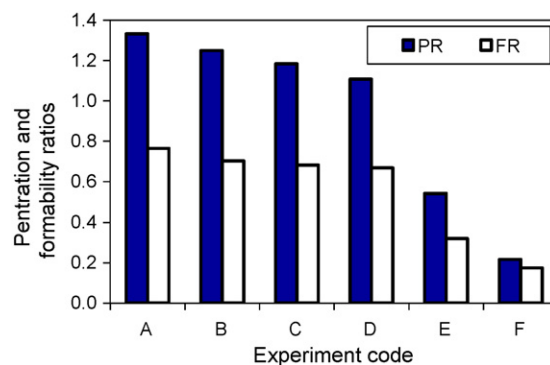


Fig. 8. Penetration and formability ratios related to the evaluated shielding gases.

Dissimilar properties of two pieces of sheet metal in a tailor welded blank can cause forming problems such as decreased formability and/or metal flow. Generally, a thinner material resists a much smaller force than a thicker material. When the thinner material undergoes plastic deformation, the thicker one is still deforming in the elastic region. This is why the TWBs fail at their thinner region. The weld line may move towards thicker material because the thinner, weaker material undergoes more deformation than the thicker, stronger one during the deformation process. This kind of weld line movement can finally result in tearing failure of the thinner material. In E and F experiments, the fractures took place in the weld zone and the crack initiated and propagated along the weld line. By decreasing the penetration ratio, the formability ratio also decreased and this is shown in Fig. 8.

### 3.4. Shielding gases and welding process stability

Zinc vaporizes at a temperature of 1180 K whereas steel starts to melt at 1809 K. Due to this huge difference problems occur during the laser welding of galvanized steels especially in lap joints. This problem is less effective in butt joints so the effect of zinc evaporation was neglected in this study.

High power CO<sub>2</sub> laser welding was characterized by the interaction between the plasma and incident laser beam. The height of this interaction is named interacting plasma height. The plasma interacting height had a significant effect on the energy transfer during the CO<sub>2</sub> laser welding process and it can be mathematically described as [10]:

$$I(h) = I_0 \exp(-\beta h) \quad (1)$$

where  $I(h)$  is the laser energy transmitted through plasma,  $I_0$  is the laser incident energy,  $\beta$  is the plasma absorption coefficient for laser energy and  $h$  is the plasma interacting height. The laser energy absorbed by workpiece equals to  $I(h) \cdot (1 - R)$  where  $R$  is workpiece reflectivity. For small  $R$ , the laser energy absorbed by workpiece approximately equals to that transmitted through plasma. So in the CO<sub>2</sub> welding process, the higher the interacting plasma height, the smaller the laser energy absorbed by workpiece and the shallower the weld penetration. The ideal interacting plasma height, which guarantees the optimum absorbed energy, can be obtained by changing the nozzle direction and flow rate of the shielding gas.

Shielding gas played the role of suppressing plasma plume, preventing oxidation and protecting the optics against spatter in the laser welding. The plasma had a special period (formation–growth–disappearance), as noticed by a high speed camera, which was closely related to potential differences between the substrate and shielding gas ionization potentials, where the larger the difference in potential, the longer the plasma period. When the plasma did not exist during the period, the incident laser beam directly reached the workpiece and acquired full penetra-

**Table 3**

Characteristic properties of shielding gases and base material.

| Properties                           | Shielding gas |        |               |               |               |       | Fe    | Zn |
|--------------------------------------|---------------|--------|---------------|---------------|---------------|-------|-------|----|
|                                      | He            | Ar     | 75% He–25% Ar | 50% He–50% Ar | 25% He–75% Ar |       |       |    |
| Ionization potential (eV)            | 24.5          | 15.76  | 22.315        | 20.13         | 17.945        | 7.83  | 0.793 |    |
| Ion. P. difference (eV) <sup>a</sup> | 16.67         | 7.93   | 14.485        | 12.30         | 10.115        | –     | –     |    |
| Th. conductivity (W/mK)              | 0.1381        | 0.0159 | 0.1076        | 0.077         | 0.0465        | –     | –     |    |
| Atomic weight (g/mol)                | 4.00          | 39.95  | 43.95         | 43.95         | 43.95         | 55.85 | 65.37 |    |
| Density (kg/m <sup>3</sup> )         | 0.178         | 1.784  | –             | –             | –             | 7870  | 7140  |    |

<sup>a</sup> Ionization potential difference (eV) = ionization potential of shielding gas – ionization potential of iron.

tion. Table 3 represents ionization potentials, atomic weights and densities of the shielding gases and base material.

Therefore, it was necessary to remove the plasma plume by the shielding gas for obtaining a full penetration. As the incident laser beam reached the base metal, the iron first ionized to Fe<sup>2+</sup> with a low ionization potential (7.83 eV). The shielding gas removed the plume and it could also be directly ionized at its own ionized potential, as listed in Table 3.

Helium had a very good thermal conductivity and a better ability to suppress plasma formation because it had very high (24.5 eV) ionization potential. Thus, helium had the longest plasma period and had very satisfactory penetration result, as seen in Fig. 4. The plasma plume formation of He, carbon dioxide and Ar gas was studied in previous work [11,13] and it was found that the plume of helium had an oval shape on the workpiece and it could be controlled by a very small shielding gas flow rate. Generally, helium was known as the best shielding gas for achieving the required penetration and formability for high power CO<sub>2</sub> laser welding. But economically, it is more expensive than other shielding gases, the average prices of He and Ar are approximately 9.5 and 3.8 €/1 m<sup>3</sup> of gas, respectively according to German prices—April 2010.

As shown in Table 3, Ar had lower ionization potential (15.76 eV) than helium and it had one-tenth as much thermal conductivity as helium. Although Ar had a large ionization potential difference compared to iron, full penetration did not occur. Thus it formed a plume which was largely confined to being above the workpiece [11,13]. Therefore, Ar was very unsatisfactory for penetration and formability, as shown in Figs. 4 and 6. Ar also frequently produced lots of spatter, so it produced a bad surface appearance for a weld bead. Conclusively, Ar was the worst shielding gas for high power CO<sub>2</sub> laser welding.

According to Eq. (1), the lower  $\beta$  value, the higher the absorbed energy by the workpiece. It was found that  $\beta$  of the He–Fe plasma was much lower than that of Ar–Fe [10], so the addition of Ar can decrease the laser energy absorbed by workpiece and also the weld penetration. When a mixture of He and Ar was used as a shielding gas, its ionization potential falls between the ionization potential of He (high, 24.5 eV) and of Ar (low, 15.76 eV), as listed in Table 3. It was found that the lower the He percentage in He–Ar mixture, the lower the penetration, strength and formability ratios.

In order to increase the shielding gas speed (cm/min) impacted on the interaction zone, a higher shielding gas rate (cm<sup>3</sup>/min) was used. The gas velocity ( $V$ ) is computed by the nozzle diameter ( $d$ ) and the gas flow rate ( $V_{FR}$ ) reading from flowmeter and it can be presented by Eq. (2):

$$V_g = \frac{4V_{FR}}{\pi d^2} \quad (2)$$

The gas velocities, were examined in this research, were 7.08 and 3.54 cm/min where the shielding gas nozzle diameter is 6 mm. The welding process is then strongly affected and it was observed that the weld width is decreased, as shown in Figs. 9 and 10. Our result was accepted with the previous studies [12]. When the shielding gas speed in the interaction zone increases, the weld width and the plasma plume size are reduced where the high shielding gas

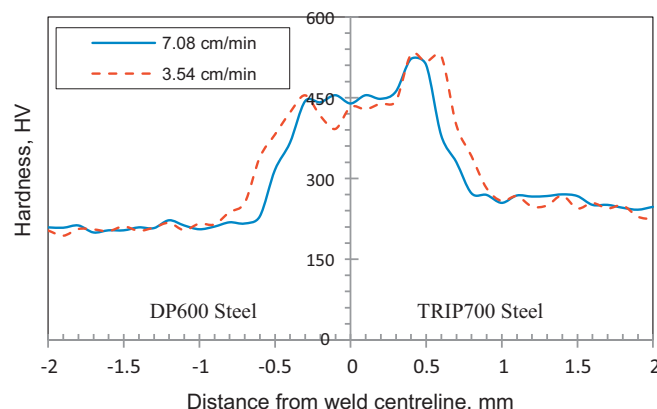


**Fig. 9.** Hardness distribution at 7.08 and 3.54 cm/min helium speed (DIN EN 1043-2: 1996, 100 g as a load and 10 s as a load holding time).

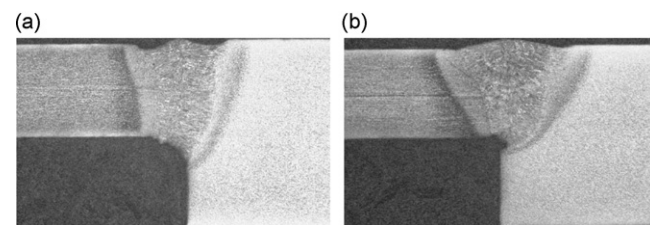


**Fig. 10.** Macrosections of the welds at a) 7.08, sample A, and b) 3.54 cm/min, sample G, helium speed.

speeds increase heat loss produced by the convection on the top surface of weld pool affecting the metal vapor flow ejected from the capillary. This allows the hydrodynamic flow to move faster and ionization–recombination opportunities to enhance. The plasma fluctuation was related to the keyhole instability and this fluctuation was likely caused by the variation of the keyhole opening.

#### 4. Conclusions and future plan

This paper evaluated the effects of shielding gas types and flow rates on CO<sub>2</sub> laser tailored blank weldability of DP/TRIP automotive steels. The following points were concluded:

- CO<sub>2</sub> laser welding of DP/TRIP steel sheets was strongly influenced by changing shielding gas types and speed.
- He was better than Ar as a shielding gas for achieving the penetration and formability for CO<sub>2</sub> laser beam welding of DP600/TRIP700 steel sheets, but economically, it is more expensive. So it is so important to make a correlation between the shielding gas price and the desired properties.
- The higher the helium shielding gas speed (flow rate), the deeper the weld penetration and the lower weld width.

Looking forward to numerical simulation of the influences of shielding gases on laser weldability of tailor blanks of advanced high strength steels can be carried out in the next work.

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