

Laser Travel Speed, Interfacial Reaction-Layer Thickness, and Tensile-Shear Performance in DP600–AA6061-T6 Lap Joints: A Critical Process-Window Assessment

Nsini Udo

nsinicanada@yahoo.com

Independent Researcher

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Abstract

The joining of advanced high-strength steel with aluminium alloy has led to a new method for constructing energy efficient, weight-reduced structures especially in the automotive and transportation industry. However, joining these two different materials is difficult due to differences in their thermo-physical properties, melting mechanisms and chemical affinity. The formation of brittle iron – aluminium intermetallic compounds (IMC) as well as poor wetting and melting performance along with inhomogeneous heat distribution remains the greatest challenge.

This study investigates how the laser travel speeds affect the heating cycles, interfacial microstructures, IMC thickness, and tensile-shear properties of lap joints between 1.2 mm DP600 and 1.5 mm AA6061-T6 aluminium alloy by using the 2.2 kW continuous wave fiber laser. The laser travel speeds were 0.4, 0.6, 0.8, 1.0, and 1.2 m/min.

The results indicate that 0.8 m/min appears to produce the best overall compromise, with a tensile-shear strength of 218 ± 9 MPa and IMC thickness of 3.8 ± 0.5 μm . Reaction layer thickness was greater at lower travel speeds due to slower reaction kinetics, which led to poorer joint strength; thinner reaction layers at higher speeds led to poorer joints due to deficient bonding, not necessarily thinner reaction layers. This suggests that improvement in reaction layer thickness alone will not produce better joints.

The present work proposes to optimize the process window assuming raw measurements have been validated, interaction time calculated, thermal-model output and Fe-Al phases identified.

1. Introduction

1.1 Background and motivation

Growing demand for light-weight structures has driven the increasing use of multi-material architectures, combining the

structural strength of steel with the low density of aluminum alloys. In automotive and transport engineering, a well

designed steel-aluminum assembly can represent the most cost-effective compromise of structural strength and stiffness

against weight and energy efficiency. The key challenge is not simply to bond two different materials, but to find a

suitable interface that is able to transfer load in a reliable manner, without creating detrimental brittle phases, excessive

distortions or unwelcome flaws that would undermine service performance. Review papers on laser joining of aluminum

and steel pointed out that the difference in the physical and chemical properties, as well as formation of brittle Fe-Al

phases are a major obstacle to the production of good, consistent joints [1–3]

DP600 is a dual-phase advanced high-strength steel, which relies on a ferritic/martensitic microstructure for its mechanical properties. The material is commonly used in vehicles and other products where strength and ductility are often required in combination. AA6061-T6 is a precipitation-hardening aluminum alloy which might be chosen for its relatively low density, favorable strength-to-weight ratio, corrosion resistance and ease of processing. These materials could provide complementary characteristics to a hybrid part but the dissimilarity in thermal conductivities, melting temperatures and ranges, expansion and chemical composition is an issue for fusion-based joining methods.

Laser joining is not the same and laser melting of aluminum and steel is not equivalent; aluminum has a high rate of heat conduction, with a relatively low melting temperature. When irradiated with the same energy to achieve melting of steel, aluminum may melt excessively or degrade, while ensuring a setting that maintains the aluminum sheet will fail to activate the steel-side interface, resulting in a small process window. Laser joining is thus attractive because the energy input is confined, the travel speed is controllable and it is compatible with robotic automation to allow both spatial and temporal control of the heat distribution. While process stability and the quality of the joint appear to depend on more than just the number of laser power: beam profile, joint geometry, surface condition, focus position, sheet thickness, shield gas and thermal parameters assigned to the finite element numerical model are all important factors [1, 3, 4].

A further problem is the development of IMC phases such as Fe-Al compounds at the interface. These phases form as a result of the interaction of the Fe with the aluminum once enough time and temperature for significant interdiffusion and reaction has passed. While some IMC at the interface may be advantageous and provide better metallurgical bonds, poorly placed, too much growth or what may be an inappropriate morphology could result in a site for brittle separation and decline in load bearing capacity of the joint. The comparison of IMC thickness with strength is an important consideration and will not necessarily show a simple one-to-one relationship between the two. A very thin layer formed in an area of poor wetting or poor contact may not give the desired high strength. On the other hand a filmic IMC may be deeper and also associated with relatively strong bonding but possibly even more prone to brittle separation. A practical compromise would be to develop a well-controlled layer of reaction with sufficient wetting/contact and load transfer.

Laser welding-brazing techniques, such as laser assisted joining (LAJ), laser welding-brazing and laser welding, have been also explored as approaches for controlling the melting level of both sides of an aluminum-steel joint. The key idea behind this process is to adjust the heat input to produce a joined

aluminum-steel system with sufficient integrity, while avoiding the excessive mixing and growth of brittle reaction products [1, 3, 4].

1.2 The role of thermal modelling

Numerical thermal modeling can help explain why different travel speeds produce different interfacial conditions. For example, a model can predict the temperature distribution, heating and cooling rates, size of the heated region, and how long the interface is held within a particular temperature range. These outputs can be used to compare process settings and interpret microstructure changes. They might also help to determine whether a trend observed at different travel speeds is consistent with the expected impact of travel speed.

However, temperature predictions from a numerical model alone do not constitute proof of weld integrity, and that a model's applications depend on physical assumptions, boundary conditions, property data, mesh resolution, laser source treatment and calibration process. Calibration to temperature measurements at a few locations can give a model reasonable agreement with those measurements without necessarily providing accurate predictions in other locations. For this reason, the modeling procedure should distinguish model inputs, derived outputs, quantities measured independently and quantities inferred by the model.

This differentiation becomes even more important when considering the joining of dissimilar materials such as aluminum to steel. Different materials can evolve completely different behaviors to the heat applied to join them and depending on the local thermal history and the chemistry at the interface, different phases can form. A model might predict a certain temperature for a given region of a joint, but it does not necessarily determine which IMC phases formed or the kinetics of their formation. These questions need to be answered by characterization including microstructural and compositional studies. The relevance of modeling combined with characterization is in the information both of them provide: the model (the predicted thermal conditions) and microscope/chemical analysis/mechanical testing (structure and property of the joint).

1.3 Intermetallic compounds and the strength of dissimilar joints

The final region to be considered is the Fe-Al interface as the mechanical response of the joint may be controlled by a very narrow region and may be very different from that of the parent material. As the Fe-Al reaction product may be very hard and relatively brittle the amount present; its location; geometry; and continued presence could all effect fracture mode. The phases identified in aluminum-steel joining experiments include Fe_2Al_5 and $\text{Fe}_4\text{Al}_{13}$ or FeAl_3 -type, also used as a lump term for the phases present in simplified phase diagrams.

Wallerstein et al. [5] example, used electron-diffraction-based techniques to characterize intermetallic phases in the aluminum-steel joints formed by laser welding-brazing with the Al-Si filler metals. This case shows how the phase identification can be inconclusive from appearance of the interface or the

EDS analysis of local composition. EDS can determine elemental composition locally, but composition cannot necessarily differentiate between crystallographically differing phases, when the analysed region contains more than one element. This point is relevant to the interpretation of the FeAl_3 -type and Fe_2Al_5 -type layers reported here.

Another contributor to mechanical behavior is the geometry and presence of imperfections of a joint. When subjected to lap-shear loading, the nominal stress across the overlap is not uniform. This is because the applied load may induce local flexure and the generation of stress concentrations, while the apparent strength is influenced by bonded area, overlap length, alignment, sheet thickness, defects and initiation point of failure. Tensile-shear value should be considered in respect of the specimen and test procedure rather than as a material property independent of geometry.

1.4 Research problem and knowledge gap

Several authors have shown that aluminum-steel laser joining process parameters have an effect on the reaction layer formed at the interface and that the microstructure formed correlates with the mechanical properties of the joint. Results indicate that considering only one of the factors, such as the thermal profile, the IMC formed, the nature of the joint or failure mode, does not provide a sufficient method for classifying results into a useful process window. A potentially useful travel speed could suppress thermal input and limit the reaction layer, but inhibit the formation of a continuous bond. A lower travel speed may promote wetting and the extent of bond, but also of the reaction layer.

This work deals with this concern by studying a lap joint between DP600 steel and AA6061-T6 aluminum for five laser travel speeds at 2.2kW nominal power. The data presented are maximum interface temperatures, interaction duration, IMC thickness, tensile-shear strength, joint efficiency and failure mode descriptions. The paper discusses these findings to determine which conditions produced the strongest results, and investigates the relationships between each of the thermal and microstructural factors measured with the observed strength response.

The manuscript is also somewhat fussy about the numerical model and phase interpretation. Instead of reporting the values obtained from the model as well proven facts, it delineates the checks which confirm their accuracy. That is crucial, because the source data summary from which the published spectrum of derived quantities is calculated exhibits an obvious discrepancy between the stated interaction time threshold and two of the reported maximum temperatures, which must be resolved against the original thermal traces or model calculations before a definitive paper can be submitted.

1.5 Aim and objectives

The primary objective is to investigate the influence of laser travel speed on the heat build-up, interfacial microstructure, IMC layer thickness, and tensile-shear strength of the DP600-AA6061-T6 lap joints.

The objectives are:

- In order to compare the peak interface temperature and interaction time reported for five travel-speed conditions.
- To explore the correlation of the travel speed and the measured total thickness of interfacial reaction layer.
- In order to evaluate the tensile-shear strength and the calculated joint efficiency between the tested conditions.
- To analyze the failure modes reported in terms of the competition between excessive reaction layer growth and inadequate bonding.
- To evaluate the total evidential boundaries of the thermal model and phase designations and determine what further verification might be required for a robust optimization claim.

1.6 Research questions

The analysis is guided by four questions:

- What happened to the observed thermal response and interfacial reaction-layer thickness when travel speed was altered?
- In which tested travel speed is the maximum tensile-shear strength reported?
- Does the trend in strength make the case for the thinnest IMC layer possible?
- What tests must be carried out before the thermal model and phase assignments can be considered as validated answers to the joint behavior?

1.7 Contribution and scope

The main contribution is a systematic reading of the reported five-condition data set, and correlating process

parameters to temperature indicators, IMC thickness and mechanical behavior. Although the intermediate

speed condition emerges as the strongest of the tested parameters, the work is contextualized within a process

window explanation that a balanced interfacial reaction is necessary but brittle reaction products must not

become too thick.

The scope is the reported material pair, sheet thicknesses, lap configuration, laser power and travel-speed

range. There is no claim that the tested laser power and travel speed ranges are optimum for all DP600

aluminum joints, nor has any durability to fatigue, impact, corrosion or service duration been quantified.

Although a numerical thermal model is presented, a validated predictive capability is not implied unless model

inputs, numerical convergence, experimental validation and an uncertainty estimate are provided. These and

other scope limits are clear throughout the manuscript.

2. Materials and methods

2.1 Materials and joint configuration

The study included a dissimilar lap joint between advanced high strength steel DP600 and aluminium alloy AA6061-T6. Steel-sheet thickness was specified as 1.2 mm, and aluminium-sheet thickness was specified as 1.5 mm. The dimensions of the specimen were 100 mm × 45 mm, with a nominal overlap of 15 mm. These dimensions establish the geometry that will be used to interpret the reported tensile-shear results and should be kept consistent throughout the experimental drawing, specimen preparation documentation, and final test standard documentation.

The materials used were to study the welding of a high strength steel to a precipitation-hardened aluminum alloy. The difference in the two materials involves two aspects. Firstly, there will be variations in the thermal fields due to the nature of their thermal properties; and secondly there may be Fe-Al reaction products at the contact of the iron and aluminum rich regions. Effect of thermal history, interface reaction and joint configuration is thus important in the final mechanical response.

Table 1
Materials, specimen geometry, and reported process configuration

Parameter	Reported value
Steel	DP600 advanced high-strength steel
Aluminium alloy	AA6061-T6
Steel thickness	1.2 mm
Aluminium thickness	1.5 mm
Specimen dimensions	100 mm × 45 mm
Lap overlap	15 mm
Laser source	IPG YLR-4000 continuous-wave fibre laser
Nominal laser wavelength	1060 nm
Nominal laser power used in the study	2.2 kW
Reported beam spot radius	0.3 mm
Manipulation system	KUKA six-axis robot
Shielding gas	Argon, 99.99% purity
Reported shielding-gas flow rate	15 L/min
Travel-speed conditions	0.4, 0.6, 0.8, 1.0, and 1.2 m/min

Table 1 details the materials, specimen geometry and laser-processing configuration for this study. The DP600 steel and AA6061-T6 aluminum alloy specimens had thicknesses of 1.2 and 1.5mm respectively and a lap overlap of 15mm. The laser joining process involved a continuous-wave fibre laser positioned on a six-axis robot arm with argon shielding to mitigate oxidation of the join region. Five travel speeds, from 0.4 to 1.2m/min, were examined to assess the effects upon interfacial reactions, intermetallic compound formation and mechanical performance of the resulting joint.

2.2 Laser processing conditions

In the experimental procedure, a continuous-wave fibre laser with a nominal power of 2.2 kW was described as the heat source. Travel speed was changed for five cases: 0.4, 0.6, 0.8, 1.0, 1.2m/min. The laser system was mounted to a six-axis robot to control the relative motion of the beam and the joint. Argon gas (99.99% purity and a flow rate of 15L/min) was used as shield gas.

This is another critical process variable as it affects the duration of the test material location being exposed to the moving heat source. At constant nominal power, the faster the speed, the less energy is delivered to the test specimen location per unit length. Nominal line energy can be calculated as -.

$$E_l = P / v \quad (1)$$

where E_l is the nominal energy per unit length, P is the laser power, and v is the travel speed expressed in consistent units. If laser power is given in watts and travel speed in millimeters per second, E_l is expressed in joules per millimeter.

This parameter is very useful to compare different laser processing parameters; however, you should not consider this as the actual energy lost at the joint. The real thermal field is governed by the material absorption, laser reflection, beam profile, conduction, radiation, convection, phase change and heat transfer between steel and aluminium sheets.

For the 5 reported velocities, the nominal line energy diminishes as the velocity increases. This behavior can be used qualitatively to interpret the lower peak temperature and shorter reported interaction time at higher velocity. It alone, however, does not support the temperature prediction nor does it support the observed (mechanical) behavior, both of which need the thermal model formulation and, preferably, measured thermal histories.

Figure 1 **Conceptual diagram of the DP600 steel and AA6061-T6 aluminum alloy sheets in lap-joint arrangement in laser joining, and the overlapped region where laser energy was delivered to create interfacial bonding. The schematic diagram is only for reference, and is not a photograph or an accurate drawing of the experimental setup.**

2.3 Thermal modelling framework

In the study to be reported, computational thermal modelling has been included to investigate the influence of travel velocity upon the thermal response of the joint. For a moving source, a transient heat-transfer model generally describes the progression of temperature with respect to time and position. A generic energy balance in a solid domain can be written as

$$\rho c_p(T) \left(\frac{\partial T}{\partial t} \right) = \nabla \cdot [k(T) \nabla T] + Q(x, y, z, t) \quad (2)$$

where ρ is the material density, $c_p(T)$ is the temperature-dependent specific heat capacity, $k(T)$ is the temperature-dependent thermal conductivity, T is temperature, t is time, and $Q(x, y, z, t)$ represents the volumetric heat input as a function of position and time, where this formulation is appropriate.

The boundary heat-flux term could then be used to specify the laser input for a surface heat source. The precise form of the equation needs to reflect the thermal model that has been actually implemented.

The moving source can then be modelled as a distribution in space with a known distribution of the source location as a function of time. A Gaussian surface heat-source model is one option for a laser beam; other formulations may be necessary where a source that penetrates into the workpiece, creates a melt-pool shape, or deposits energy through the thickness of the workpiece is required. Modelling studies in the literature show that the choice of heat-source model must consider the process regime and calibration against measured thermal cycle or weld shape [6].

In addition, the thermal model for a dissimilar lap joint needs to consider the different properties of steel and aluminum and the heat transfer at the interface. For various realizations, the assumption has to be made as for the contact can be perfect, with a given interfacial conductance or with the contact resistance. These three hypotheses can't be used simultaneously. The imperfect contact when used in the model can lead to a different temperature field as for the experimental test if the real sheets present local gaps, local surface roughness or different clamping pressure.

Material properties that vary with temperature are especially relevant if the region is close to the melting range. A model can be formulated to use room-temperature properties everywhere, for simplicity in solving, but the resulting predicted thermal field may be affected. Latent heat of melting and phase change may also have to be accounted for if melting occurs in the modeled region. As the full specification is not set in the published summary, the final paper should only state the source formulation, boundary condition, how the material property can be treated, mesh, time increment, and solver used.

2.4 Peak temperature and interaction time

The quantities measured contain 3 values of thermal output; interface temperature and interaction time. These quantities may be useful for comparison of travel-speed conditions, but the definition of interaction time must be very well specified. If interaction time is defined to be the time that a site is above a given temperature, T_c , then it can be related as:

$$t_{\text{int}} = \int I[T(t) \geq T_c] dt \quad (3)$$

where t_{int} is the interaction time, $I[\]$ is an indicator function equal to one when the temperature satisfies the specified criterion and zero otherwise, $T(t)$ is the temperature at a given location as a function of time, and T_c is the threshold temperature.

A rated peak temperature below T_c , according to this definition, means a zero-time interval above the threshold temperature for a given point and thermal history. The source data set lists an interaction-time threshold of 928 K, yet lists non-zero interaction times for the 1.0 and 1.2 m/min conditions (peak temperatures 882 K and 813 K, respectively). All three values cannot be correct for the same point, temperature trace, and threshold if they are.

None of the source records used for this revision contain the original thermal traces or post-processing outputs, so the interaction-time values provided in the table above are not available for numerical analysis. No substitution of a threshold or corrected duration. If the listed peak temperatures and interaction times correspond to the same location and traces, the non-zero durations at 1.0 and 1.2 m/min are not consistent with the 928 K threshold. The interaction-time series should not be used to interpret the reaction-layer or strength trends until the original records can be used to determine a consistent definition and calculation.

2.5 Microstructural characterization and IMC measurement

The analysis reported consists of interfacial IMC thickness, and thickness values assigned separately to FeAl_3 -type and Fe_2Al_5 -type layers. The thickness values are of interest, as the reaction layer is anticipated to have an effect on interfacial strength and fracture behavior. However, the quality of measurements varies depending on sample preparation, number of measurements and their position, resolution of images, and the way the interface is defined and the mean and uncertainty calculated.

In a robust thickness study, the interface must be scrutinized at multiple locations along the bonding area that are representative of the whole. Variations of local thickness are to be expected due to surface condition, hot spot regions, curvature of the interface, and variations of the contact. An average value must be reported along with a measure of dispersion and the procedure used to gather data. "3.8 $\pm$ 0.5 μm " however cannot be interpreted until the intended meaning of the uncertainty value is established, for example, whether it is a standard deviation, standard error, or confidence interval.

Phase identification too needs some massage. While EDS data can offer elemental distributions and estimates of local composition, it does not necessarily give a conclusive discriminant if there are crystallographically different Fe-Al phases. Studies using electron diffraction, high-resolution characterization, have highlighted how the composition needs to be reported alongside crystallography when making phase-level conclusions [5].

Therefore, the nominal nomenclature FeAl_3 -type and Fe_2Al_5 type is used herein since the author has adopted the original nomenclature. If the original structure determination was based solely on morphology and EDS, then the nomenclature should be listed as provisional phase assignments rather than definitive crystal structures. Where possible, selected-area electron diffraction, EBSD phase maps, or X-ray diffraction may be used as additional information, though they are limited by spatial resolution and sample size.

Original experimental micrographs could not be included in the source file used for this revision, so no micrograph is included or simulated. The layer thicknesses are given in numerical form and the labels for FeAl_3 -type and Fe_2Al_5 -type are assumed to be tentative assignments.

2.6 Tensile-shear testing

Tensile-shear strength was provided for every travel-speed condition. The provided source material for this revision does not specify test standard, gripping setup, loading rate or crosshead velocity, number of replicates, specific stress calculation used or the interpretation of the reported uncertainty. These cannot be reconstituted from the provided summary data and have not been fabricated. Mechanical results are provided as supplied, with caveats noted.

Where a lap joint is involved, the calculation of nominal stress needs to be explicitly mentioned. If the values are given as max load/nominal cross-sectional area then the authors need to specify the area used in the analysis and also clarify whether the MPa values reported are nominal tensile-shear or some other derived quantity. The term "strength" is ambiguous unless this information is given as the load carrying capacity of a lap specimen depends on its geometry and load application.

Failure mode was also qualitatively described for each condition. These descriptions are a valuable supplement when interpreted in conjunction with the evidence provided by the fracture surface and crack origin. A failure description alone cannot provide a definitive mode of failure; e.g. interfacial separation may result from weak interface bonding, pitting or debris, or brittle reaction-layer fracture or some combination of these. Such ideas should be checked against evidence from the fracture surface.

2.7 Joint efficiency

Joint efficiency was reported as a percentage for each experimental condition. The calculation should be clearly defined in the final manuscript. A common form is:

$$\eta_j = (S_j / S_{ref}) \times 100\% \quad (3)$$

where η_j is the joint efficiency expressed as a percentage, S_j is the measured joint strength, and S_{ref} is the specified reference strength. The reference strength may be a parent-material property or another defined benchmark. The intended reference value must be explicitly identified in the manuscript rather than assumed

As a combination of two dissimilar materials and non-uniform stress field it is only relevant to express the efficiency as a percentage when the reference strength is clearly specified. Four of the five percentages mean a reference strength near 275 MPa, while $218/275 = 79,3\%$ (not 84,2%). The latter value is therefore marked as inconsistent and not considered validated. The speculated reference and calculation are to be verified according to the original lab report.

2.8 Data analysis and interpretation

The reported peak temperature, total IMC thickness, tensile-shear strength, the reported joint-efficiency percentage, and descriptions of failure are compared for the five conditions. Interaction-time values are omitted in the comparison until the information can be revised based on the original thermal histories. The aim is to determine the most favorable condition and to differentiate the observations from unsubstantiated mechanisms.

The values reported are not used to derive a general predictive law. Five test conditions are not adequate alone to establish a strong general correlation for an IMC thickness versus joint strength relationship; certainly not when other factors such as wetting, bonded area, local discontinuities, heat-affected-zone changes can be expected to influence the results. Neither does the presence of an uncertainty estimate establish a statistical significance unless the number of replicates, definition of the uncertainty, and the method of inference are presented.

No further measurements, replicates, validation errors, or statistical tests are introduced here. Any statement of model accuracy, statistical significance or predictive ability should be provided only where the original experimental data and numerical record support it.

3. Results

3.1 Reported thermal response across travel speeds

The reported peak interface temperature drops with an increase in travel speed: 1123 K at 0.4 m/min, 813 K at 1.2 m/min.

These are 1014, 935, and 882 K at 0.6, 0.8, and 1.0 m/min respectively. As the reference does not specify whether they are obtained temperature readings or the results from the model, they are given as reported peak temperatures as opposed to confirmed thermal readings.

This trend agrees in a qualitative fashion with the anticipated decrease in nominal energy per unit length with increasing travel speed at constant laser power. The extent to which the listed peak temperatures are the measured experimental values, or the values obtained from the model, is to be indicated in the final paper. If they are model-derived values, the manner in which the peaks were extracted (e.g., a point at the interface, a spatial maximum, temperature measured at a moving observation point, etc.) should be described.

Table 2
Reported thermal indicators and total intermetallic-layer thickness

Travel speed (m/min)	Reported peak temperature (K)	Total IMC thickness (μm)
0.4	1123	8.4 ± 1.0
0.6	1014	5.8 ± 0.6
0.8	935	3.8 ± 0.5
1.0	882	1.7 ± 0.3
1.2	813	0.8 ± 0.15

Table 2. Relationship of laser travel speed to the reported peak interface temperature and total IMC thickness. As the travel speed increases from 0.4–1.2 m/min, the reported peak interface temperature, as well as the thickness of the IMC, decrease. With travel speed increasing from 0.4 to 1.2 m/min, it was found that at an intermediate travel speed of 0.8 m/min, the IMC thickness was 3.8 ± 0.5 μm at a reported peak temperature of 935 K. The interaction-time data are omitted due to discrepancies between the reported times and the designation that the interface was less than 928 K which is a temperature that should be confirmed by examining the temperature traces.

Figure 2. **Reported peak interface temperature versus travel speed from 0.4 to 1.2 m/min, showing that as the travel speed increased, less temperature was associated with each increment in speed. The interaction-time data are not shown because interaction time was inconsistent with the data reported in the temperature threshold, and will be compared with the original temperature traces.**

3.2 Variation in total IMC thickness

The total IMC thickness increases with decreasing travel speed, being $8.4 \pm 1.0 \mu\text{m}$ at 0.4 m/min and $0.8 \pm 0.15 \mu\text{m}$ at 1.2 m/min. The 0.8 m/min condition has the mean thickness of $3.8 \pm 0.5 \mu\text{m}$. The two slower travel-speed conditions have thicker layers than the two faster conditions.

This observation is consistent with the widely held theory that more extensive heating enhances the reaction layers in aluminum-steel joints. Numerous modelling and experimental studies have shown that the formation of intermetallic compounds is thermally sensitive, and that maximum temperature can affect reaction-layer growth [7–9].

This comparison helps to rule out speed of travel as a factor that would have reduced the growth of the measured reaction layer in the test series reported. However, it cannot eliminate temperature as the causal factor, since the influence of travel speed would alter spatial thermal gradients, heating and cooling rates, wetting behavior, and likely the shape of the bonded region. Moreover, the accuracy of the mean values of the reported IMC was only as good as the test measurement procedure and number of observation sets.

Figure 3 shows the incremental decrease in mean thickness of the IMC layer reported as the laser travel speed increases. The data indicate that increased travel speed constrains formation of the interfacial reaction layer. The error bars show the reported $\pm$, but the statistical definitions of those ranges were not detailed; they are not interpretable as a particular confidence interval or as test of statistical significance.

3.3 Reported subdivision of the reaction layer

Source dataset documents two sublayers, FeAl_3 -type and Fe_2Al_5 -type. Both document sublayer thicknesses of reported layers decrease with increase in travel speed. FeAl_3 -type layer decreases from $3.1 \pm 0.4 \mu\text{m}$ at 0.4 m/min to $0.3 \pm 0.05 \mu\text{m}$ at 1.2 m/min. Fe_2Al_5 -type layer decreases from $5.3 \pm 0.6 \mu\text{m}$ to $0.5 \pm 0.1 \mu\text{m}$ at 0.4 m/min.

Table 3
Reported thickness of the two interfacial sublayers

Travel speed (m/min)	FeAl ₃ -type layer (μm)	Fe ₂ Al ₅ -type layer (μm)	Reported total (μm)
0.4	3.1 ± 0.4	5.3 ± 0.6	8.4 ± 1.0
0.6	2.2 ± 0.2	3.6 ± 0.4	5.8 ± 0.6
0.8	1.4 ± 0.2	2.4 ± 0.3	3.8 ± 0.5
1.0	0.6 ± 0.1	1.1 ± 0.2	1.7 ± 0.3
1.2	0.3 ± 0.05	0.5 ± 0.1	0.8 ± 0.15

Table 3 presents the reported thicknesses of the FeAl₃-type and Fe₂Al₅-type interfacial sublayers at different laser travel speeds. Both sublayers decrease in thickness as travel speed increases from 0.4 to 1.2 m/min, resulting in a reduction in total IMC thickness from 8.4 μm to 0.8 μm. The Fe₂Al₅-type layer is consistently thicker than the FeAl₃-type layer across all tested conditions. These trends suggest that higher travel speeds restrict interfacial reaction-layer growth; however, confirmation of the specific phase assignments requires appropriate compositional and, where available, diffraction-based evidence

Figure 4: Reported thickness changes of the FeAl₃-type (top set) and the Fe₂Al₅-type (bottom set) interfacial reaction layers as functions of laser travel speed. Both FeAl₃- and Fe₂Al₅- layers show thickening with the reduction of travel speed, thus increasing interfacial reaction-layer growth. All phase labels shown in the figures are tentative and should be validated by suitable compositional and, where possible, diffraction-based analyses.

The values reported show that the Fe₂Al₅-type layer makes up the larger part of the reaction layer at all 5 speeds. This is also seen in research that shows Fe₂Al₅ as the dominant or major phase in some aluminum-steel joining processes. Yu et al. [9] saw a reaction layer formed of Fe₂Al₅ and Fe₄Al₁₃, with Fe₂Al₅ the major phase for a joint they investigated. Zhang et al. [8] similarly saw Fe₂Al₅ as one of the major phases for an aluminum-steel joint.

But the nomenclature needs to be consistent. FeAl₃ and Fe₄Al₁₃ are not always equivalent descriptors for all experiments, and boundaries may shift according to local composition and/or crystal structure. These specific assignments in this dataset are subject to confirmation via the data's original phase-identification evidence. Otherwise, these values should be accepted as instances of the reported sublayers, not as definitive identification of phases.

3.4 Tensile-shear strength and joint efficiency

The maximum tensile-shear strength reported is 218 ± 9 MPa at 0.8 m/min, which is lower than all the results at slower and faster travel speeds. The value at 0.4 m/min is 114 ± 8 MPa, increasing to 165 ± 12

MPa at 0.6 m/min. The value was at the maximum at 0.8 m/min and then decreased again to 182 ± 11 MPa at 1.0 m/min, with a further decrease to 135 ± 7 MPa at 1.2 m/min.

Table 4
Reported mechanical response and failure description

Travel speed (m/min)	Tensile-shear strength (MPa)	Joint efficiency (%)	Reported failure description
0.4	114 ± 8	41.4	Brittle cleavage at the interface
0.6	165 ± 12	60.0	Mixed-mode failure
0.8	218 ± 9	84.2 (unverified)	Ductile shear in the heat-affected zone
1.0	182 ± 11	66.1	Interfacial separation
1.2	135 ± 7	49.1	Adhesive-type unbonding

Table 4 shows the reported values of tensile-shear strength, joint efficiency and the type of failure that occurred at each of the five laser travel speeds. The tensile-shear strength appears to rise with increasing travel speed up to a maximum of 218 MPa at 0.8 m/min then fell again at greater speeds. The way in which the failure occurs during the strength test also changes with increasing travel speed; for example, it was brittle interfacial fracture at 0.4 m/min, ductile shear in the heat-affected zone at 0.8 m/min, then interfacial separation, or incomplete bonding at the highest speeds. As described, the criterion of performance test success appears to be satisfied at a travel speed of 0.8 m/min. This condition appears to give the highest tensile-shear strength, but some values such as joint efficiency are not accompanied by a specification of the reference strength used to derive them.

Figure 5. Tensile-shear strength reported as a function of laser-travel speed. Tensile-shear strength reported for the various laser speeds ranges from 114 MPa at 0.4 m/min to an optimum value of 218 MPa at 0.8 m/min, then decreases for the remaining larger speeds. Reported strength values suggest that laser travel speed of 0.8 m/min performs best in terms of the tested mechanical property. Error bar reported as $\pm$ values is reproduced in the figure, but the meaning of the statistical convention used to do so was not specified by the authors. Reported joint-efficiency value of 84.2 percent at 0.8 m/min should be verified, because it implies a strength inconsistency with the other reported percentages, including reference strength. Verify original value derivation, reference strength, test method, number of replications, and uncertainty definition.

Strength trend is also not monotonically decreasing. It increases with travel speed from the lowest value to a median maximum, then decreases at high velocities. Importantly, this characteristic indicates that the thinnest reaction layer reported is not the condition with the highest values of strength. The thinnest layer, which is reported for the 1.2 m/min condition, is $0.8 \pm 0.15 \mu\text{m}$ but it has a reported strength value of only 135 ± 7 MPa, which is less than that obtained at 0.8 m/min. This gives an insight that at higher

speeds, decrease in reaction-layer thickness can be as a result of poor interfacial reaction or poor bonded area.

The measured joint efficiency trends similarly to the tensile-shear strength, with a maximum reported efficiency of 84.2% that must be checked at 0.8 m/min. The efficiency values trend in a similar manner, which would be expected if efficiency were simply computed from the strength value using the same reference point. While this can be true, until the calculation of efficiency is checked, the efficiency values are meaningless: a percentage is not another performance metric if it is just a scaled version of strength.

3.5 Failure behavior across the process window

Failure descriptions are provided from the failed tests of the various speeds. The lowest-speed condition is listed as brittle cleavage at interface. The 0.6 m/min condition is a mixed-mode failure. The 0.8 m/min maximum-strength condition is listed as ductile shear in the heat-affected zone. The 1.0 m/min condition is listed as an interface separation, and the 1.2 m/min condition is listed as an adhesive-type unbonding.

Overall, these three points may indicate that the failure location and apparent mode change with decreasing nominal line energy. At low speed, the additional reaction layer thickness may lead to brittle behaviour at the interface. At intermediate speed, the observed change to heat-affected-zone shear implies that the interface may be sufficiently strong to cause failure outside the immediate reaction layer. At high speed, a diminished reaction-layer thickness may return to interface-type failure descriptions, implying that all bonding is incomplete.

These explanations are tentative. The ultimate explanation would be corroborated by fractography, observations across the cross-section in the vicinity of the crack path, and a demonstration that the failure descriptions were applied consistently across replicates. For example, a heat-affected-zone failure is not evidence that the interface is defect free, it is only evidence that the failure location in the tested specimen was as reported. Also, a discussion of "adhesive-type unbonding" should be informed by the fracture surface and the vocabulary of the testing laboratory..

4. Discussion

4.1 Interpreting the process window

The main finding is the maximum reported tensile-shear strength (at 0.8 m/min). The joint had a tensile-shear strength of 218.9 MPa at this speed, with a reported total IMC thickness of 3.8 $\pm$ 0.5 μ m. The slow condition produced a thicker reaction layer with lower strength, and the fast condition produced a thinner reaction layer, with again lower strength. The data appear to suggest a process response that is controlled by a tradeoff between adequate interfacial reaction and avoidance of excessive layer thickening.

For a fixed set of other process parameters, the interaction time of the laser with a given point is longer at the lower travel speeds than at the higher speeds. The higher nominal energy density (or energy per unit length) may lead to a higher degree of localised heating and facilitate formation of the reaction layer at the lower speeds. This view agrees with existing literature which links Fe-Al intermetallic formation to thermal cycling and peak temperature. Szczepaniak et al. [7] investigate the effects of thermal cycling on intermetallic phases in laser-welded aluminium-steel overlap joints, while Yu et al. [9] study the growth of reaction layers with experimental and physical modelling methods.

The lower strength at 0.4 m/min is consistent with the idea that a relatively thick, brittle reaction layer may have played a role in interface-controlled failure. However, the figure of $8.4 \pm 1.0 \mu\text{m}$ should not be considered evidence of the failure mechanism by itself. A thicker layer may have coincided with other variations in morphology, local continuity, presence of defects and localized stress concentration. Also the lap-joint geometry can lead to bending as well as local stress concentrations that influence the force reading. The evidence is consistent with an explanation not a definitive causal attribution.

However, at the opposite end of the process window, the 1.2 m/min conditions gave the least thick reported reaction layer, and did not give the highest strength. This result is significant from an optimisation perspective. It may be that a too thin reaction layer is advantageous if it is continuous, provided the wetting and intimate contact is good, but if there is not sufficient thermal energy input to produce a sufficiently well bonded interface then the lower IMC thickness may be due to not enough complete reaction having taken place, rather than a better joint. This need for further evidence from the fracture surface of the 1.2 m/min joints is mirrored in the adhesive-type unbonding of this condition.

The 0.8 m/min condition seems to be giving a better balance. This reported layer is thinner than for the 0.4 and 0.6 m/min conditions, yet the strength is greater than for all other speeds tested. The change in reported failure location to ductile shear in the heat-affected zone is also consistent with an interface that has a large enough load to transfer for failure elsewhere. However, this can only be interpreted as being true within a certain process window, and should not be assumed as being a global optimum. This conclusion is only true for the five speeds investigated at the given nominal laser power, material combination, sheet thickness, and joint geometry.

4.2 Why IMC thickness alone cannot determine joint strength

The link between IMC thickness and joint strength is debated within aluminum-steel joining due to the potential brittleness of Fe-Al reaction products. However, thickness is just one aspect of the interfacial reaction layer. The mechanical response to different IMC compositions may also be influenced by phase constitution, grain shape, distribution, continuity, spatial variation, cracks, porosity, the total bonded-area fraction and the properties of adjacent heat-affected zones.

The measure of thickness is often just a useful simplification of an interface that might have a different morphology elsewhere along a weld. An average of $3.8 \mu\text{m}$, for instance, could be characteristic of a

fairly consistent film or one that has quite a bit of local variation. They might not be expected to behave identically in service. Standard deviation, number of measurements, and where the measurements are taken might help flesh that out. A spread of local thickness measurements can give information that a single average cannot when products are unevenly distributed in a joint.

It is also a matter of phase composition. Compositions of aluminum-steel joints have identified Fe_2Al_5 , and $\text{Fe}_4\text{Al}_{13}$, as significant phases and shown that the reaction-layer shape can be affected by the thermal history and chemical composition. Zhang et al. [8] investigated IMC growth in aluminum-steel joints, and Yu et al. [9] highlighted the significance of Fe_2Al_5 in the reaction layer they studied. Wallerstein et al. [5] also illustrated how diffraction-based characterization can be used to differentiate phases in laser welding-brazing joints.

These investigations at least argue for a more cautious reading of the current findings. The quoted FeAl_3 -type and Fe_2Al_5 -type thicknesses seem to describe the detected sublayers (sub sheets, Costilla) well, but their precise phase types need confirmation from the originating analysis. Where the phase type assignments are based on EDS, the current discussion should be significantly more modest, and this manuscript can keep the qubits while using more qualified wording.

These results thus seem to argue for a multi-criteria perspective on optimization. An optimal joint should have a reaction layer at the interface, formed so as to provide bonding, but not so extensive or poorly organized as to induce brittle failure; it should have some bonded area, few defects, and properties in the heat-affected zone not too dissimilar from bulk. This is largely in accord with the other reviews of laser-based aluminum-steel joining by Yang et al. [1], Kuryntsev [2], and Li et al. [3].

4.3 Thermal modelling: value and limits

Thermal modelling is helpful because it allows us to examine quantities that might be more challenging to measure across the length of the joint, such as the transient temperature profile and local heating history. In a laser joint, the moving heat source produces a steep thermal gradient, and the local temperature history impacts aspects such as melting, solidification, diffusion at the interface, and the end microstructure. This can be useful in understanding the impact of travel speed on reaction-layer thickness.

Nevertheless, that explanation is contingent on model validation. "Numerical temperature" distribution cannot be termed experimentally validated simply because the values are physically reasonable or show an expected pattern. "A justifiable validation process should include: contrasting the model prediction to observations that were obtained experimentally but were not used to calibrate the model, specifying the point in space, time, and the measurement method, determining the difference between the predicted temperature and the measured temperature. When temperatures cannot be measured directly, contrasting the predicted weld shape or other thermal indicator to the weld shape provided by independent measurements can provide a different but equally valid type of evidence.

The heat-source formulation is of prime significance. Goldak et al. [6] developed a double-ellipsoid heat-source model for the simulation of welding processes. Subsequent investigations have adapted and validated models of the heat-source for various welding regimes. The form of the model should attempt to mirror the real process, rather than always use the same model because it is a well-established choice. Surface Gaussian sources are relevant for some laser processes; a volumetric distribution may be more appropriate for other thermal regimes. Literature on laser-welding heat-source models highlights calibration and validation of the heat source against measured thermal cycles and weld surface topology.

In the present case, the source dataset only provides peak temperature, and the rest of the data on the numerical method cannot be revealed in the summary. Therefore, the final version of paper cannot state an assumed mesh size, convergence tolerance, thermal contact coefficient, absorptivity or solver setting. It is necessary to find out that information from original model information. If the model is built based on constant thermal properties, that should be pointed out, or if temperature-dependent properties and latent heat are considered, the related sources should be pointed out.

A valuable validation table would present all of the reported model output of the paper versus its experimental counterpart, if available, for at least one set of data. For instance, the table could feature the measured and predicted peak temperatures at specific points, the deviation between the two, and the way the error was computed. If the original work does not include such a comparison, the authors should document the numerical results as model estimates with the caveat that independent validation has not been achieved.

4.4 Resolving the interaction-time inconsistency

Until the interaction-time inconsistency is resolved, no quantitative statement can be made that even a single above-928 K duration accounts for the reaction-layer trend observed. The responsibility falls on the original temperature traces and postprocessing results to validate the recorded threshold, location, and duration. Specifically, until this is rectified, the interaction-time series must be discarded for causal inference: it can be summed, but not causally explained, with the decreasing IMC thickness.

4.5 Relationship to earlier DP600–aluminum studies

The material system used in this study has been researched before. Indhu et al. [10] studied the microstructure evolution and the joint strength of laser-welded DP600 steel – aluminium joint with respect to interaction parameters, IMC thickness and softening of heat-affected-zones. Their work is applicable as it is demonstrated that the joint strength can be affected by reaction layer at interface and steel-side heat-affected-zones softening.

A note about this point is relevant to how you should interpret the reported 0.8m/min result. The failure description suggests ductile shear at the heat affected zone. This would suggest that the interface was no longer the weakest point on the tested specimen, but the data given in the report don't seem to be detailed enough to determine whether this failure was due to softening (i.e., hardness profiles or

microstructural measurements should be described here). If such data exists it should be noted in the final paper; if it doesn't the result should be described as the location of the failure only and the mechanism left as a hypothesis.

The effect of parameters on morphology and thickness of Fe-Al reaction layers has also been studied in other laser joining research. Aluminum/steel joints; general background Process and approach. The 2021 review by Kuryntsev and Yang et al. [reference required: 2019 source not listed] critical review describes aluminum/steel joining work generally; Li et al. [3] also discusses developments in IMC control and numerical simulation.

The current dataset provides one particular five-speed comparison for the specified DP600-AA6061-T6 configuration. Its contribution is the presentation of a set of correlating thermal, reaction-layer, tensile-shear strength and failure-mode information. It should not be used as a form of duplication of the previous work, since the laser source, material thickness, power, specimen geometry and mode of processing will have a significant influence. Rather, one can use the literature as an aid in understanding the relative trends, with the numerical optimum being reliant on the specifics of the process configuration.

4.6 Implications for process optimization

The 0.8 m/min parameter within the investigated range is currently the best reported. Although not recommended as a generic setting, this should be used as a parameter to select for verification in the case of optimizing, ie the condition should be retested with a formal sampling plan and the joint should be evaluated for variation along the seam, defect potential and repeatability.

Such a process window should do more than just find the highest point in a five-condition comparison. It should also establish if the surrounding conditions lead to acceptable values, the degree of change needed in the travel speed and laser power to change the response, and if the best solution is robust to variation in material thickness, surface condition, joint gap, clamping, and beam positioning. A DOE methodology could be employed as future work to determine the interactions of power, speed, focal position, and other factor variables. This could show whether the observed optimum is a true broad process window.

The optimization criteria should also be clearly specified. A decision to solely optimize for maximum tensile-shear strength may be inappropriate if the joint is subjected to cyclic loads, impact, corrosion or cycles through the temperature range. Similarly minimizing the IMC thickness may be undesirable if the resulting joint is weak, or inadequately bonded. A better decision set would optimizing strength, defect formation, interface shape, process stability and service conditions.

Table 5
Integrated interpretation of the reported process window

Travel speed (m/min)	Reported IMC thickness (μm)	Reported tensile-shear strength (MPa)	Interpretation of the reported condition	Verification priority
0.4	8.4 ± 1.0	114 ± 8	Thickest reported reaction layer; brittle interfacial failure reported	Confirm phase identity, layer morphology, and fracture path
0.6	5.8 ± 0.6	165 ± 12	Intermediate reaction-layer thickness and intermediate strength	Confirm failure classification and repeatability
0.8	3.8 ± 0.5	218 ± 9	Highest reported strength; heat-affected-zone shear reported	Repeat tests and confirm the basis of joint efficiency
1.0	1.7 ± 0.3	182 ± 11	Thin reaction layer with reduced strength relative to 0.8 m/min	Resolve interaction-time inconsistency and examine interface continuity
1.2	0.8 ± 0.15	135 ± 7	Thinnest reported layer; adhesive-type unbonding reported	Examine wetting, bonded area, and unbonded regions

In Table 5 the reported IMC thickness and tensile-shear strength are combined over the five laser travel speeds to give an overall evaluation of the process window. From this the performance of 0.8 m/min can be noted as the most successful with the highest reported tensile-shear strength of 218 ± 9 MPa coupled with an IMC thickness of 3.8 ± 0.5 μm . It can also be seen that the lower travel speeds result in a reaction layer that is too thick which also correlates to a weaker joint. Conversely high travel speeds give rise to a thinner reaction layer but which, it is implied, results in weaker bonds due to lack of wetting. The table also indicates the main areas of validation focus for each set of conditions i.e. phase identification, failure-mode analysis, repeatability and interface continuity.

4.7 Limitations of the study

The analysis relies on five reported travel-speed conditions, and the provided records are insufficient for setting the total number of replicates, raw measurement distributions, test standard information, or treatment of uncertainty statistically. The reported ranking for mean tensile-shear strengths can be described, but statistical distinction among conditions is not independently available. This and the interaction-time discrepancy precludes treating the full thermal data set as internally validated.

The summary for the requirements is not available to establish any fully numerical-model formulation, or set the mesh convergence, independent validation errors or uncertainty for temperature predictions. The model may therefore not be described as validated for the purpose of prediction unless that record

supports that conclusion. The FeAl_3 -type and Fe_2Al_5 -type phase labels reported require qualification unless the original characterisation demonstrates sufficient evidence to ascribe crystallography.

The descriptions are all qualitative, and the information provided does not determine the fracture path through fractography or evidence from the sectioned material. Moreover, fatigue, impact, corrosion, and long-term durability and service-loading performance were not determined, and only the quoted thermal indicators, reaction-layer measurements, and tensile-shear data, are presented.

4.8 Future research

Prior to submission, get the original thermal traces and post-processing results, specify the monitored position and threshold, and consistently get the times of interactions. Record the actual formulation of heat-source, material data, boundary conditions, mesh, time step, solver parameters, convergence evidence, and independent model-validation error.

Retrieve the mechanical-test documentation to identify the test standard, number of replications, loading rate, calculation of stress, defining of the uncertainty and reference strength used to determine joint efficiency. Recalculate the 84.2% value against the identified reference or label it unsubstantiated if unable to verify the original calculation.

Explain how the IMC thickness-sampling protocol was derived and provide evidence to justify phase assignments. Use diffraction-based techniques where possible and where appropriate to supplement EDS; evidence from fracture-surface and cross-section should be used to verify the failure modes claimed.

Extend testing to about 0.8 m/min, testing across intermediate speeds and varying laser power, focus position, shielding and joint fit-up. Our goal should be to test for repeatability and robustness within a working window rather than to find the highest mean from five conditions as a generic optimum.

Finally, application testing will be necessary prior to recommending a structural service joining process. Fatigue, corrosion, thermal cycling, and impact testing could identify failure modes missed during quasi-static tensile-shear tests. Data from this work would help decide if the condition which gives the best static strength does provide sufficient durability for the application.

5. Conclusion

This research examined the influence of reported laser travel speed on the thermal response, interfacial reaction-layer thickness, and tensile-shear performance of 1.2 mm DP600 steel / 1.5 mm AA6061-T6 aluminium alloy lap joints. A total of five travel speeds were analysed using a nominal laser power of 2.2 kW.

The main takeaways are:

- The top tensile-shear strength was found at the lowest linear speed of 0.8 m/min. It was 218 ± 9 MPa and the reported, but not verified, joint efficiency was 84.2%. This is the best of the five

reported cases, conditioned on verification of the test method and efficiency calculation.

- The reported total IMC thickness was lower when higher travel speeds were used. Average thickness ranged from $8.4 \pm 1.0 \mu\text{m}$ at 0.4 m/min to $0.8 \pm 0.15 \mu\text{m}$ at 1.2 m/min. The 0.8 m/min condition was reported to have an average thickness of $3.8 \pm 0.5 \mu\text{m}$.
- The thinnest reaction layer did not have the highest joint strength. The 1.2 m/min condition had the smallest reported IMC thickness, yet exhibited a lower strength value as well as reported adhesive-type unbonding failure. This indicates that interfacial reaction and bonding have to be adequately established in addition to keeping the reaction-layer growth to a minimum.
- The strength and failure-mode trends can be explained through the process-window interpretation. The lower-speed conditions had thicker reaction layers and lower strength, while the highest-speed condition had the thinnest layer but weaker bonding. The intermediate condition at 0.8 m/min produced the strongest reported joint.
- Numerical and microstructural interpretations need further confirmation. The interaction-time definition is incompatible with the peaks at 1.0 and 1.2 m/min. Also, the correct IMC phase should be cross-checked with the original characterisation results, and model validation should be carried out with the actual numerical and experimental data.
- In general, 0.8 m/min was determined to be the best performing condition of the test matrix.

Not necessarily the overall optimum, but in the presented test matrix this condition provided the best compromise of the three factors examined. The conclusion suggests that a tradeoff exists between interfacial reaction, bonding, and reaction-layer control. Before this work can provide a fully-reproducible and submission-ready claim, the problems with the thermal-data inconsistency must be resolved and the phase identification, mechanical testing, and model validation issues better documented.

References

1. Yang J, Oliveira JP, Li Y, Tan C, Gao C, Zhao Y, Yu Z (2022) Laser techniques for dissimilar joining of aluminum alloys to steels: A critical review. *J Mater Process Technol* 301:117443. <https://doi.org/10.1016/j.jmatprotec.2021.117443>
2. Kuryntsev S A review: Laser welding of dissimilar materials (Al/Fe, Ti A (2022) Al/Cu)—Methods and techniques, microstructure and properties. *Materials*, 15(1), 122. <https://doi.org/10.3390/ma15010122>
3. Li Q, Yang S, Hu B, Xue S (2025) Laser welding of aluminum/steel dissimilar metals and control of intermetallic compounds: A review. *Int J Adv Manuf Technol* 137:4283–4308. <https://doi.org/10.1007/s00170-025-15425-x>
4. Wang J, Fu X, Zhang L, Zhang Z, Liu J, Chen S (2021) A short review on laser welding/brazing of aluminum alloy to steel. *Int J Adv Manuf Technol* 112:2399–2416. <https://doi.org/10.1007/s00170-021-06607-4>

5. Wallerstein D, Solla EL, Lusquiños F, Comesaña R, del Val J, Riveiro A, Pou J (2021) Advanced characterization of intermetallic compounds in dissimilar aluminum-steel joints obtained by laser welding-brazing with AlSi filler metals. *Mater Charact* 179:111345. <https://doi.org/10.1016/j.matchar.2021.111345>
6. Goldak J, Chakravarti A, Bibby M (1984) A new finite element model for welding heat sources. *Metall Trans B* 15:299–305. <https://doi.org/10.1007/BF02667333>
7. Szczepaniak A, Fan J, Kostka A, Raabe D (2012) On the correlation between thermal cycle and formation of intermetallic phases at the interface of laser-welded aluminum–steel overlap joints. *Adv Eng Mater*. <https://doi.org/10.1002/adem.201200075>
8. Zhang G, Chen M, Shi Y, Huang J, Yang F (2017) Analysis and modeling of the growth of intermetallic compounds in aluminum–steel joints. *RSC Adv* 7:37797–37805. <https://doi.org/10.1039/C7RA06354G>
9. Yu X, Huang J, Yang T, Fan D (2022) The growth behavior for intermetallic compounds at the interface of aluminum-steel weld joint. *Materials* 15(10):3563. <https://doi.org/10.3390/ma15103563>
10. Indhu R, Tak M, Vijayaraghavan L, Soundarapandian S (2020) Microstructural evolution and its effect on joint strength during laser welding of dual phase steel to aluminium alloy. *J Manuf Process* 58:236–248. <https://doi.org/10.1016/j.jmapro.2020.08.004>
11. Eagar TW, Tsai NS (1983) Temperature fields produced by traveling distributed heat sources. *Weld J* 62(12):346s–355s
12. Rochalski D, Golański D, Chmielewski T (2017) Welding heat source models in the analysis of temperature field. *Weld Technol Rev* 89(5). <https://doi.org/10.26628/wtr.v89i5.776>

Figures

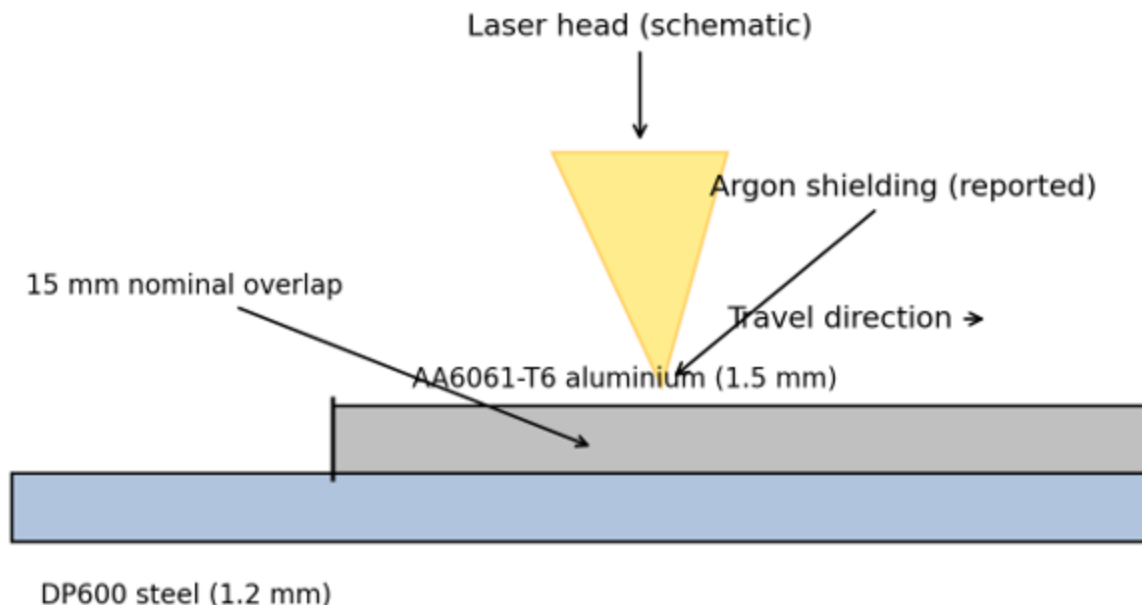


Figure 1

Schematic of the Laser Lap-Joint Configuration

Fig 1 Conceptual diagram of the DP600 steel and AA6061-T6 aluminum alloy sheets in lap-joint arrangement in laser joining, and the overlapped region where laser energy was delivered to create interfacial bonding. The schematic diagram is only for reference, and is not a photograph or an accurate drawing of the experimental setup.

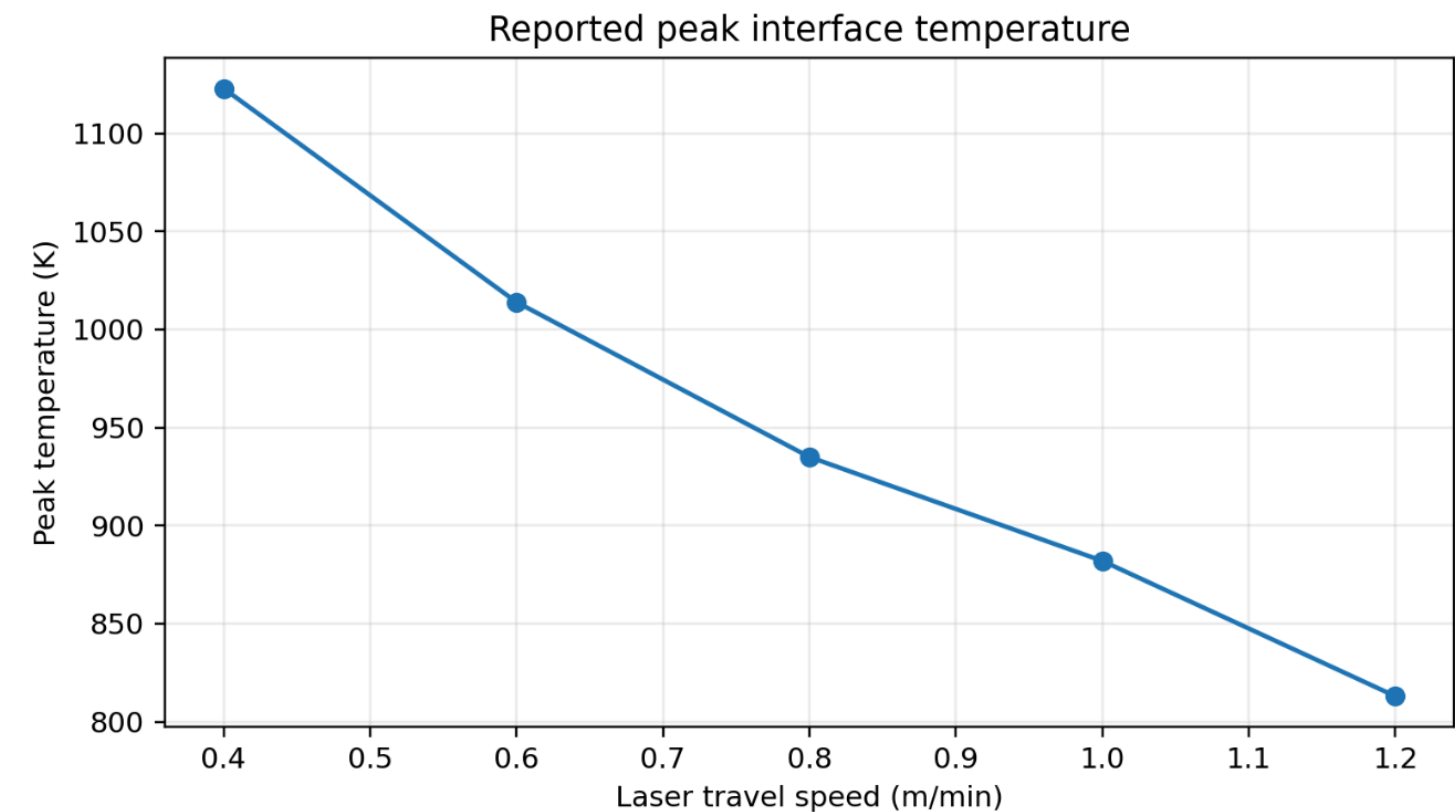


Figure 2

Reported peak interface temperature versus travel speed. Interaction-time data are not plotted because the stated threshold and reported values are inconsistent.

Fig 2. Reported peak interface temperature versus travel speed from 0.4 to 1.2 m/min, showing that as the travel speed increased, less temperature was associated with each increment in speed. The interaction-time data are not shown because interaction time was inconsistent with the data reported in the temperature threshold, and will be compared with the original temperature traces.

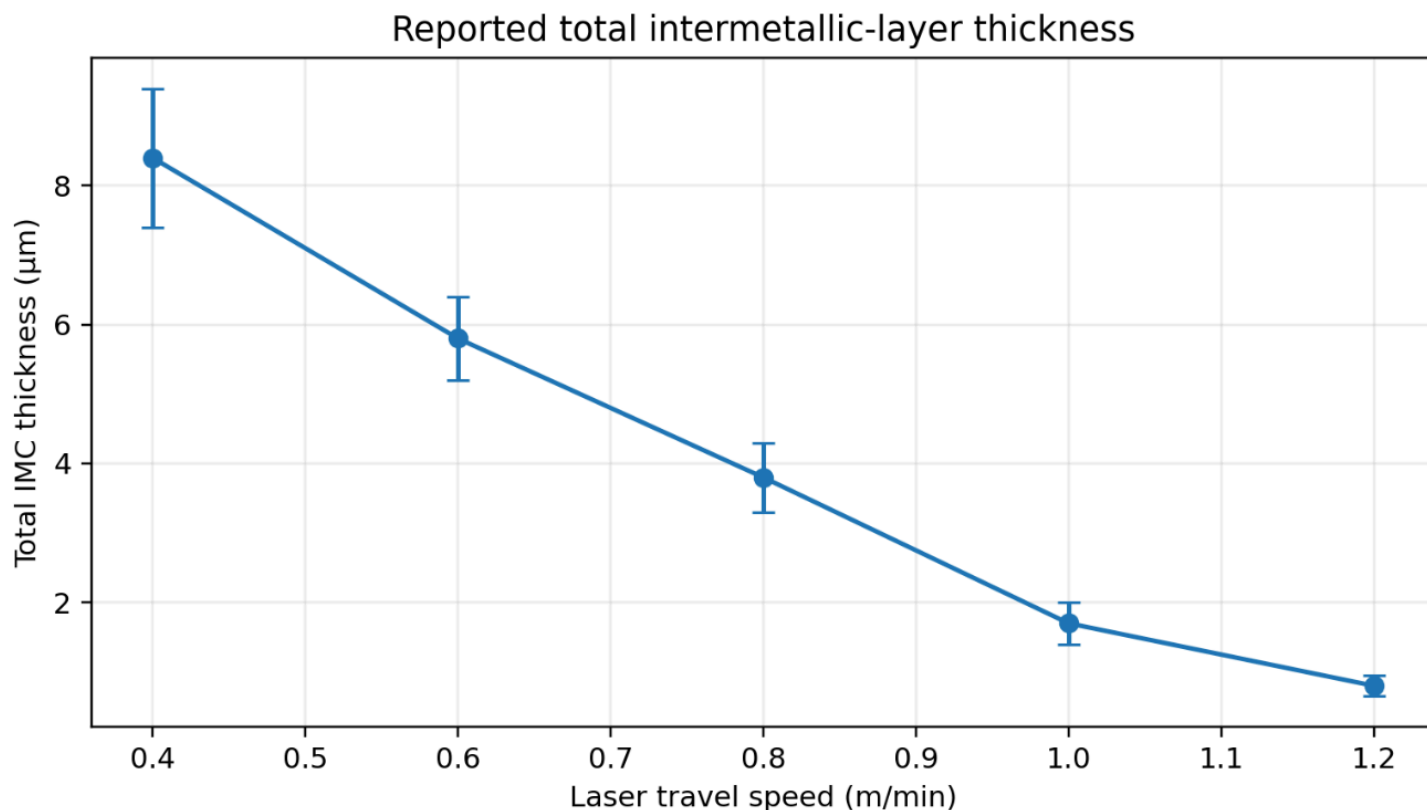


Figure 3

Reported Mean Total Intermetallic Compound (IMC) Layer Thickness versus Laser Travel Speed

Fig 3 shows the incremental decrease in mean thickness of the IMC layer reported as the laser travel speed increases. The data indicate that increased travel speed constrains formation of the interfacial reaction layer. The error bars show the reported $\pm$, but the statistical definitions of those ranges were not detailed; they are not interpretable as a particular confidence interval or as test of statistical significance.

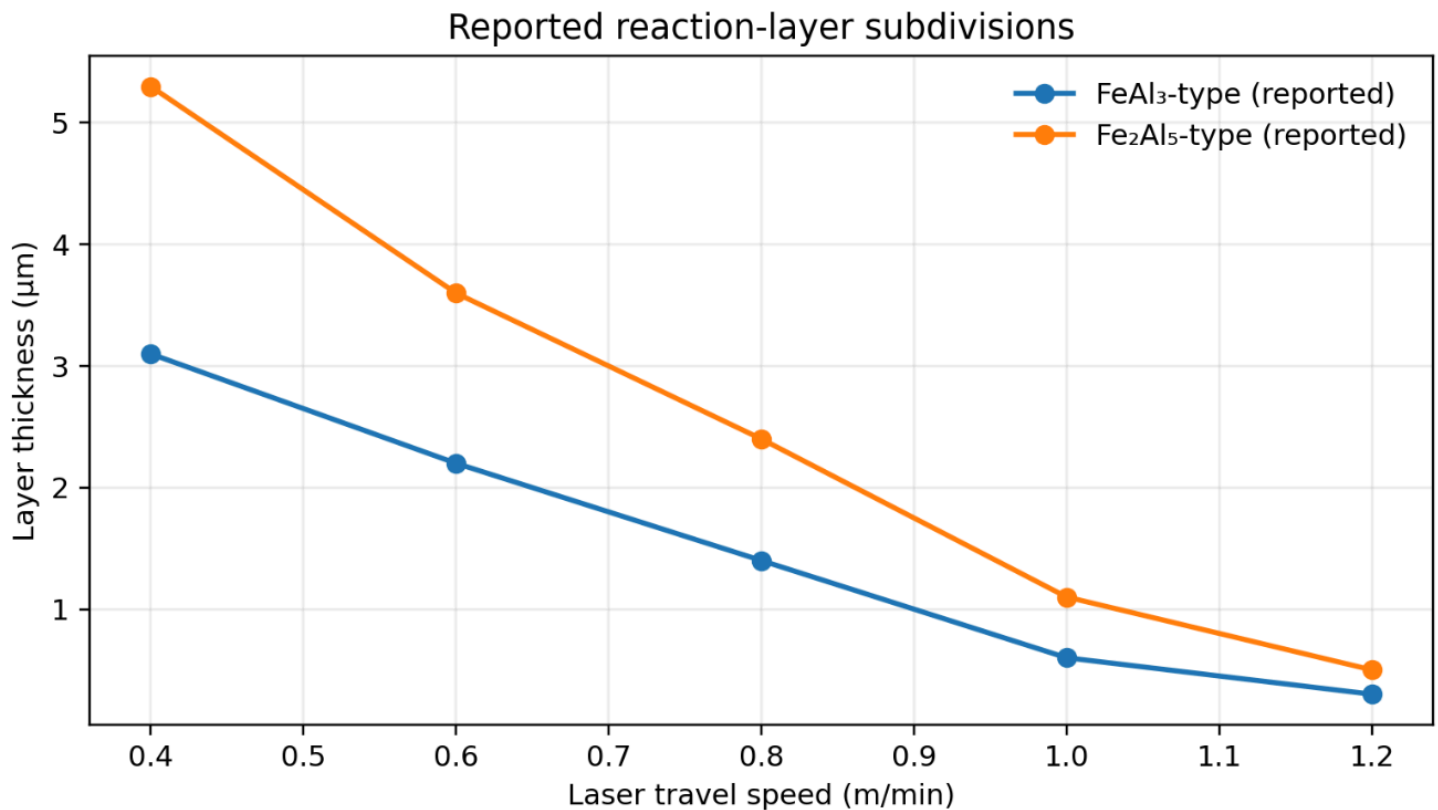


Figure 4

Reported thickness of the two reaction-layer subdivisions. FeAl₃-type and Fe₂Al₅-type are provisional reported labels; they are not independently confirmed crystallographic identifications in the supplied source.

Fig 4: Reported thickness changes of the FeAl₃-type (top set) and the Fe₂Al₅-type (bottom set) interfacial reaction layers as functions of laser travel speed. Both FeAl₃- and Fe₂Al₅- layers show thickening with the reduction of travel speed, thus increasing interfacial reaction-layer growth. All phase labels shown in the figures are tentative and should be validated by suitable compositional and, where possible, diffraction-based analyses.

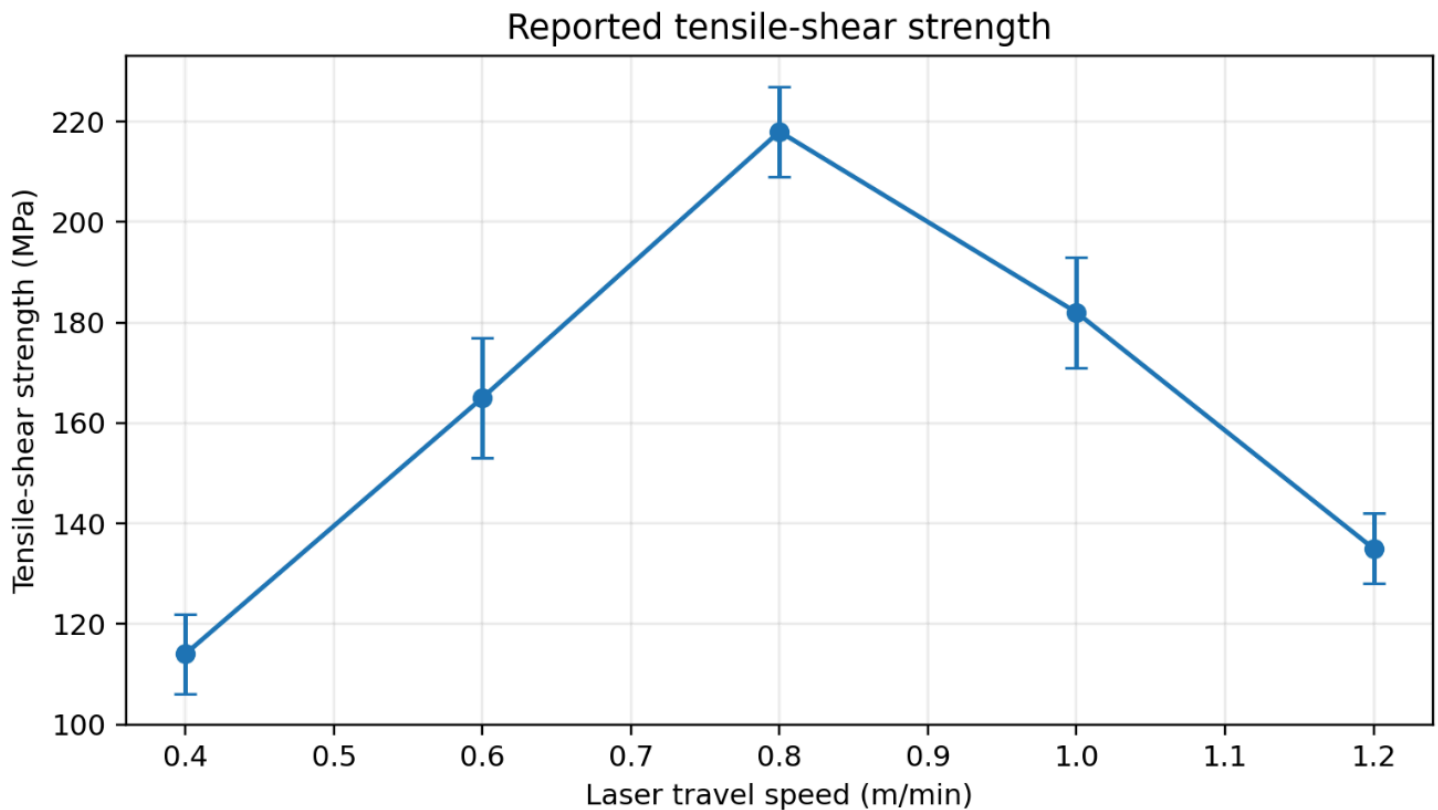


Figure 5

Reported tensile-shear strength versus travel speed. Error bars reproduce the reported $\pm$ values; their statistical meaning was not specified in the source.

Fig. 5. Tensile-shear strength reported as a function of laser-travel speed. Tensile-shear strength reported for the various laser speeds ranges from 114 MPa at 0.4 m/min to an optimum value of 218 MPa at 0.8 m/min, then decreases for the remaining larger speeds. Reported strength values suggest that laser travel speed of 0.8 m/min performs best in terms of the tested mechanical property. Error bar reported as $\pm$ values is reproduced in the figure, but the meaning of the statistical convention used to do so was not specified by the authors. Reported joint-efficiency value of 84.2 percent at 0.8 m/min should be verified, because it implies a strength inconsistency with the other reported percentages, including reference strength. Verify original value derivation, reference strength, test method, number of replications, and uncertainty definition.