UQAR

Université du Québec à Rimouski

Étude des propriétés mécaniques, analyse de la microstructure et détection des défauts des soudages par laser oscillant et linéaire des alliages d'aluminium

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A mon père,

A ma mère, qui est parti, mais qui reste toujours dans mon cœur,

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RÉSUMÉ

Dans le but d'améliorer la qualité des soudures et les propriétés mécaniques, l'objectif de ce mémoire était d'explorer la méthode de soudage au laser de l'aluminium. Un laser à fibre à onde continue de 3 kW et des plaques d'alliages d'aluminium 6061-T6 et 5052-H32 ont été utilisés pour l'étude. Cette étude a examiné la viabilité du soudage de l'aluminium au laser à l'aide d'un système robotisé. Les plaques d'aluminium ont été soudées au laser, la qualité de la soudure et les caractéristiques mécaniques ont été évaluées. Cette opération a été réalisée à l'aide d'un bras robotisé à 6 axes. Les résultats ont démontré que des soudures de haute qualité avec des microstructures et des caractéristiques mécaniques comparables ont été générées par le système robotisé par rapport à celles créées par le soudage manuel.

Avant d'analyser la microstructure et les propriétés mécaniques des soudures, les paramètres de soudage appropriés ont été identifiés. La phase initiale de l'étude consiste à appliquer une stratégie de conception d'expériences (DOE) pour optimiser les paramètres de soudage au laser. Les résultats du DOE ont montré que le débit de gaz de protection et la vitesse de soudage avaient plus d'impact que les autres paramètres dans le soudage oscillant de matériaux similaires AA6061-T6, tandis que l'amplitude et la vitesse de soudage avaient le plus d'impact sur la qualité de la soudure du soudage linéaire de matériaux dissemblables AA6061-T6 et AA5052-H32.

En outre, une fine structure dendritique équiaxe avec des grains alignés perpendiculairement à la direction de soudage a également été trouvée dans la zone de fusion, d'après l'étude microstructurale. Par rapport au métal de base, la zone affectée thermiquement présentait une structure dendritique plus grossière et une croissance notable des grains. Des tests de traction ont été utilisés pour les essais mécaniques. Selon les résultats, les soudures présentaient une résistance maximale à la traction de 208,4 MPa pour les matériaux similaires AA6061-T6 et de 206,9 MPa pour les matériaux dissemblables AA6061-T6 et AA5052-H32. Ce mémoire propose une étude approfondie du processus de soudage laser de l'aluminium, y compris l'optimisation des paramètres, l'analyse microstructurale, les essais mécaniques et la technique d'inspection. L'étude fournit des informations utiles sur l'amélioration de la qualité des soudures et des qualités mécaniques, ainsi que sur l'optimisation du processus de soudage au laser.

Mots clés : *Soudage par laser, propriétés mécaniques, alliages d'aluminium, microstructure, soudage linéaire, soudage oscillant.*

ABSTRACT

With an emphasis on improving weld quality and mechanical properties, the purpose of this thesis was to explore the aluminium laser welding method. A 3-kW continuous wave fibre laser and sheets of the 6061-T6 and 5052-H32 aluminium alloys were used for the study. This study looked into the viability of welding aluminium with a laser utilizing a robotic system. The aluminium sheets were laser welded, the quality of the weld and mechanical characteristics were assessed. This was done using a 6-axis robotic arm. The outcomes demonstrated that high-quality welds with comparable microstructures and mechanical characteristics were generated by the robotic system compared to those created by manual welding.

Prior to analyzing the microstructure and mechanical properties of the welds, the study first identified the appropriate welding parameters. The study's initial phase involved applying a Design of Experiment (DOE) strategy to optimize the laser welding parameters. The results of the DOE showed that shielding gas flow rate and welding speed had more impact than the other parameters in oscillating welding of similar materials AA6061-T6, while amplitude and welding speed had the greatest impact on the weld quality of linear welding of dissimilar materials AA6061-T6 and AA5052-H32.

Moreover, a fine equiaxed dendritic structure with grains aligned perpendicular to the welding direction was also found in the fusion zone, according to microstructural investigation. When compared to the base metal, the heat-affected zone displayed a dendritic structure that was coarser and had noticeable grain growth. Tensile tests were used for the mechanical testing. According to the findings, the welds had a maximum tensile strength of 208.4 MPa for similar materials AA6061-T6 and 206.9 MPa for dissimilar materials AA6061-T6 and AA5052-H32. This thesis offers a thorough investigation of the aluminium laser welding process, including parameter optimization, microstructural analysis, mechanical testing, and inspection technique. The study offers insightful information on the enhancement of weld quality and mechanical qualities as well as laser welding process optimization.

Keywords: *Laser welding, mechanical properties, aluminium alloys, microstructure, linear welding, oscillating welding.*

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INTRODUCTION GÉNÉRALE

1. Contexte et Généralité

La consommation d'énergie, la production de déchets, les émissions de gaz à effet de serre, la pollution de l'air et de l'eau, la perte de biodiversité et l'utilisation des ressources sont autant d'effets environnementaux importants du processus de fabrication. L'aluminium est le deuxième métal et le métal non ferreux le plus fabriqué après l'acier [1-2]. Il est produit en plus grande quantité que tous les autres métaux non ferreux réunis [3]. La production d'aluminium a été un pollueur important. L'industrie a progressivement amélioré ses performances environnementales au cours des 20 dernières années. Du fait que de nombreux polluants sont générés au cours du processus, ces progrès ont été un peu lents. Il est donc difficile de résoudre les problèmes environnementaux à court terme, car l'évolution de la technologie nécessite d'importantes dépenses financières et de recherche et a des répercussions sociales telles que la diminution de la main-d'œuvre.

Dans les secteurs de l'aérospatiale et de l'automobile en particulier, l'aluminium est utilisé pour remplacer les composants en acier. Selon une étude, le remplacement de l'acier doux par de l'acier à haute résistance ou de la fonte permet d'éviter 13 à 20 kg d'émissions de gaz à effet de serre par kilogramme [4]. L'aluminium est l'une des matières premières les plus recyclées en raison de son utilisation importante dans les secteurs de la construction, de l'emballage, de l'automobile, de l'aérospatiale et de la distribution électrique, ainsi que de sa valeur relative. Selon l'Association de l'aluminium, 90 % de l'aluminium utilisé dans la construction et les pièces automobiles est recyclé à la fin de sa durée de vie utile [5]. En outre, 75 % de l'aluminium produit historiquement est encore utilisé aujourd'hui [6-7]. Dans la croûte terrestre, l'aluminium occupe la troisième place en termes de fréquence et est l'élément métallique le plus répandu (7,96 %) [8]. Il doit être extrait de minéraux dans des minerais car il est rarement trouvé sous sa forme élémentaire en raison de sa réactivité, en particulier avec l'oxygène.

Les parties suivantes présentent un bref historique de la découverte et de la production historique de l'aluminium, une description des processus de production contemporains et une explication de la technologie employée dans chaque activité afin de comprendre complètement les opérations de l'industrie mondiale de l'aluminium. Il est alors possible de déterminer le potentiel des récupérations de chaleur perdue, d'examiner leur taille et d'évaluer les mérites et les contraintes de mise en œuvre de la technologie actuelle. L'aluminium est l'un des matériaux haute performance les plus faciles à fabriquer, ce qui correspond généralement à des coûts moins élevés. Il s'agit également d'un métal léger et relativement moins coûteux qui peut être traité thermiquement pour atteindre des niveaux de résistance assez élevés. Les alliages d'aluminium présentent des inconvénients tels qu'un faible module d'élasticité, une capacité relativement limitée à des températures élevées (130 °C) et une vulnérabilité à la corrosion dans les alliages à haute résistance [9].

Différents métaux sont mélangés à l'aluminium pour former des alliages, qui sont utilisés dans diverses applications industrielles. Ces alliages sont utilisés en raison de leurs qualités uniques, notamment leur malléabilité, leur légèreté, leur conductivité thermique et électrique et leur résistance à la corrosion.

Les alliages d'aluminium se présentent sous diverses formes, et chacune d'entre elles possède des qualités uniques qui la rendent adaptée à un usage particulier. Les alliages d'aluminium 2024, 6061, 7075 et 5052 sont les plus utilisés. Chaque alliage possède des caractéristiques physiques distinctes, notamment la résistance à la traction, la résistance à la corrosion, la dureté, la limite d'élasticité, la ductilité, la ténacité et la conductivité.

De nombreux secteurs, notamment l'aérospatiale, l'automobile, la construction, l'emballage, l'électronique et la marine, utilisent des alliages d'aluminium. Ils sont fréquemment utilisés dans des situations où une combinaison de légèreté, la résistance à la corrosion et la résistance mécanique est nécessaire. En raison de leurs caractéristiques uniques, telles qu'une conductivité thermique élevée, un point de fusion bas et une faible conductivité électrique, les alliages d'aluminium utilisés pour le soudage par laser requièrent des techniques de soudage particulières.

L'aluminium ayant un faible taux d'absorption de la lumière, le soudage des alliages d'aluminium nécessite plus d'énergie que le soudage des autres matériaux. Pour créer une soudure de haute qualité, des paramètres de soudage particuliers doivent être appliqués. En outre, en raison de la sensibilité de l'aluminium aux variations de température et de vitesse, les paramètres de soudage doivent être contrôlés avec précision afin d'éviter la formation de fissures ou de porosités dans la soudure.

Pour le soudage par laser, les alliages d'aluminium sont fréquemment utilisés en raison de leurs caractéristiques uniques. Afin d'obtenir une soudure de haute qualité, des conditions de soudage particulières doivent être utilisées en raison des caractéristiques des alliages d'aluminium. L'utilisation d'alliages d'aluminium pour le soudage laser a fait l'objet de nombreuses études, qui fournissent des informations cruciales pour l'application de cette méthode. Les alliages d'aluminium des familles 5000 et 6000 ont été utilisés dans cette étude ; ils présentent de bonnes propriétés mécaniques, une résistance moyenne à la traction, une bonne résistance à la corrosion et de bonnes performances d'usinage. Ces deux matériaux ont été utilisés avec succès dans des applications navales et en haute mer, ainsi que dans les secteurs de l'automobile, de l'aérospatiale et des transports [10-11].

Table 1. Principaux éléments d'alliage dans le système de désignation des alliages corroyés [12].

Alliage	**Principaux éléments d'alliage**
1xxx	Principalement de l'aluminium pur
2xxx	Cuivre
3xxx	Manganèse
4xxx	Silicium
5xxx	Magnésium
6xxx	Magnesium et silicium
7xxx	Zinc
8xxx	Autres éléments (fer ou étain)
9xxx	Non attribué

Table 2. Composition chimique d’aluminium [13].

Occurrence	L'aluminium est présent sous forme de composé, principalement dans le minerai de bauxite.
Oxydation	L'aluminium se combine à l'oxygène pour former de l'oxyde d'aluminium lorsqu'il est exposé à l'air humide.
Pyrophore	Lorsque l'aluminium est sous forme de poudre, il s'enflamme facilement s'il est exposé à une flamme.
Capacité à former des alliages	Il existe des centaines de compositions d'alliages d'aluminium. Les éléments alliés comprennent le fer, le cuivre, le manganèse, le silicium, le magnésium et le zinc.
Réactivité avec l'eau	L'aluminium réagit rapidement à l'eau chaude
Réactivité avec les alcalis	Réactif avec l'hydroxyde de sodium
Réactivité avec les acides	L'aluminium réagit avec les acides chauds

Table 3. Composition physique d’aluminium [13]

Couleur et état	Solide, non magnétique, non lustré, blanc argenté avec une légère teinte bleutée
Structure	L'aluminium a une structure cubique à faces centrées qui est stable jusqu'au point de fusion.
Surface	Les surfaces en aluminium peuvent être très réfléchissantes
Dureté	L'aluminium commercialement pur est mou. Il est renforcé lorsqu'il est allié et trempé
Ductilité	Haute ductilité. L'aluminium peut être battu très fin
Malléabilité	Grande malléabilité. L'aluminium est très facile à façonner ou à plier.
Dilatation thermique	L'aluminium a un coefficient de dilatation thermique de 23,2. Il se situe entre le zinc, qui se dilate davantage, et l'acier, qui se dilate deux fois moins que l'aluminium
Conductivité	Bon conducteur électrique et thermique
Corrosion	L'aluminium est résistant à la corrosion grâce à une couche d'oxyde autoprotectrice.
Densité	L'aluminium a une faible densité, mesurée par la gravité par rapport à l'eau, de 2,70. À titre de comparaison, la densité du fer/de l'acier est de 7,87.
Point de fusion et point d'ébullition	L'aluminium commercialement pur a un point de fusion d'environ 1200°F et un point d'ébullition d'environ 4,478°F. Ces valeurs changent lorsque l'aluminium est allié.

Le soudage est un procédé qui utilise la chaleur pour fusionner deux pièces de métal et former une liaison solide et durable. Il permet de mettre au point des assemblages de qualité supérieure présentant une résistance mécanique et une longévité importante. Il peut être utilisé pour souder une variété de métaux, y compris les métaux réfractaires, les alliages d'aluminium et les aciers. Les procédures de soudage modernes sont plus précises, plus efficaces et plus sûres que jamais grâce à l'évolution des matériaux et des technologies au fil des ans. Il existe plusieurs techniques de soudage, chacune présentant des avantages et des inconvénients en termes de niveau de qualité, de coût et de temps de fabrication. Le soudage par résistance par points (**figure 1**), le soudage à l'arc (**figure 2**), le soudage par friction-malaxage (**figure 3**) et le soudage au laser (**figure 4**) sont les techniques de soudage les plus utilisées et citées dans différents articles.

En raison des propriétés thermiques et électriques uniques de l'aluminium par rapport aux aciers couramment soudés, le soudage par résistance par points de l'aluminium peut s'avérer techniquement difficile. Outre l'apparition de fissures et de porosités dans la soudure, l'un des principaux problèmes rencontrés lors du soudage par résistance par points de l'aluminium est la dégradation de sa couche d'oxyde superficielle [14]. De nombreux facteurs, tels que l'oxydation, la conductivité thermique élevée, la faible conductivité électrique, les variations d'épaisseur de la pièce, etc. peuvent y contribuer. La **figure 1** présente le procédé du soudage par résistance par point. Entre deux électrodes ou mâchoires en alliage de cuivre, les éléments à souder sont superposés et serrés localement. Lorsqu'un courant de soudage traverse l'ensemble pièce/électrode, l'effet Joule augmente la température à la jonction des deux pièces où sont placées les deux électrodes [15].

L'aluminium possède une couche d'oxyde à point de fusion élevé qui persiste même après la fusion du métal, ce qui rend le soudage par l'arc difficile. Les propriétés thermiques et physiques uniques de l'aluminium peuvent être à l'origine de divers problèmes technologiques [16]. La conductivité thermique élevée, la production d'oxyde, la réflectivité élevée et la conductivité électrique sont les principaux défis à relever lors du soudage par l'arc de l'aluminium. La **figure 2** présente le procédé de soudage arc plasma.

Le soudage par friction-malaxage est une technique de soudage de pointe qui permet d'assembler des matériaux d’une épaisseur allant jusqu'à 12 mm et de produire une structure à grain fin exempte de défauts importants. Elle permet également de souder des matériaux métalliques sans ajout de matériau [17]. Cette procédure est assez lente et peut se heurter à un certain nombre de problèmes techniques : La génération de chaleur, La déformation du matériau, Le contrôle du processus, etc. La **figure 3** présente le procédé de soudage par friction-malaxage.

Un faisceau laser est utilisé dans le processus de soudage par fusion connu sous le nom de "soudage par laser" pour chauffer et faire fondre les bords des composants à souder, afin de les assembler de manière métallique [18]. Cette méthode de soudage est fréquemment utilisée pour combiner des composants en acier inoxydable, en aluminium et en titane et fonctionne particulièrement bien pour les pièces minces et les joints complexes. La **figure 4** présente le procédé de soudage par laser.

Grâce à sa grande productivité et à son adaptabilité, le soudage par laser devient rapidement l'un des procédés d'assemblage les plus efficaces de l'industrie. Il a également suscité beaucoup d'intérêt en raison de sa rapidité de traitement et de production. Les principaux avantages du soudage laser par rapport aux procédures de soudage traditionnelles sont la production rapide de soudures serrées, profondes et précises, une zone affectée par la chaleur très réduite et des distorsions thermiques très minimes en raison de la concentration de la puissance dans une très petite région. Comparé à d'autres techniques de soudage, le soudage par laser présente un certain nombre d'avantages. Tout d'abord, le faisceau laser peut être focalisé avec précision sur une très petite zone, ce qui permet de souder de petites pièces. En outre, le faisceau laser peut être focalisé rapidement et précisément, ce qui permet de souder des composants complexes présentant une grande variété d'angles et de formes. Enfin, il permet un contrôle précis de la température, ce qui réduit le risque de déformation ou de distorsion des pièces.

Toutefois, en raison de l'équipement spécifique et du savoir-faire technologique nécessaires pour effectuer correctement le soudage par laser. En outre, si le laser n'est pas utilisé correctement, il peut être nocif, d'où la nécessité de prendre les mesures de sécurité qui s'imposent. Enfin, le soudage par laser est un procédé de soudage sophistiqué et précis qui a beaucoup à offrir en termes de qualité, de vitesse et de précision. Toutefois, pour l'utiliser de manière sûre et efficace, il peut être coûteux et nécessiter des connaissances techniques.

Le soudage au laser de l'aluminium présente toutefois certaines difficultés. La forte réflectivité de l'aluminium peut rendre difficile la focalisation du faisceau laser. En outre, les variations de température et de vitesse peuvent avoir un impact sur la qualité de la soudure lors du soudage de l'aluminium. L'application du soudage laser de l'aluminium s'est élargie et la qualité des soudures s'est récemment améliorée dans un certain nombre d'industries, notamment la construction navale, l'automobile et l'aérospatiale. Toutefois, il reste des problèmes à résoudre pour accroître la fiabilité et l'efficacité de cette technique de soudage. Les avantages et les difficultés du soudage laser de l'aluminium, les paramètres de soudage idéaux, les effets sur les propriétés mécaniques des soudures et les développements les plus récents de la technologie du soudage laser peuvent tous être étudiés. En particulier, l'optimisation des paramètres de soudage pour améliorer la qualité de la soudure et les propriétés mécaniques a permis des avancées considérables dans la technologie du soudage.

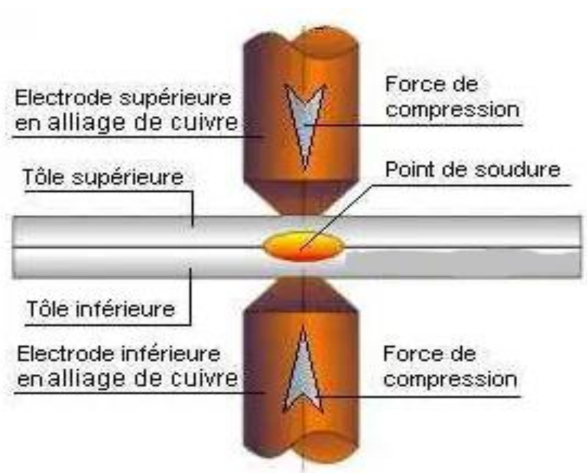

Figure 1. Soudage par résistance par points [15]

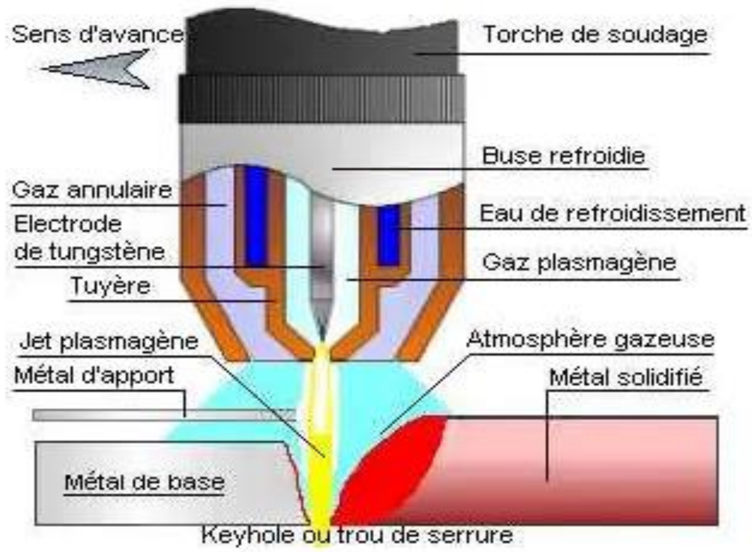

Figure 2. Soudage à l'arc d'aluminium [16]

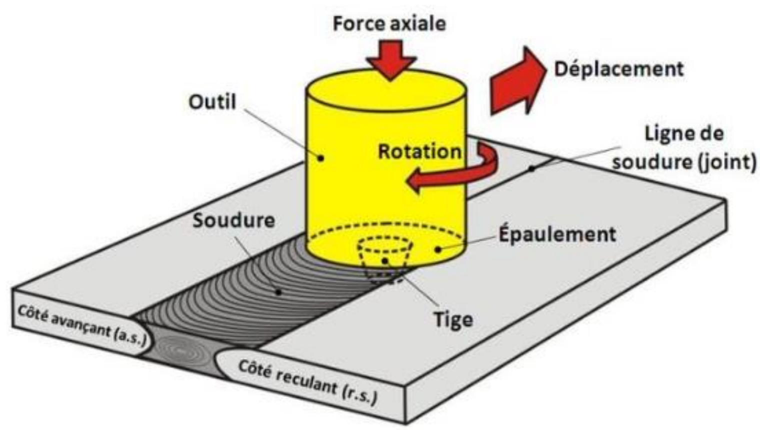

Figure 3. Soudage par friction-malaxage [17]

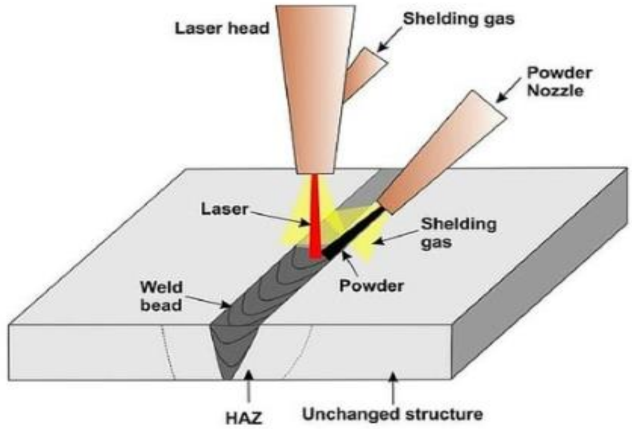

Figure 4. Soudage par laser [18]

2. Problématique

La procédure d'assemblage connue sous le nom de soudage par laser est réputée pour sa haute qualité, sa grande précision, sa faible distorsion, sa faible déformation, sa haute fréquence, ses bonnes performances, sa grande flexibilité et sa rapidité [19]. En outre, elle rend possible la robotisation, l'automatisation, les mesures d'économie de main-d'œuvre et la systématisation des processus [20], et les industries l'utilisent de plus en plus.

Tout d'abord, en raison de la concentration intense de chaleur sur la zone de soudure, le soudage par laser peut entraîner une déformation des composants. En appliquant des méthodes de soudage particulières, telles que le soudage par balayage, qui répartissent la chaleur sur une plus grande surface, cette déformation peut être réduite au minimum. D'autre part, le soudage par laser peut rendre les soudures poreuses. Les porosités sont des zones creuses qui peuvent affaiblir une soudure et en dégrader la qualité. Le contrôle des paramètres de soudage, notamment le débit du gaz de protection, la puissance du laser et la vitesse de soudage, est essentiel pour éviter ce phénomène. L'environnement, en particulier la présence de poussière, de particules et d'autres impuretés, peut affecter le soudage par laser. Ces impuretés peuvent absorber l'énergie du laser et dégrader la qualité de la soudure.

Il est donc essentiel de maintenir le lieu de travail propre et de réguler la qualité du faisceau laser. La taille du cordon de soudure, qui dépend en fait des paramètres du processus, détermine la majorité des propriétés mécaniques d'une soudure au laser. Le contrôle de ces paramètres est crucial pour générer des cordons de soudure ayant la taille et les propriétés requises afin de tirer pleinement parti des avantages offerts par le procédé.

Toutefois, il est essentiel de comprendre comment les phénomènes mécaniques, thermiques ou métallurgiques du soudage par laser affectent la qualité finale du produit. Dans certaines circonstances, les défauts ou irrégularités de soudage peuvent augmenter le risque de fracture, ce qui peut constituer un risque pour la sécurité [21]. Les trois principales catégories de défauts dans le soudage par laser sont la porosité, les défauts internes ou invisibles et les erreurs géométriques ou d'apparence [20]. La porosité se développe facilement dans les soudures profondément pénétrées produites par le soudage laser à haute puissance. Lors du soudage par laser, les conditions thermiques peuvent entraîner des déformations qui modifient les dimensions des pièces soudées. Les distorsions sont des changements de dimensions provoqués par des processus thermiques [22].

La productivité est réduite en raison des travaux de rectification supplémentaires qui peuvent être difficiles à réaliser si la distorsion de soudage dépasse la limite de tolérance, ce qui entraîne des rejets et des retards dans les calendriers de production [23-24]. Le contrôle de la conformité géométrique du produit est donc une étape cruciale du processus de production. C'est pourquoi l'industrie s'intéresse de plus en plus au développement de techniques et de réponses pour mesurer et gérer la distorsion [28]. La surveillance, le contrôle et l'optimisation des paramètres de soudage, ainsi que la prédiction des anomalies, deviennent absolument essentiels pour garantir une qualité optimale du produit fini. En fonction de la technique de surveillance employée, les caractéristiques de la surveillance du processus de soudage par laser peuvent changer. Pour créer une soudure laser sûre et de haute qualité, il est nécessaire de procéder à un contrôle de la production, à une détection en ligne ou à un système de contrôle adaptatif [23-24].

Pour comprendre les processus de génération de défauts de soudure, il faut observer directement les événements qui se produisent pendant le soudage par laser. La recherche a récemment fait des progrès significatifs et les systèmes sont déjà utilisés dans le monde réel.

La gestion du processus de soudage par laser doit se concentrer sur un certain nombre d'aspects, notamment les montages et la forme des composants, ainsi que le bain de fusion, le trou de serrure, les éclaboussures, les signaux de rayonnement et les signaux auditifs émis tout au long du processus de soudage. Ces caractéristiques, qu'elles soient géométriques, thermiques, auditives ou visuelles, peuvent être extrêmement importantes pour la surveillance du processus [25].

Pour obtenir les meilleurs résultats en termes d'efficacité et de fiabilité de la surveillance, il faut garantir une qualité exceptionnelle des données. Une variété d'outils de mesure peut être prise en considération en fonction du type de qualités qui doivent être évaluées. Différentes modalités peuvent fournir les données essentielles à la définition, au suivi, à la prévision et à la réglementation. Deux éléments clés dans la construction d'un système de surveillance sont la sélection de l'équipement de mesure et la sélection des conditions de mesure. Pour obtenir les meilleures performances en termes d'efficacité et de fiabilité de la surveillance, il faut garantir une qualité exceptionnelle des données. Le caractère dynamique et même instable du processus fait des décisions à prendre un problème substantiel [26].

3. Objectifs

L'objectif de cette étude est d'identifier les meilleurs paramètres opératoires pour réduire la distorsion thermique et la porosité des cordons de soudure afin de proposer une méthode pour améliorer la qualité du soudage laser des alliages d'aluminium.

Les procédures de cette thèse utilisent des techniques statistiques pour étudier et quantifier les effets des facteurs de processus sur la qualité des soudures et leurs contributions à la fluctuation de ces divers attributs. Dans le but de créer le modèle de prédiction le plus précis et le plus fiable possible, ces procédures conduisent à l'établissement de multiples possibilités de modèles de prédiction et à leur évaluation selon des critères prédéterminés.

Trois objectifs distincts, liés aux étapes du projet, sont pris en considération pour atteindre ce but. Il s'agit en particulier de :

- Choisir les meilleures techniques de surveillance du processus et les paramètres à surveiller, ainsi que les stratégies de prédiction et d'optimisation, pour servir de base à une stratégie globale visant à réduire les problèmes de qualité dans le processus de soudage par laser.

- Examiner l'impact des différents facteurs du processus sur la forme des cordons de soudure et les propriétés microstructurelles à l'aide d'un plan expérimental structuré et de méthodes d'analyse statistique éprouvées.

- Utiliser les modèles empiriques créés par Taguchi pour explorer les impacts de la puissance, de la vitesse, de l'amplitude du laser et de la distance focale, ainsi que du gaz de protection, sur la résistance à la traction et la microstructure de matériaux similaires et dissemblables.

4. Methodologie

La première étape du travail consiste en une étude approfondie du développement des technologies applicables au processus de soudage, tant en termes de systèmes de mesure pouvant être utilisés pour recueillir les données nécessaires à la caractérisation du processus de soudage qu'en termes de concepts et de méthodes d'inspection et de surveillance continue du processus, qui ont un grand potentiel d'utilisation dans les systèmes industriels à taux de production élevés. Cette méthodologie expose les étapes suivies pour étudier et évaluer différentes approches de surveillance et d'inspection utilisées dans l'industrie du soudage par laser. En outre, des concepts clés de l'inspection non destructive (IND) et de l'analyse des défauts sont intégrés pour évaluer la capacité des méthodes de surveillance à détecter et à quantifier les imperfections dans les soudures. Dans le but de définir les paramètres potentiels qui seront mesurés, contrôlés et régulés dans le processus de soudage par laser, cette étude de la littérature présente les différentes méthodologies de contrôle ainsi que les principales failles que l'on peut y trouver.

Dans la deuxième phase de ce projet, il s'agira de déterminer et d'analyser la relation entre les paramètres du processus de soudage laser linéaire et les performances mécaniques lors du soudage de plaques AA6061-T6 dans une configuration bout à bout sans espace entre les composants soudés. La méthodologie adoptée pour cette étude est essentiellement expérimentale, combinant des techniques d'analyse qualitative et quantitative. Cette approche permet une évaluation des caractéristiques mécaniques des soudures, tout en offrant une compréhension approfondie de la transformation de la microstructure lors du soudage laser linéaire. La recherche est structurée autour de l'analyse comparative de soudures réalisées sous différentes conditions de soudage laser linéaire. Le programme ANOVA sera utilisé dans cette étude pour définir la signification statistique, comparer les résultats et extraire les impacts et les contributions des variables telles que la puissance de soudage, la vitesse de soudage et le gaz de protection. La validation de la méthodologie est réalisée en comparant les résultats obtenus avec des références connues pour les alliages d'aluminium similaires 6061-T6.

La dernière étape consiste d'abord à analyser les paramètres de soudage laser oscillant pour les deux alliages d'aluminium AA6061-T6 et AA5052-H32, dans une configuration bout à bout, ainsi que l'utilisation de l'argon comme gaz de protection. La méthodologie adoptée pour cette étude est principalement expérimentale, combinant des techniques de conception d'expériences et d'analyse statistique pour déterminer les paramètres de soudage les plus efficaces. Cette approche permet d'évaluer de manière systématique l'effet de chaque paramètre sur les performances de soudage des alliages d'aluminium dissemblables. Afin d'obtenir de meilleurs résultats, cette étude déterminera également les impacts, les contributions et les interactions entre les paramètres choisis, tels que la puissance, l'amplitude et la distance focale, pour qu’au final les comparer avec les résultats de l’étude précédente et voir ce qui peut porter de plus aux futurs travaux dans le même domaine. Ce travaile a été aussi confirmé en comparant les résultats obtenus avec des références établies pour les alliages d'aluminium dissemblables 6061-T6 et 5052-H32.

5. Organization du mémoire

Le mémoire est divisé en trois chapitres de type article, en plus de l'introduction générale, et se termine par une conclusion générale. L'introduction générale fournit des informations de base sur le soudage en général, le soudage par laser en particulier, en mettant l'accent sur les idées fondamentales de la procédure de soudage laser.

Le premier chapitre fournit des informations générales et met en évidence les idées et concepts clés directement liées à l'évaluation et au contrôle de la qualité du soudage au laser des alliages d'aluminium. De plus, il donne un aperçu succinct des différentes méthodes et outils utilisés pour la caractérisation, la prédiction et l'optimisation du processus de soudage, ainsi que pour la surveillance continue et intelligente.

Afin de définir avec précision les paramètres d'opération qui ont la plus grande influence sur la distorsion géométrique, les modèles empiriques de Taguchi ont été utilisés dans le deuxième chapitre de l'étude du processus de soudage pour des matériaux d'aluminium similaires AA6061-T6. L'analyse a été réalisée à l'aide de l'application ANOVA et s'est concentrée sur la microstructure et les propriétés mécaniques des pièces soudées.

Le troisième chapitre comprend une recherche sur la manière dont les caractéristiques mécaniques des métaux soudés dans la formation de joints bout à bout sont affectées par les réglages de soudage laser oscillants de deux alliages d'aluminium dissemblables, 6061-T6 et AA5052-H32. Les essais pour ce projet ont suivi la conception de Taguchi et leurs résultats ont été examinés à l'aide de l'approche ANOVA afin de trouver le modèle mathématique optimal qui prédit avec précision la réponse dans les limites des paramètres d'entrée.

Enfin, une conclusion générale résume rapidement les objectifs de cette mémoire, résume les résultats de cette étude et établit les relations entre eux. Cette conclusion générale souligne l'importance de cette thèse pour les prochaines études.

CHAPITRE 1 : REVUE DE LITTÉRATURE - MÉTHODES DE SURVEILLANCE ET D'INSPECTION DU SOUDAGE PAR LASER

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1. Résumé du premier article

Diverses méthodes et techniques de surveillance et d'inspection du soudage au laser ont été mises au point de nos jours, à la fois en cours de processus et après le processus. Cette étude présente une brève description du soudage par laser, de la surveillance et de l'inspection des défauts, et résume certaines études et applications qui ont été classées en fonction de la technologie appliquée (traitement d'image, émissions acoustiques, radiographie à rayons X, signal optique, contrôle par ultrasons (UT), technique des courants de Foucault (ECT)) pour l'inspection de la qualité. En outre, l'étude actuelle cherche à cartographier les approches existantes utilisées pour corréler les défauts et les caractéristiques des soudures avec les paramètres du processus. Un système de contrôle de la qualité et des paramètres de traitement optimaux doivent être mis en œuvre efficacement pour obtenir une soudure de bonne qualité et réduire les coûts totaux, ce qui est particulièrement important dans la production industrielle. En outre, l'évaluation de la qualité du soudage au laser est décrite en termes de lacunes et d'implications de la recherche.

Mots-clés: *Soudage par laser, serveillance et inspection, production industrielle, traitement d'image, rayons X, laser ultrasons.*

2. Contributions

Ce premier article, intitulé « Literature review: Laser welding - monitoring and inspection methods » fut essentiellement rédigé par son premier auteur Anas Ghazi Jerniti qui a également réalisé toutes les recherches, tableaux, figures et défini la méthodologie pour définir et détailler les techniques de surveillance et d'inspection proposé par l'article. Ahmad Aminzadeh a été bien présent dans l'organisation du travail et a prodigué des conseils pour améliorer la méthodologie du travail fait. Noureddine Barka a participé dans la révision de l'article et agi comme superviseur du projet. Il a également contribué à l'amélioration de la méthodologie et la rédaction de cette revue de littérature.

3. Titre du premier article

Literature review: Laser welding - monitoring and inspection methods

4. Abstract

A variety of monitoring and inspection methods and techniques for laser welding have been developed nowadays both in- and post-process. This review presents a brief description of laser welding, monitoring and inspection of defects, and summarizes some studies and applications that have been classified based on the technology applied (image processing, acoustic emissions, X-ray radiography, optical signal, ultrasonic testing (UT), eddy current technique (ECT)) for the quality inspection. Furthermore, the current study seeks to map the existing approaches used to correlate weld defects and characteristics with process parameters. A quality control system and optimal processing parameters must be implemented efficiently to achieve a good quality weld, and to reduce total costs, which is especially important in industrial manufacturing. In addition, the quality assessment in laser welding is described in terms of research gaps and implications.

Keywords: *Laser welding, monitoring and inspection, industrial manufacturing, image processing, X-ray, laser ultrasounds.*

5. Introduction

Laser welding is a complex manufacturing process in which the visually identifiable quality of the weld is affected by several process variables and other factors, such as defects in the microstructure of the material, contaminations on the surface of the workpiece, and modifications to the laser beam properties, resulting in an unacceptable product (**figure 5**). Possible welding defects affect the mechanical properties of welded components, and as a result, the risk of stress on parts increases significantly.

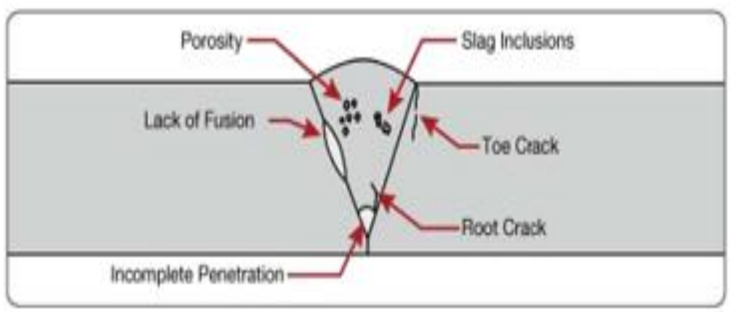

Figure 5. Possible defects in laser welding [1]

Nowadays, good quality of the welding seam in a product is important for modern industry. Monitoring and quality control is an essential tool in manufacturing systems, and it is necessary to maintain production results within inevitable limits [2]. As a complex and uncertain dynamic system, we have discussed how welding can be monitored.

The monitoring of a process, and thus quality assessment, follows three categories: pre-process, in-process, and post-process.

The pre-process focuses on tracing the welding seam, the in-process is concerned with monitoring the stability of the keyhole shape, and the post-process is mainly concerned with the form of weld seam after welding (**figure 6**). Camera-based and ultrasonic solutions are dominant in the pre- and the post-process. For the in-process quality inspection, Optical [visual (VIS), ultraviolet (UV), and infrared (IR)] and acoustic detectors, x-ray radiography, and camera-based solutions have been generally integrated.

In the table below, an overview of the main quality standards and technologies, depending on the stage of quality assessment, is presented (**Table 4**). The formation of different weld defects is concerned by the quality assessment, such as cracking, porosity, undercut, inclusions, and humping effect.

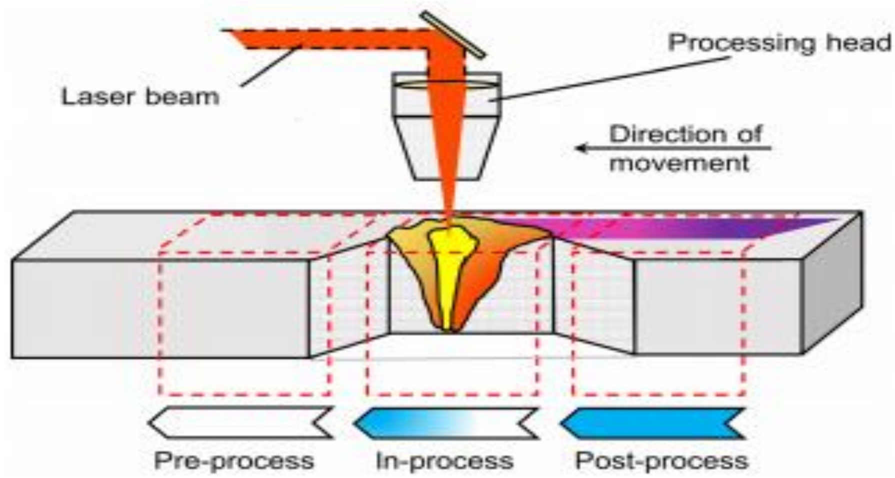

Figure 6. Classification of monitoring stages in the time accomplished [1]

Table 4. Quality criteria and technologies used for inspection.

Quality assessment categories	Main quality standards	Technologies
Pre-process	Seam tracking, clamping, gap, part geometry	Machine vision
In-process	Weld defects, melt pool dimensions, spatters	Plasma monitoring, keyhole and melt pool camera, spectroscopy, acoustic emissions, x-ray monitoring [3]
Post-proces	Weld geometry, visible defects	Machine vision, ultrasonic testing, visual inspection, ECT

- **Monitoring of welding process**

The first instinct is to think of inputs (welding parameters) as the original values we can directly manipulate, and they need to be adjusted whenever necessary in order to bring the outputs to their desired values [4]. In spite of the ease of such manipulation, their effects on the final outputs can take a number of steps. In this sense, welding can be viewed as a series of sub-processes with their own inputs and outputs as intermediate variables. Monitoring intermediate variables that are close to the final outputs may be a way to produce the desired outputs. The backside width of the weld bead can be used as a measure of the weld penetration, so we may choose to fix all welding parameters and welding conditions. When all the welding conditions are held constant, we understand that, if we apply the inputs (welding parameters) as predetermined, a certain temperature field and three-dimensional shape of the weld pool surface is produced. The backside width of the weld bead would be produced at the desired level if the temperature field and weld pool surface geometry were obtained.

In this instance, the temperature field and the welding pool surface are intermediate variables that bridge the inputs and the outputs but are closer to the outputs than the inputs. The inputs and the weld joint penetration are influenced by many welding conditions. The process can be broken down into two cascade sub-processes, such as sub-process 1, which produces the temperature field from the original inputs and sub-process 2, which is responsible for determining the backside width of the weld bead from the inputs as shown in **figure 7**; There will be less complexity in the second sub-process than in the whole process.

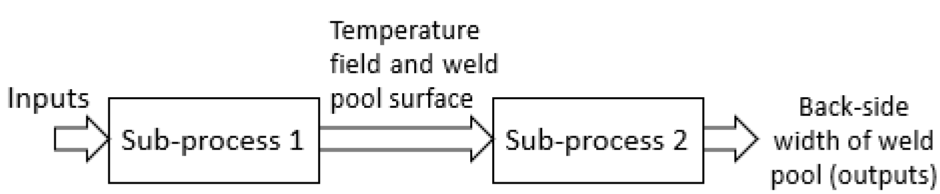

Figure 7. An example of artificial decomposition of complex system [4]

Instead of directly measuring the width of the weld bead, we could monitor the temperature field and the three-dimensional surface of the weld pool. If neither the required temperature field nor the three-dimensional weld pool surface is achieved, the desired backside width may not be achieved. The welding parameters (inputs of sub-process 1) should therefore be adjusted to achieve the required temperature field and three-dimensional weld pool surface. This allows the less complex system sub-process 1 to be monitored and controlled in order to maintain the final output, the backside width of the weld bead. As shown in the example above, different stages of the process may be monitored.

To check that welding parameters are correct, the lowest level inputs (welding parameters) can be monitored for example the waveforms of the welding current and arc voltage, as well as the wire feed speed and the shield gas flow rate. A real-time adjustment would have to be made to individual parameters if they are not correct. Monitoring welding conditions such as weld seams and joint groove geometry at the second level is another way to ensure that the nominal welding conditions are met. Intermediate variables may be measured at the third level. There is a relationship between the welding parameters and welding conditions as well as the temperature field and the weld pool surface which are not the final outputs, but are correlated more closely with the final outputs than the welding parameters and welding conditions.

There is also an influence of welding conditions on the intermediate variables with the outputs, but such welding conditions are either not measurable or difficult to measure. The actual thickness of the plate and the actual chemistry of the weld pool may still affect the back-side bead width, even when the temperature field and the three-dimensional surface of the weld pool are known. In addition to thickness and chemical composition, the welding conditions can also be considered, although measuring them is difficult. It may be appropriate to monitor intermediate variables (temperature field and weld pool surface), rather than welding conditions (thickness chemical composition), if the deviations from the nominal constants are not significant and their effects on the relationship to the final outputs are minimal. The outputs would need to be monitored directly if these welding conditions differ significantly from their nominal constants.

The monitoring of the welding process, from a certain point of view, can be broken down into four major levels and can be further decomposed into sub-processes. In order to devise an engineering solution, it is important to determine where and how to conduct the monitoring within the system, as well as how the system can be decomposed. It would be necessary to design appropriate control algorithms and training in order to determine the recommended welding parameters because the welding process is highly complex as a system, and monitoring the final outputs as feedback would be quite complex. **Figure 8** shows how such a complex control system is decomposed into a few sub-processes and monitored for disturbances, inputs, and outputs within each sub-process. Complex systems can be simplified by combining smaller systems. With the use of real-time monitoring technologies, such artificial decomposition of a complex system may greatly facilitate our efforts to find better strategies for controlling the complex welding process.

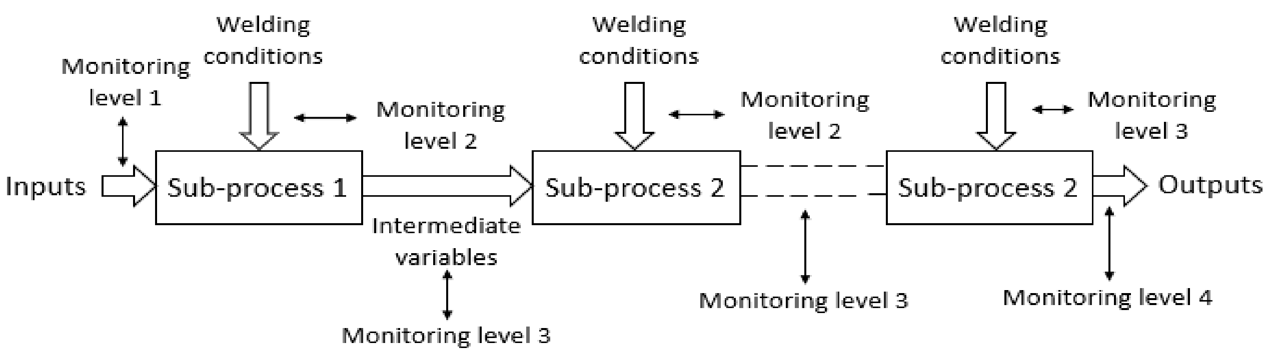

Figure 8. Artificial decomposition of complex system for effective monitoring and control [4]

In this chapter, the most recent and efficient methods with will be discussed in detail with some advantages and disadvantages, which can be important in the study of inspection of defects in laser welding and help identify defects and ensure that the weld meets specified standards.

6. In-process quality assessment of laser welding

Due to the interactions of the laser with the materials that occur during the laser welding process, energy is emitted in various forms [5]. As far as in-process quality inspection techniques are concerned, optical (UV, VIS, IR) and acoustic sensors are often used to identify weld defects and monitor the evolution of depth of penetration. However, recently camera-based solutions have been incorporated into laser welding operations for the same purposes, providing significant advantages over traditional monitoring systems. Vision and IR cameras provide spatial and temperature information about the heat-affected zone during the LW process and further detailing of the data can lead to a reliable assessment of the quality of welds.

The reflected laser beam is the amount of radiation from the laser source, which is not absorbed by the material. Hence, the developed quality assessment methods rely on acoustic, optical or thermal sensors, which are usually combined to improve the performance of the laser welding system.

For In-process quality assessment stage, the main categories will be introduced in the next subsection and are presented in the **figure 9**.

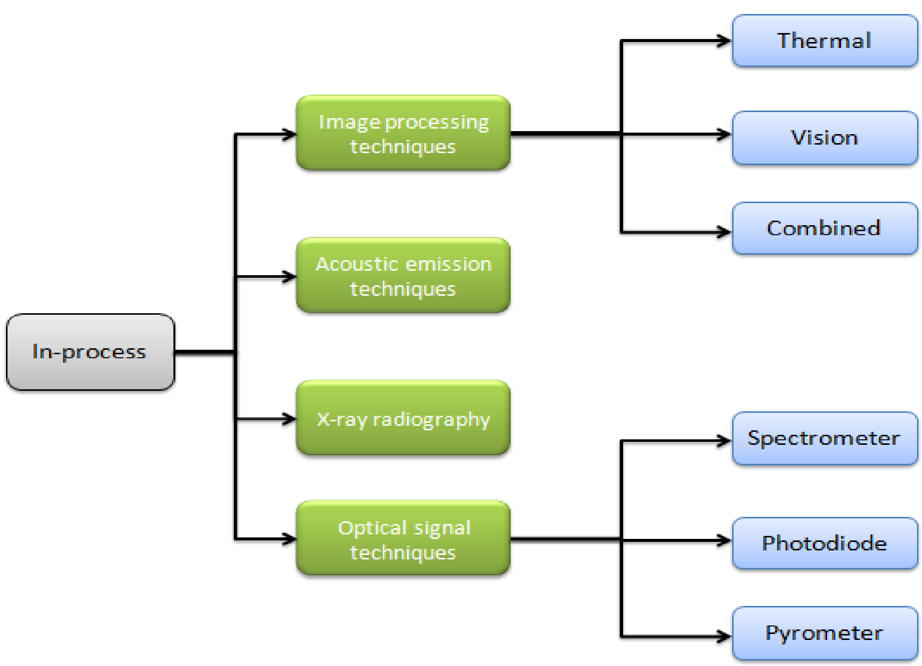

Figure 9. In-process quality assessment methods

1.1 Image processing techniques

i. Thermal

IR Thermal cameras are a sensing technology used in laser welding applications to capture the temperature distribution of the welded component. Thermal cameras are passive sensors that print infrared rays emitted by all objects with a temperature above absolute zero [6]. Today, thermal imaging monitoring systems are increasingly being implemented in industry, since they offer many advantages over other technologies used for weld pool temperature detection [7].

On the other hand, an online process monitoring system for quality assurance, aiming to maintain the required depth of penetration, which in conduction welding is more sensitive to changes in heat sinking [8]. The implementation of the empirical rule indicates that the maximum penetration in conduction welding is obtained when the surface temperature is just below the boiling point. Therefore, the control system was intended to maintain the temperature at this level.

To achieve this, a standard semiconductor complementary metal oxide color camera can be used, providing real-time measurement of the temperature of the soldering area. In addition, a closed loop control system can be implemented, which ensures complete penetration into the weld by controlling the focus position and laser power [9]. The degree of penetration can be analyzed by the keyhole image intensity profile. The lack of research studies, as noted from the above, can be explained by the fact that IR camera modules usually, due to their dependence on the emission of materials, cannot adequately examine welding properties and defects which require more detailed data in order to match the temperature profile with the parameters the quality.

Moreover, several other disadvantages, such as high cost, low resolution, and low sampling speed, have limited its wide application to industrial manufacturing [10]. As a result, the temperature distribution on the surfaces of the parts becomes available quantitatively and with high accuracy. Besides related approaches to overcome the material emission problem, IR modules are usually combined with other vision cameras and/or optical sensors, with the aim of obtaining more information about the melt-basin state.

ii. Vision

Nowadays, the use of vision systems as a monitoring technology for a molten pool is proposed to be one of the most intuitive ways. In laser welding monitoring technology, the use of camera is also being actively developed and there are ongoing efforts to monitor and control welding processes [11].

In this regard, the vision sensor is based on the principle of laser triangulation and provides information, regarding the geometrical features of the weld [12]. Through the visual analysis of the 3D profiles obtained from the weld, the positions and sizes of the weld defects must be determined. The A calibrated charged device (CCD) sensor and structured light can be used to extract surface information, such as pond depth, from captured images. Then, the image is processed based on ray tracing technology to calculate the depth of the weld pool surface using the laser position and propeller angle, along with the intrinsic and external parameters of the CCD sensor.

Finally, it has been demonstrated by many experiments that the method can automatically measure and monitor the weld pool surface within an acceptable error range. A visual system with an additional laser light source was developed in order to obtain molten pond images for quality assessment [13]. The area, maximum distance between shadow and keyhole, maximum width, and shadow tilt can be specified as evaluation properties.

The results of the experiments indicated that the quality of the weld can be online, and it is revealed by observing these characteristics. One step further, a camera-based closed-loop control system using an image processing algorithm for full penetration hole determination was proposed and concluded that the given approach was adaptable to partial penetration welding processes. The control system was able to reach and maintain partial penetration, even under variable welding conditions, while the cross-sectional variance (standard deviation over the mean value) in all experiments was less than 10%. In a different approach, the paper in [11] describes a coaxial monitoring system, which integrates an image camera, lighting and filters. The special system was applied to a remote laser welding application (**figure 10**). Keyhole and full hole penetration areas were calculated by image processing, and their behaviors under different welding conditions were examined.

The keyhole was monitored using different band-pass filters and a coaxial illumination laser. Filters suitable for welding steels and aluminium alloys have been proposed.

The result of this study is corroborated by the fact that it is possible to monitor and control measures of welding quality, such as penetration through the implementation of a coaxial camera system, even for remote laser welding via a scanner. Finally, an interesting approach is presented by Tenner in [14], [15] in which two high-speed cameras are used in order to measure the velocity and fluid flow within the keyhole. As a result, the authors were in a position to demonstrate the influence of fluid dynamics within the keyhole on laser power, feed rate, and the gap between two zinc-coated steel plates.

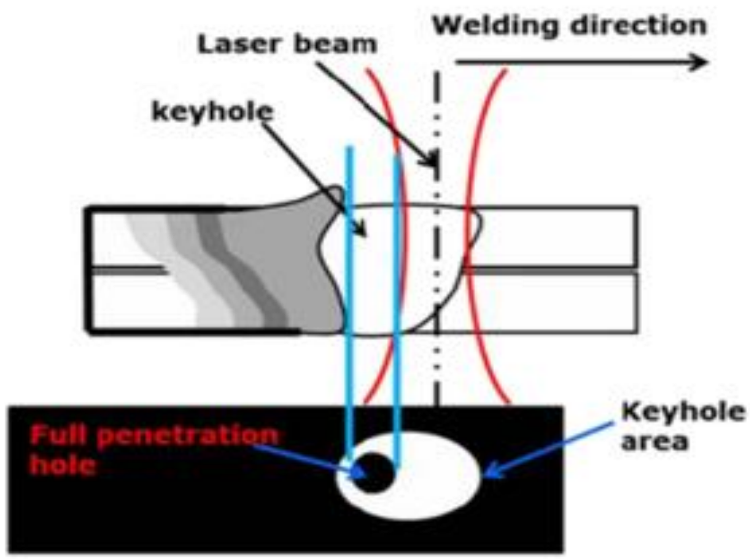

Figure 10. Definition of the keyhole parameters [11]

iii. Combined vision and thermal image processing techniques

As noted from the previous section, vision sensing can make a significant contribution to laser welding quality assessment, by providing higher spatial scaling, precise positioning and identification of welding defects.

However, vision cameras (CCD and CMOS) are not suitable for detecting medium and long wave infrared, and for this reason, specific infrared cameras are required [16]. Passive lighting was completely insufficient to capture the details of the molten pond by providing very dark shapes of the melt pool [17].

Diffused light alone revealed more details about the melt pool region, but the best results were obtained from combining focused and diffused laser light. In this regard, the combination of different thermal and visual methods of quality inspection in laser welding applications would integrate the advantages of each method and would enable engineers to monitor various welding defects and their amounts. The infrared camera was found to be able to detect the local heat pattern, any contamination between the film and the container, and the cooling behavior of the material after welding.

On the other hand, the visual system introduced the quality assurance system for the safety of sealed products. In contrast to the above study, the study described in [18] focused on controlling the development of temporal stress and cracking hardening in laser welding of aluminium alloys. High-speed monitoring of visible and infrared radiation was performed to measure molten pool geometry, solid-liquid interface velocity, and temperature profile during laser spot welding. The rate of solidification along with the interface velocities, during the weld cooling procedure, were investigated in order to obtain a crack-free and full penetration weld with overlapping spot welds.

Among other things, it was concluded that the orifice with full penetration could be clearly observed, and that the dimensions of the weld pool were successfully correlated with the dimensions of the penetration. Evaluation of laser welding quality using camera-based monitoring systems, both in the NIR and VIS spectral range, is also the subject of research in [19]. Welds are classified on the basis of various weld defects. For example, the geometry of the weld pool was related to complete penetration, holes and spots could be identified without additional lighting, and the thermal effect of the weld seam could reveal lost fusion. Combined camera-based solutions (vision and thermal) depict an expensive monitoring technology, and therefore, its use in laser welding has not been widely adopted.

1.2 Acoustic emission techniques

Acoustic emissions contain significant information about the laser welding process and can indicate certain aspects of the quality of the weld. It has also been claimed that acoustic sensing techniques can be applied to processes involving melting, vaporization, plasma generation, and keyhole formation [16]. Moreover, acoustic emissions can provide useful data regarding the rapid phase change in the material as well as crack formation and diffusion [20]. Despite the flexibility offered by contactless acoustic sensors in applications where the use of contact sensors is not feasible, the presence of noise from ambient areas and slower signal transmission within the material renders sound detectors unhelpful in adaptive control and in-process quality assessment approaches.

Therefore, studies in the literature focus on improving identification accuracy and developing intelligent algorithms to correlate signals with weld geometry and defects [13]. By implementing the wavelet analysis, there is a significant difference between the acoustic emission signal (AE) from the desired deep penetration welding and that obtained when there are alignment problems and excessive gap [20]. Low frequency (<781 Hz) intensity is reduced when welding defects occur. Based on the detailed information obtained from the AE signals, a moving average curve of the signal intensity was determined. The curve was used to identify defects and to identify welding phase transitions. Two types of ultrasound acoustic emission in order to derive the relationship between acoustic signals and thermal phenomena such as melting, evaporation and plasma generation, which occur during laser processing [21].

The author concluded that the “acoustic mirror” signal is mainly generated by back-reflection of the laser beam modulated by the fused collector (between 100 and 600 kHz) rather than by modulating the laser cavity (5-25 MHz). The signal was strongest on the beam guide mirror being closest to the work piece. When the keyhole was created, the sonic mirror signal became weaker, while the "sonic crater" signal became stronger. Ultimately, acoustic sensing techniques can be applied to in-process monitoring and control systems for laser operations, and to assess the quality of the examined welds. Another step forward, the acoustic emission data were sampled and analyzed for different process conditions, such as laser power and pulse duration [22].

Then, through an experimental model, it was shown that acoustic emission signals have clear correlations with process parameters and represent characteristics of the welding process, including welding types and potential crack initiation mechanisms during LSW.

Finally, an artificial neural network was used to predict the weld ability of stainless steel online [23]. The authors speculated that welding quality data obtained from wavelet analysis could be fed to an online industrial application in order to control critical welding parameters or alert the operator of a problem. Internal welding defects and deviations from the desired surface profile can then be corrected before the defective parts are produced.

1.3 X-ray techniques

Embedded X-ray imaging, during laser welding itself, is a well-established method for examining keyhole behavior with a side view through the material. Image acquisition became faster, and the maximum possible width of the sample increased [24]. In this regard, there is an in-situ X-ray video imaging inspection technology, which made it possible to recover the resolved time and space information about the keyhole geometry, during the laser welding process [24]. Alternatively, the welding phenomenon of the effects of laser power, power density and welding speed on weld formation can be explained by high-speed cameras and real-time imaging system of X-ray transmission [14].

Moreover, the study in [25] exploits the potential of X-ray imaging techniques used online as well. An algorithm developed for real-time automatic inspection of welding defects in X-ray images, using improved image smoothing and image information merging, based on heuristic search techniques.

As a result, the algorithm can detect various kinds of welding defects, such as slag inclusion, blow hole, incomplete penetration, lack of fusion, and undercut. Experiments indicated that the system was efficient, reliable and could be used for industrial purposes. Finally, the real-time observation of keyhole and shaft behaviors in pulsed and continuous wave laser welding can be observed by high-speed X-ray and optical transmission methods, cavity forming process, and suppression measures.

1.4 Optical signal techniques

Optical sensing techniques are frequently used to monitor laser processing. Optical sensors in the literature are classified differently according to the author [13]. A usual classification made by many authors is a division into spatially resolved technologies (vision system, for example, CCD and CMOS cameras), spatial integration techniques (photodiodes), or spectroscopic techniques (spectrometer) [26]. In this section, methods for assessing quality, based on special optical sensors, are included. Pyrometers are also included in this section. The authors in [27] combined the inline correlative imaging system (ICI) with the beam guiding system at the camera port of a commercial optical fixed laser head and were able to dynamically direct the ICI system beam across the sample surface, at millisecond timescales. By sampling data from multiple points in and around the phase change region, they were able to implement autofocus and correct any motion error and distortion continuously at the measured keyhole depth.

In addition, transverse measurement sweeps of the leading region, in common joint configurations, enabled seam tracing to correct the closed-loop geometry of the incomplete parts. The common realization of these capabilities makes System ICI a more robust and versatile solution for welding process control and quality control. On the other hand, the authors in [28] have combined the optical setup of the Laser-Induced Breakdown Spectrometer (LIBS) with the interferometer by providing accurate in-situ depth measurements and detailed crater profile mapping. The raw information extracted from the spectroscopy spectrum can be directly related to the depth measurement and topography, resulting in accurate mapping of the profile, along the sample surface.

i. Photodiode

Photodiode sensors are widely used in industry due to their simple structure and low cost. The optical radiation signals that can be detected by the photodiodes during laser welding can be in the range of UV (200-400 nm), VIS (400-700 nm), NIR (700-1100 nm), and IR (1100-1700 nm). The corresponding signals are analyzed in order to provide information about the welding condition and to detect defects.

According to the research conducted, it was concluded that photodiodes are usually used to detect a vapor or plasma plume, reflecting laser energy and thermal radiation. In this regard, plasma and spray measurements, during laser welding with diodes UV and IR, have alarmed the authors in [29]. Five welding factors (optimal heat input, slightly slow heat input, low heat input, partial joining, due to gap mismatch and nozzle deviation) that affect weld quality, and the correlation between the input signal and these factors was investigated by experiments. A system was also developed to perform real-time assessments of weld quality using fuzzy pattern recognition with measured signals. Signals UV and IR received from photodiodes have also been used to assess weld quality in [30], [31].

On the other hand, in [31], the experimental work provided a better understanding and accurate evaluation of laser welding by quantification and feature analysis extracted from different optical sensors (UV, IR, VIS). Indicatively, the variable propensity for visible light emission and metallic plasma volume at the top is consistent, while the intensity of laser intensity is sensitive not only to laser power but also to keyhole size. Moreover, due to the pressure released from the bottom of the keyhole, the visible light emission and laser reflection were reduced when full penetration appeared during the welding process. However, the authors presented in [32] a method that is mainly based on the visible spectrum range. This radiation is converted into electrical signals, the characteristics of which are studied in the domains of time and frequency. The characterization of these properties allows the welds to be classified according to their quality.

The results showed that 97.1% of the defects were detected. According to the authors, although these results were technically satisfactory, they did not achieve the goal of detecting all defects. Moreover, the study in [33] also used a photodiode reading in the visible and infrared range which succeeded in identifying not only lack of penetration but also craters, spatters, blowholes, underfill, lack of fusion, or pores. The initial infrared signal collected by the weld monitor was linearly correlated with the depth of penetration in partial penetration welds [34], [35].

Complete penetration was indicated by a significant decrease in the direct current (DC) level of the signal, as well as an increase in the AC component. The welding monitoring technique, according to the authors, was very sensitive to penetration depth, especially full penetration detection.

However, partial misalignment and oil contamination result in large differences in the output of the weld monitor. Finally, the authors describe in [36] the development of a monitoring system that uses photodetectors to measure radiation signals from the melt pool. By changing the focus of the laser beam, along the z-direction, the depth of penetration of the weld material was measured. The latter showed that the penetration depth was dependent on the frequency fluctuations of the plume signals, which can be used to monitor the quality of the weld.

ii. Spectrometer

Spectroscopy has been widely used in laser welding for plasma column detection. Plasma observation indicates the formation of undercuts in the welds. The usual setup of the sensor inspection technique is shown in **figure 11**, and since it can be drawn from the schematic, the optical emission is collected by a collimator and transmitted by an optical fiber to the spectrometer, where the signal is analyzed [37]. Recently, the use of the special sensor has gained wide acceptance in industrial applications [38], [39], mainly due to its low cost and small size. The monitoring technique approach, adopted in [37], relied on correlation analysis of optical plasma spectra, which were generated in-process and recorded through a spectrophotometer. Experiments were performed to determine the relationship between optical signals and weld quality. The quality of the welds was finally assessed by online detection of common defects, such as lack of penetration with excellent spatial accuracy.

Rizzi and colleagues [40] developed a regression model, which allowed to study the effect of the laser beam on the response parameters, namely, plasma column temperature, penetration depth, and molten area. A spectrometer was also used in [41] to collect the optical emission of the weld region. The sensor data was used to calculate the electron temperature and thus to determine the weld quality of the overlapping welds.

The special in-process monitoring method was implemented in a proportional-integral (PI) controller, which modulates the laser power, targeting a constant penetration depth.

In this paper, a new spectroscopic closed-loop control system is described, capable of stabilizing penetration depth, during laser welding processes using laser energy as a control variable. The plasma electron temperature was monitored, and by a quantitative relationship between penetration depth and plasma temperature, extracted experimentally, the system reduced components rejected due to incomplete or excessive weld penetration. There is a different method for optimization and feedback control of the laser welding process, based on spectroscopy [38]. A light frequency and adaptive modulation of the laser beam during the process were analyzed by an optical element. The relationship between the focal properties of the laser beam, the weld depth and frequency characteristics was extracted experimentally. The function of the method is illustrated for a variety of welding parameter settings that are frequently used in industrial practice.

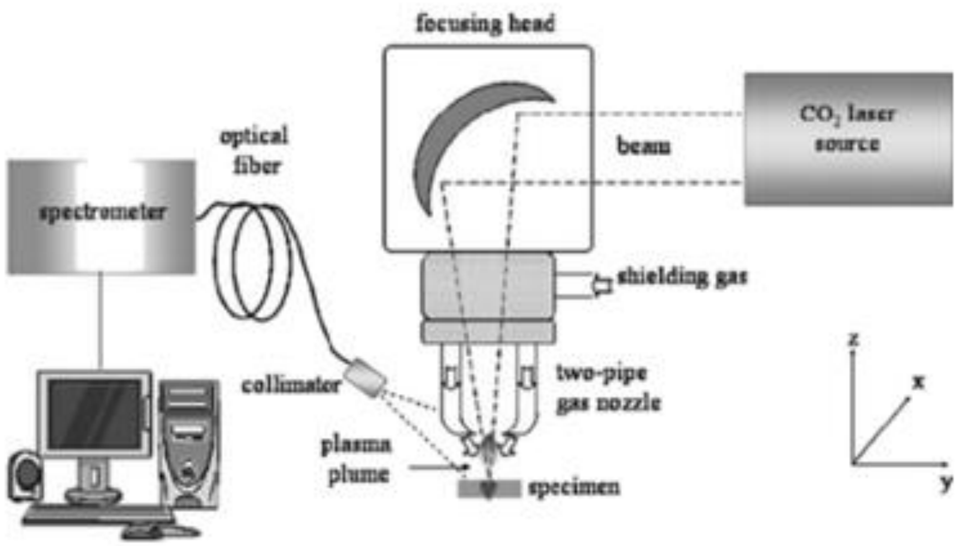

Figure 11. Monitoring system with spectrometer [37]

iii. Pyrometer

Pyrometers are another class of sensing technology, adopted in laser welding for quality assessment. The intensity of thermal radiation reflects changes in temperature and can be detected using a pyrometer sensor [13]. The presence of defects or the values of penetration and width can be obtained from changes in the temperature field. Pyrometers can be used for real-time temperature monitoring and online quality control [42]. Moreover, pyrometers are preferred due to their low cost, simplicity of use, high sampling efficiency, and special software developed for this purpose. Furthermore, a monitoring system, based on pyrometers, was developed and attempted to optimize the laser welding process [43], [44] and [45]. The true temperature, heating/cooling rates, and solidification time were determined, and acceptable variance in brightness temperature was found. Next, the authors proceeded to the relationship between feedback sensing and welding defects. Finally, it was concluded that the performance of the sensors was adequate for process control.

7. Post-process quality assessment of laser welding

Post-process quality inspection is usually done by known techniques such as eddy current testing, ultrasound, visual or radiography [46]. Special inspection methods can check the conformance between standards and weld quality, by inspecting the surface and subsurface of the weld and the surrounding base materials. The effort of automated testing procedures in these technologies is too high, and it is not possible to implement an online solution. Thus, the quality feedback loop is larger compared to online solutions. For this reason, most of the studies presented in this section relate to the application of these methods in post-process examination. However, some papers that focus on developing real-time automatic inspecting algorithms, based on X-ray imaging, were also cited.

The primary categories for the post-process quality evaluation stage are shown in **figure 12** and will be discussed in more detail in the following subsection.

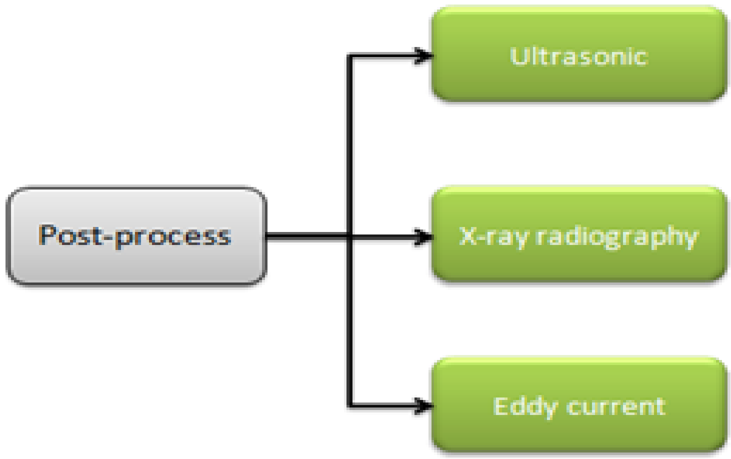

Figure 12. Post-process quality assessment methods

7.1 X-ray radiography

Radiography relies on the ability of X-rays and gamma rays to pass through metals and other opaque materials into ordinary light, producing photographic recordings of transmitted radiant energy [46]. All materials will absorb known amounts of this radiant energy, and thus, X-rays and gamma rays can be used to show discontinuities and impurities within the opaque material. A permanent film record of the internal conditions will show the basic information by which the soundness of the weld can be determined. Low speed and potential radiation hazards limit its use. The results in most cases require operator interpretation and are rarely used in automated environments. In addition, X-ray techniques are expensive due to parts tampering and required protection; thus, it cannot be applied to typical production cycles of a welding machine.

However, there are many studies that have examined and improved radiography testing in laser welding processes. Indicatively, the porosity of the joints of dissimilar materials was examined using X-ray imaging [47]. Porosity examination indicated clear trends associated with laser welding speed, while the geometry of the weld pool was also captured by X-ray technique.

A method for automatic defect recognition on an x-ray welding image, based on the Support Vector Machine (SVM) [48], is also introduced. In addition, an approach to defect recognition has been developed, based on X-ray image processing techniques [49]. The novelty in this study was the implementation of an effective method based on fuzzy theory. Using the proposed algorithm, the images were filtered by applying fuzzy reflection via local image properties, with the aim of detecting small objects with low contrast. One step further, X-ray imaging inspecting technology has been adopted in order to optimize laser parameters while assessing specific defects [50].

Finally, there is a method to reconstruct the 3D shape of the melt pool and capillary for a keyhole laser welding process [51]. Three different diagnostic methods, including X-ray, optical videography, and metallographic cross sections, were combined to obtain 3D data for a solidus-liquidus surface. A detailed description of the experimental setup and a discussion on the different ways of combining the 2D datasets of the three different diagnostic methods with a 3D model were given. The proposed method improved the understanding of the basics of the laser welding process and provided the possibility to calibrate or verify computer-aided process simulations.

7.2 Eddy current technique

Surface and subsurface inspection are provided by eddy current systems, which use electromagnetism. A coil is electrically charged, which creates a magnetic field inside and around it. In a dynamic magnetic field, an electrically conductive material will be inducted by electromagnetic induction and induce eddy currents. It is possible to detect longitudinal and surface traversal cracks, submergence deficiencies, pit cracks, pores, and other discontinuities by conventional eddy current techniques. In a study of laser-welded seams, eddy currents were used to detect defects and to classify them [52]. Material defects and changes in characteristics affected the eddy current signals. There were areas of satisfactory quality, with superficial pores and lacking contact, as well as unwelded joints identified in the impedance level plot. Eddy current data were pre-processed and assigned to the distinct regions to locate the X-ray samples.

Radiography and metallography produced results in good agreement with the results of the laser welding process.

As in the previous study, a vision-based system was developed to automatically detect cracks in materials, focusing on surface cracks for identification [53]. The magnetic particle inspection was then used to detect cracks in materials containing ferromagnetic elements. With the vision system calibrated to convert pixels into millimeters, the average length and width of each crack were calculated. Both before and after testing, crack width measurements were consistent, indicating a correct measurement of crack size by the system. Using several coils in a single probe in a collaborative sequence to prevent mutual interference, Eddy Current Array (ECA) technology was developed, which augmented the technology's capabilities. This sequence allows for a complete and comprehensive scan of the surface. In order to inspect target materials correctly, the coils should have the impedance and penetration required.

Finally, this technique can be easily automated for fast inline laser welding, as well as monitoring and controlling the laser welding process after it has been completed. Despite the advantageous features of eddy current technique (the technique does not require human intervention, it is non-destructive, contactless, and does not require the part to be prepared), there are limitations: it applies only to conductive materials, the probe must access the surface, and reference standards are needed to set up the measurements. Finally, since the technique is difficult to detect many critical defects and the test material can only penetrate a limited depth, eddy currents are often used in conjunction with other screening methods.

7.3 Ultrasonic

Ultrasonic inspection involves generating ultrasonic waves that interact with the welded joint. This causes incident waves to reflect or diffract. The reflected or diffracted waves are then detected and analyzed. The use of a progressive array ultrasound for laser welding thin aluminium sheets was investigated [54]. Radiographic and metallographic inspections were also compared to this technique. The results of this study indicate that it is possible to determine not only the weld line but also the existence of grouped pores when receiving ultrasonic attenuation waves from the base metal separately.

It was not possible to verify whether detecting cracks in the welding line could be done using ultrasonic wave attenuation principle since no microcracks were visible by metallographic inspection on the welded samples. Furthermore, a new ultrasonic technology was introduced, which can be used to inspect laser welds of tailored blanks inline [55]. It was necessary to separate the defective blanks immediately in an application that dealt with a large-volume production process.

As part of the process integration, a quick inspection speed of 10 m/min and signal processing techniques that can be automated at moderate cost are also required. Therefore, the development of ultrasonic technique relied on free electromagnetic acoustic transducers (EMATs), which excite and detect guided ultrasonic waves (panels) with horizontal shear polarization. The time taken for the ultrasound to travel from one end to the other was measured by using a non-contact electromagnetic acoustic transducer placed across a pulsed Nd:YAG Q-switched laser (time-of-flight measurement) [56]. Based on the quality of the weld, the geometry of the weld was calculated. The next step is to use this data as a reaction to control the welding process.

Furthermore, the EMAT [57] hybrid system has been developed to illuminate the surface with a laser beam derived from a high energy pulsed laser, thereby being able to detect diffracted waves of very low amplitude. Ultrasonic waves of relatively large amplitude were generated by the laser source. In order to determine geometric quantities using time-of-flight methods, it is necessary to know the speed of sound. The measurement accuracy of these systems is severely limited, so they are not suitable for in-process application in a high temperature environment due to known standardized material temperatures.

Ultrasonic sensors were applied for non-destructive testing during welding because of advances in electronics and ultrasonic sensors. The development of ultrasonics over several decades has led to the development of a variety of techniques for inspecting welded components. A sensor using ultrasound converts electrical pulses into mechanical vibrations or vice versa.

In order to generate and detect ultrasound, a variety of principles have been applied, including capacitive, piezoelectric, electromagnetic acoustic transducers (EMAT), ultrasonic phased array sensors, and laser ultrasonic sensors. Inspecting welding processes has been carried out using one or a combination of these sensors [58].

Usually, a pulsed laser generates an ultrasonic wave which is detected by a continuous wave laser interferometer (**figure 13**). Different types of waves, such as compression, shear, surface and guided waves, can be generated in thermoelastic processes or by laser ablation of a surface. The incident laser power can be varied to generate ultrasonic amplitudes of a wide range. In non-destructive thermoelastic regimes, the compression wave amplitude cannot exceed 110 nm without surface constraint at an approximate 25mm distance from the source. Depending on the maximum laser power, amplitudes of up to about 40 dB are possible in the ablation regime.

Currently, there are two main approaches that are used to detect the ultrasonic moment of a surface. The first method makes light scattered or reflected from a surface interfere with a reference beam, thereby providing the optical phase and consequently measuring instantaneous displacement of the surface. To detect changes in light frequency, the second approach is designed as an optical spectrometer with high resolution. As a result, it provides an output that depends on the surface velocity. It is more practical to use the first approach at lower frequencies and with reflecting surfaces. In particular, the second one may be more sensitive to rough surfaces during high frequencies. Ultrasonic wave interactions inside the workpiece are similar despite the different methods of generation and detection than in contact ultrasonics. Clearly, the advantages of laser ultrasonics are that they are couplant-free, non-contact and can be conducted remotely from the workpiece.

Moreover, its spectral response is flat over a wide range of frequencies. In addition to having high spatial resolution, light beams can also be made extremely small, giving access to confined spaces, and they can also be scanned easily across the workpiece.

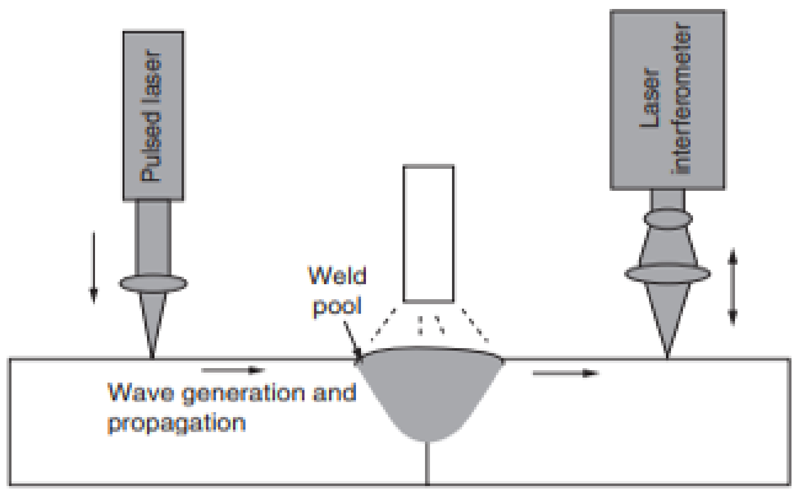

Figure 13. Schematic of laser ultrasonic for online inspection of a welding process [58]

It is theoretically possible to solve the problems associated with contact transducers by means of remote ultrasound generation and reception (large stand-off distances), without physical contact with the workpiece, using laser ultrasonics. There are typically four main components to an ultrasonic laser system : Remotely excite ultrasonic waves in the surface of the workpiece by excitation of a laser ultrasonic transmitter; use a laser ultrasonic receiver to detect ultrasonic disturbances at the surface of the workpiece by echo detection; use a transporter unit to move the workpiece or to use laser beams to select the region to be inspected and use a computer unit to run the transporter, acquire the data, interpret and display the results.

Using an interferometer and detectors, the surface displacement of the workpiece can be transformed into a voltage signal if the laser beam reflecting from it changes phase or frequency[58]. However, their potential was not reached in the manufacturing environment due to two problems. Firstly, ambient vibrations may produce low-frequency high-amplitude phase fluctuations that throw conventional receivers out of quadrature, thereby reducing their sensitivity. Secondly, multiple speckles caused by lasers reflecting from rough-machined surfaces can obscure the ultrasonic signal or significantly reduce signal-to-noise ratios via phase mixing.

8. Modeling approaches to laser welding for quality measure estimation

As part of this section, the paper focuses on several models that have been developed such that they can be correlative to weld quality metric such as melt pool geometry and previously described weld defects (porosity, cracking and humping). There are two main categories of modeling in the special section. An in-depth analysis of analytical and empirical modeling is provided below. Subsections corresponding to analytical models that have been numerically solved are included.

8.1 Analytical modeling

In laser welding modeling, penetration depth is a key welding property related to the thermal field. Temperature measurements have been used as a method of estimating depth in laser processing operations [59]. Considering the temperature measurement and its location, an analytical model was used to predict the groove depth based on the temperature measurement. In order to adjust for the effects of relative motion between beam and workpiece in the model, the two-dimensional steady heat conduction equation has been solved. Based on a two-dimensional thermal conductivity model, an analytical model has been developed to estimate penetration depth [60].

In addition, the assumption of a conical keyhole was considered, along with the relationship between penetration depth and incident strength, which was assumed to be equal to the absorbed force, and the Peclet number was developed. Peclet number is determined by welding speed, keyhole radius, and thermal diffusivity, as explained by the authors. A number of experiments have validated the model, and the consistency of results with theoretical values means that it can be used to estimate depth online and to design coaxial oriented cameras. A better understanding of the physical effects in the keyhole is necessary to prevent process defects, according to Volpe and Fullerstein [61].

As a result, a semi-analytical model is used to study the keyhole properties of aluminium welding at various welding parameters, using energy, pressure, and differential equations. Analyzing the frequency of optical observations during the welding process evaluated the dynamic properties generated by different keyholes.

8.2 Empirical modeling

A series of experiments have been used to determine the optimum process parameters for laser welding in order to achieve high quality. Recent advancements in the development of empirical modeling algorithms have helped the method be widely implemented in a variety of manufacturing processes, especially those whose product quality is highly dependent on many process parameters. To improve the process parameters for weld width and strength, the authors in [62] utilized Taguchi's method along with gray relational analysis. Some of the authors of previous papers have taken a similar approach in utilizing analysis of variance (ANOVA) to determine welding process parameters that significantly influence quality characteristics [63].

As a result of slightly varying the quality measures, it was determined that weld pool area largely depended on weld speed while weld pool width primarily depended on the parameters examined. Finally, the laser power was found to be the most influential factor with regard to the width of the welded pool in the middle of the workpiece. Using a numerical model to predict transient welding conditions, the dynamic state monitor was also trained to predict time-varying keyhole geometry. The researchers concluded in [64] that the low frequency components, of acoustic signals, were considerably decreased when welding defects were present. The shape of the keyhole also had an impact on the intensity of the acoustical signals.

Additionally, a synthetic neural network (ANN) was created to diagnose welding faults based on the experiments carried out. In [22], [65] and [23], the quality characteristics of laser welds were studied using acoustic signals and ANNs as well as multiple regression methods and penetration as a quality indicator. Research has focused on classification modeling for welding quality status, as evident from the papers cited above. In a number of studies, based on different sensor feedback, alternative technologies have been proposed for establishing in-process quality assessment techniques and effective adaptive control systems.

9. Conclusion

In this literature review, new modeling methods, techniques, and approaches for quality assessment in laser welding has been improved and investigated. The corresponding articles were deployed according to the operating principle used for process monitoring. In addition, the correlation of process parameters and quality measures was another aspect that was taken into consideration.

Therefore, the study covered and looked into analytical and empirical methodologies. The information presented leads to the conclusion that non-invasive optical sensing is the best real-time monitoring method for laser welding for in-process quality assessment procedures. Specifically, in terms of the temperature field and the spatial information, thermal and vision cameras offer a more thorough view of the laser welds. However, there have been some concerns raised regarding the thorough examination of all the phenomena that take place during the melting, evaporation, and solidification phases in laser welding due to the dependence of the image-based temperature measurements on material properties, specifically, emissivity.

As it has been demonstrated above, a number of publications have surmounted this issue, and recently there has been a renewed interest among researchers in developing and implementing industrial multi-spectral and multi-modal solutions [66], [67]. The device's ability to collect a wide variety of infrared spectrum will allow for the monitoring of various magnitudes in various spectral bands. The review also noted that there has been a great deal of research done in the literature on the creation of models to match measured magnitudes and process parameters during laser welding with quality measures. While works at semi-empirical models led to the linkage of the temperature field and the evolution of the melt pool with the presence of defects, the focus has been on developing models that target the estimation of the melt pool and the keyhole's evolution under specified process parameters.

On the other hand, considering the quality prediction and re-training capabilities that machine learning and classification techniques can offer to the system, fed by previously labelled data, empirical modelling is a key tool that needs to be further integrated into real-time control and quality assessment systems.

Given the foregoing, it is evident that the most intriguing and difficult area of future study in laser-based manufacturing in general, and not just in laser welding, can be the development of a quality assessment system with cognitive features. Machine learning techniques can interfere with control systems, but they can also predict flaws and guarantee product quality because they are based on experimental modelling methods. A sustainable, modular, and adaptable manufacturing process will result from the development and integration of such systems.

This review is a general presentation of the different techniques of monitoring and inspection of laser welding. In the next steps, a deep study will be done by trying to find the best way to apply the right method to detect and define every defect in the simples welded, which is the main goal of this work.

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CHAPITRE 2 : PROPRIÉTÉS MÉCANIQUES ET MICROSTRUCTURE DU SOUDAGE LASER LINÉAIRE SUR LES ALLIAGES D'ALUMINIUM SIMILAIRES 6061-T6

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1. Résumé du deuxième article

L'utilisation généralisée des alliages d'aluminium dans les industries automobile, aérospatiale a fait du soudage laser une méthode d'assemblage essentielle pour les alliages d'aluminium. Le développement du soudage laser des alliages d'aluminium corroyés a été examiné en détail dans ce travail, sous différents angles. Nous avons soudé linéairement un alliage d'aluminium 6061-T6 de 2 mm d'épaisseur à l'aide d'un laser à fibre. Les principaux objectifs de cette étude sont d'accroître la base scientifique du soudage laser pour la fabrication fiable de joints en alliage d'aluminium et de comprendre comment les méthodes de soudage affectent la qualité des joints. Les principaux paramètres de traitement du soudage laser, tels que la vitesse, le gaz de protection et la puissance, ainsi que leur influence sur la qualité de la soudure, ont été examinés dans la première partie de ce document. Dans la deuxième section, les principales propriétés mécaniques, telles que la résistance à la traction, et les principaux défauts, tels que la porosité, les inclusions d'oxyde, la fissuration et la perte d'éléments d'alliage, rencontrés dans le soudage au laser des alliages d'aluminium, ont été examinés du point de vue de leurs mécanismes de formation et des principaux facteurs d'influence en appliquant ensuite le processus de microstructure. En raison de la modification de la vitesse de soudage et de la quantité de gaz de protection, les joints de soudure présentent désormais des variations notables.

Mots-clés: *Soudage par laser, alliages d'aluminium, résistance à la traction, microstructure.*

2. Contributions

Ce deuxième article, intitulé « Mechanical properties and microstructure of linear laser welding on Similar Aluminium alloy 6061-T6 » fut essentiellement rédigé par son premier auteur Anas Ghazi Jerniti qui a réalisé presque toutes les recherches, tableaux, figures et étudier les effets des paramètres du soudage laser linéaire de l'AA6061-T6. Pedram Farhadipour a été bien présent dans ce travail en effectuant des tests et en prodiguant des conseils pour améliorer la méthodologie du travail fait. Enfin, Noureddine Barka a participé dans la révision de l'article et agi comme superviseur du projet. Il a également contribué à l'amélioration de la méthodologie et la rédaction de cet article.

3. Titre du deuxième article

Mechanical properties and microstructure of linear laser welding on Similar Aluminium alloy 6061-T6.

4. Abstract

The widespread use of aluminium alloys in the automotive, aerospace, and other industries has made laser welding a vital joining method for alumnum alloys. The development of laser welding of wrought aluminium alloys has been extensively examined in this work from a variety of angles. We linearly welded a 2 mm thick 6061-T6 aluminium alloy using fibre laser welding. This study's main goals are to increase the scientific basis of laser welding for the trustworthy manufacturing of Al alloy joints and to comprehend how welding methods affect joint quality. The primary laser welding processing parameters, such as speed, shielding gas, and power, and their influence on weld quality, were looked at in the first section of this paper. In the second section, the main mechanical properties, such as tensile strength, and the main defects, such as porosity, oxide inclusions, cracking, and loss of alloying elements, encountered in laser welding of Al alloys, were discussed from the perspective of their mechanisms of formation and major influencing factors by applying microstructure process in the end. Due to the alteration in welding speed and shielding gas quantity, the welding joints now exhibit notable variances.

Keywords: *Laser welding, aluminium alloy, tensile strength, microstructure*

5. Introduction

Due to its many advantages over conventional welding techniques, laser welding is a highly accurate and effective welding process that has attracted a lot of interest recently. It is crucial to join multiple elements, whether they are similar or dissimilar, to create a single product with desirable properties in the discipline of mechanical engineering. There are many different ways to join materials particularly in mechanical engineering domains, including bolts and fasteners, rivet, solder, adhesive, and welding method [1].

When joining metal, welding is frequently chosen over other methods because it produces robust, long-lasting joins. Contrary to conventional welding, which has been used in many industries for a long time, laser welding promises a distinctive approach. Currently, advancements in technology have coincided with an improvement in the mechanical characteristics of aluminium and its alloys. Given their qualities, including high strength-to-weight ratios, lightness, and affordability, aluminium alloys are often utilized in industries (automotive, aviation, military, transportation, marine, etc.) [2], [3]. Due to its extrudability, weldability, corrosion resistance, heat treatment capability, and medium strength values, the 6XXX family of aluminium alloys, which make up the Al-Mg-Si alloy system, are becoming more and more popular. These alloys can provide good mechanical characteristics by generating precipitates including Mg and Si as a consequence of T6 heat treatment. As a result, AA6061-T6 alloy is one of this group's most frequently utilized alloys [4]–[6]. Due to their excellent weldability, aluminium alloys, particularly those in the 6XXX family, are welded more frequently than other non-ferrous metal kinds [7].

The welding of alloys made of aluminium presents a number of challenges. Due to aluminium's strong attraction for oxygen, an oxide layer has formed on the surface. During the process of welding, this may result in porosity and oxide residues. Argon (Ar) is utilized as a shielding gas; it cannot have oxygen or hydrogen in it. Hydrogen and oxygen should not be present in the weld pool. The high hydrogen solubility of aluminium in liquid form and its inversion in solid form further contribute to the pore issue in aluminium welding [8].

Any hydrogen sources (such as humid surfaces, etc.) are to be prevented before and while welding, and the hydrogen gas bubbles that are introduced into the weld pool need to be permitted to escape. To reduce the flaws in 6XXX series aluminium alloy welding and to improve its quality, several research have been conducted. The recovery of mechanical characteristics and microstructure is the main topic of these investigations. Additionally, studies have been done on how shielding gas compositions, power, and speed affect penetration depths, porosity, and mechanical characteristics in aluminium welds. Due to the industry's widespread usage of AA6061-T6 alloy welding, any effort that improves both performance and quality is essential. The microstructures of such materials are currently the subject of a few investigations in the literature [9]. This study looked at how the parameters selected affected the microstructure, potential flaws, and mechanical characteristics of the welded joints made of the AA6061-T6 alloy.

Because of its capacity to generate welds of excellent quality and accuracy, laser welding has become a prominent welding technique in a number of sectors. In order to melt and fuse the material being welded, the process uses a strong laser beam. The target material is laser-focused, heated to the melting point, and then the material is welded. A welded junction is then produced by moving the laser beam along the joint and melting the material [10]. Compared to other types of welding, such TIG, MIG, and stick welding, the laser welding technique offers several benefits such as high welding speed, high accuracy, low heat distortion, low material damage, and excellent weld quality. The ability to produce solid, precise, and high-quality welds using lasers when joining the same materials is only one of its many benefits. During the laser welding procedure, that intersection between both of the materials to be welded is targeted by a powerful laser beam. The materials are heated by the laser beam, which causes particles to heat up, melt and merge [11]. Conduction welding, deep penetration welding, and keyhole welding are only a few of the methods available for carrying out the procedure. The ability to weld at a high speed while retaining excellent-quality welds is one of the key benefits of using a laser to connect the same materials. This is especially advantageous in high-volume sectors of manufacturing like the automobile and aerospace sectors, at which high-speed manufacturing is essential [12].

A further benefit is the fact that the welding technique results in a minimum of heat distortion and less thermal stress. It's the case as an outcome of the laser beam's tight focus, which causes less heat to be transferred to the materials in the immediate vicinity [13].

On laser welding of comparable materials, several investigations have been done. An investigation of the impact of laser welding settings on the microstructure and mechanical characteristics of laser-welded aluminium alloys, for instance, was conducted by Zhang et al. [14]. According to the research, faster and stronger welds were produced by improving laser power and welding speed. Zhao et al.'s assessment of the aluminium alloys and laser welding of stainless steel provided a review on the subject [15]. In order to produce welds of good quality, the study emphasized the need of adjusting welding parameters such laser power and welding speed.

However, a number of factors affect laser welding. This work's primary goal is to identify the ideal laser welding circumstances used to join similar materials which is a major task that engineers are facing. In order to attain the best joint quality and variety of joints in the welded examinations, as well as to track the procedure parameter that most influences the obtaining of the highest levels for both stress and hardness and to determine the overall percentage of impact for every parameter, analysis of variance (ANOVA) technique is used. Enhancing the microstructure as well as the general quality and efficiency of the joints also led to greater mechanical performance.

6. Materials and experimental methods

6.1 Materials

Linear ar laser Beam welding has been used in similar aluminium joint; the aluminium alloys 6061-T6 were used in the present study and has received extensive study in several articles. Aluminium alloys from the AA6061 class are used extensively in the structural aviation and automotive industries because of their lightness, moderate strength, and durability. While welding, the heat treatable aluminium alloy AA6061-T6 undergoes partial annealing and overaging rather than full annealing [12].

The suffix "T6" indicates that the alloy has been subjected to a specific heat treatment, involving a solution treatment followed by artificial hardening. The effect of post-weld heat treatment (PWHT) on welded materials is a crucial aspect of welding engineering and metallurgy. PWHT is a controlled heating and cooling process applied to a welded component after the welding process. It is used to relieve residual stresses, improve mechanical properties, and enhance the microstructure of the welded joint. PWHT helps in the relaxation of residual stresses generated during the welding process. This can prevent stress corrosion cracking and reduce the risk of component failure. On the other hand, the process requires time and energy, which can increase production costs.

There are significant changes and considerations when laser welding this alloy from its initial T6 condition. Laser welding introduces a localized HAZ in the vicinity of the weld. This region experiences varying degrees of heating and cooling, affecting the microstructure and mechanical properties. The HAZ typically exhibits reduced mechanical properties compared to the base metal. This includes decreased hardness and yield strength. In The fusion zone, where the aluminium alloy is fully melted and resolidified, can exhibit changes in microstructure and mechanical properties. It may differ from the base metal due to the rapid solidification process. This can lead to variations in hardness and tensile strength.

Using a 2mm thickness of aluminium alloy for laser welding can be influenced by various factors and considerations. The choice of material thickness is often determined by the specific requirements of the application. In some cases, a 2mm thickness may be adequate to meet the structural or functional needs of the component being welded. It can provide the required strength while keeping the component lightweight, as Aluminium alloys are known for their lightweight properties and are commonly used in applications where weight reduction is essential. Thinner materials like 2mm aluminium are more responsive to heat input during the welding process. This allows for better control of the heat-affected zone (HAZ) and reduces the risk of overheating or distortion. Laser welding is often chosen for its precision and ability to create intricate welds. Thinner materials offer greater flexibility for achieving fine details in weld profiles, also they are typically requiring less time and energy to weld, which can lead to cost savings in terms of production and material usage.

The initial material's strength as well as the area surrounding the weld zone both deteriorate as a result of this Al alloy's gullibility to time at temperature, which is greater temperature and lengthy duration. Therefore, it becomes crucial to regulate the several factors, including preheating, interpass temperatures, and overall input of heat, while friction stir welding (FSW) of the heat-treatable alloys.

The most popular heat-treatable alloys, including AA6061-T6, often lose a significant amount of their mechanical strength following friction stir welding. For instance, AA6061-T6 typically has a breaking point of 310.26 MPa before welding, and after welding, its strength drops to around 186.15 MPa [16]. Table 5 and 6 show respectively the different properties of AA6061-T6 and its chemical composition. There are two methods to fix this matter: One method is to post-heat treat the alloy to restore its initial mechanical strength after welding. As a result of the Portevin-Le Chatelier (PLC) effect, certain researchers executed post-weld heat treatment (PWHT) on friction stir-welded AA6061-T6 and found that the welding effectiveness was reduced by 65% compared to standard metal [17], [18]. However, the PWHT reduced the PLC impact and restored the characteristics to their original state.

Table 5. Properties of Al 6061-T6 alloy [19]

Hardness (HB)	**95**
Density	**2.7 g x cm**
Ultimate tensile strength	**310 MPa**
Tensile yield strength	**276 MPa**
Shear strength	**207 MPa**
Elongation at fracture	**17 %**
Modulus of elasticity	**68.9 GPa**
Notched tensile strength	**324 MPa**
Ultimate bearing strength	**607 MPa**
Bearing yield strength	**386 MPa**
Poisson’s ratio	**0.33**
Fatigue strength	**96.5 MPa**
Fracture toughness	**29 MPa / m**
Machinability	**50 %**
Shear modulus	**26 GPa**

Table 6. Chemical composition of the as-received AA6061-T6 [20]

Material	Chemical composition (%)								
	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Others	Al
AA6061-T6	0.69	0.43	0.22	0.13	0.87	0.16	0.04	0.02	0.03	Remainder

6.2 Design of Experiments

In order to examine the effects of provided characteristics on responses and provide the best outcomes under realistic circumstances, DOE provides the most effective combinations of variables for those parameters. Power, shielding gas, and speed are the identified input elements in this research, and the welding process action is tensile strength. Table 7 lists the levels and factors for the three-factor analysis used in the experimental technique, whereas Table 8 displays the Taguchi method's experimental design for the experiments in Minitab^{TM}. The focal diameter and focus distance, with values of 0.20 mm and 2 mm, respectively, were set throughout the complete welding process since they have a substantial influence on the quality of the weld. These numbers were selected after considering the other variables.

Table 7. Factors and Levels for Experiment.

Factors	Levels		
	1	2	3
Argon gas (L/min)	10	12	14
Laser Power (kW)	2.5	2.7	2.9
Speed (m/min)	5	5.5	6

Table 8. Orthogonal experiment design

Experiment Number	Input parameters		
	Argon gas (L/min)	Power (kW)	Speed (m/min)
1	10	2.5	6
2	10	2.7	5.5
3	10	2.9	5
4	12	2.5	5.5
5	12	2.7	5
6	12	2.9	6
7	14	2.5	5
8	14	2.7	6
9	14	2.9	5.5

6.3 Welding and test plates

The specimen geometry for tensile tests is illustrated in **figure 14**. Both materials were cut for the test in accordance with the prescribed geometry by the Standard Test Procedures for tension testing of metallic materials ASTM E8/E8M - 16A. **Figure 15** shows the welded plates and the cutting procedure afterwards. The two plates were welded together using a robotized fibre laser (six-axis robotic system FANUC M-710ic) and Ytterbium Fiber Lasers from IPG Photonics, with a combined maximum power of 3kW, a wavelength of 1070 nm, and a focal diameter of 0.45mm for LWBs. The welding robot utilised in the experiment is shown in **figure 16**.

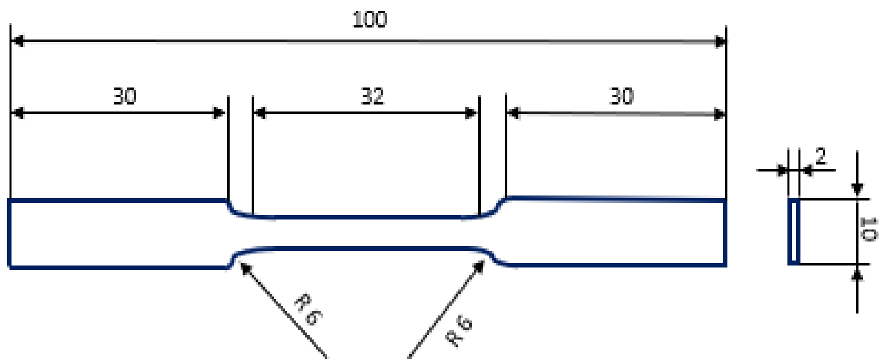

Figure 14. Test Specimen dimensions according to ASTM E8/E8M-16A

Figure 15. Samples welded AA6061

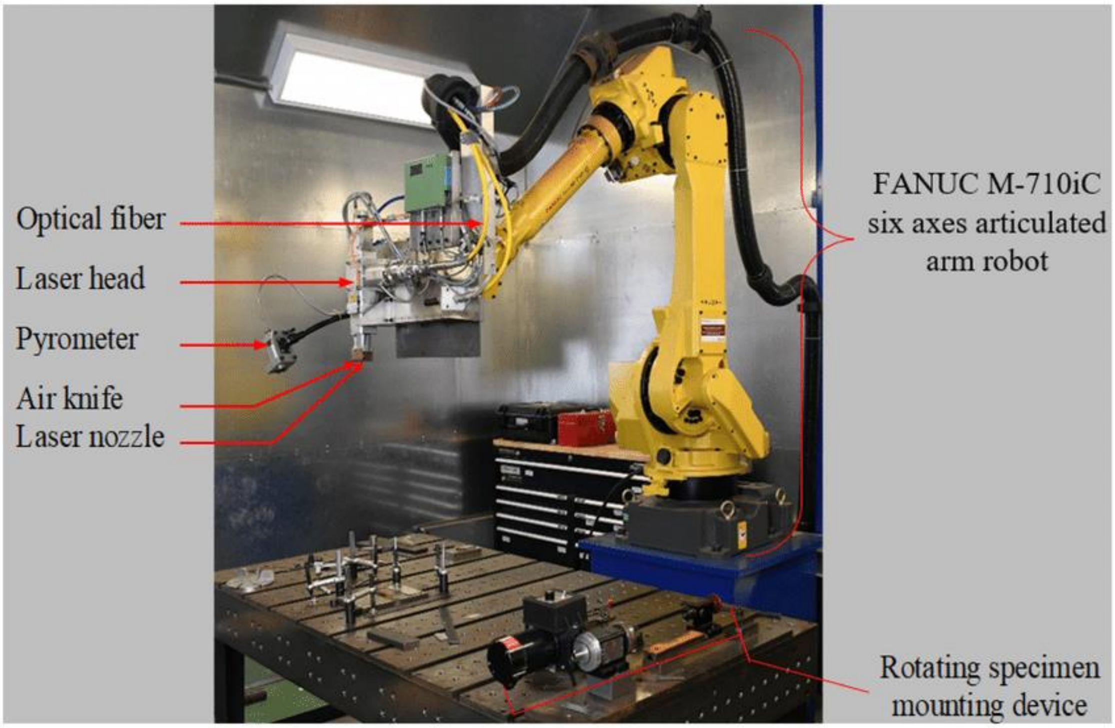

Figure 16. Automatic Fiber Laser System, six-axis-robotic system FANUC M-710ic with IPG Photonics YLS-3000 (Ytterbium Fiber Lasers) [21]

In this work, an orthogonal design of experiment spanning the complete laser welding process parameters was employed to explore the impact of laser welding input variables on weld-joint quality. The development of intermetallic phases, bead width, penetration, and mechanical strength were all examined. Choosing the laser welding conditions that would result in a high-quality weld joint was the key problem for welding the AA6061 identical material. The study's main goal was to look at how welding parameters and weld bead shape relate to one another. This led to the conclusion that welding speed was particularly an important factor, following by shielding gas and the relationship between beam power and defocusing value. The goal of future research will be on improving laser welding parameters for the most effective steel-on-aluminium assemblies' mechanical qualities and understanding how intermetallic compounds affect weld joints' mechanical characteristics.

7. Results and discussion

7.1 Tensile test

Tensile testing includes applying a force that pulls a material or component with an aim to assess its mechanical characteristics [22]. A tensile force is given to the sample throughout the test, stretching it till it breaks or deforms. It is common practice to determine and record the sample's load and displacement. This technique is frequently used to assess the durability and other properties of materials. Load-Extension curves of all tests is displayed in **figures 17**. The failure load for each tensile tested sample was gathered from the load-extension data and plotted against the different laser parameters used in the test matrix. To determine the ductility of a welded joint, elongation, a measurement of a material's capacity to stretch or deform before breaking, is utilized [23]. As can be observed, the curves seem to have the same form. The elastic zone of each curve has a comparable slope, proving that the trials had no impact on the Young modulus. However, as shown in **table 9**, there are variations in the Ultimate tensile strength between various experiments.

The test with the maximum UTS, 208.4 MPa, is test 3, and the test with the minimum UTS, 178.6 MPa, is test 8. As the parameter levels of tests 3 and 8 are actually shifted, a difference can be expected. The bulk of the fractures occurred in the fusion line after rupture, according to the fracture paths of the tensile samples. This is probably because of faults including undercuts, underfills, and root reinforcement that act as stress concentration sites and initiate crack propagation. According to the results of the tensile tests, the fusion line and fusion zone are the weakest welding conditions, and tests 6, 8, and 9 demonstrate that the failure occurred in these areas. The lowest tensile strength of test 8 can be used to determine the seriousness of the faults created during the welding process.

Table 9. Tensile Strength Results.

Test	Argon gas (L/min)	Power (kW)	Speed (m/min)	Ultimate tensile strength (MPa)
1	10	2.5	6	186.8
2	10	2.7	5.5	198.1
3	10	2.9	5	208.4
4	12	2.5	5.5	185.2
5	12	2.7	5	201.4
6	12	2.9	6	181.5
7	14	2.5	5	188.9
8	14	2.7	6	178.6
9	14	2.9	5.5	182.2

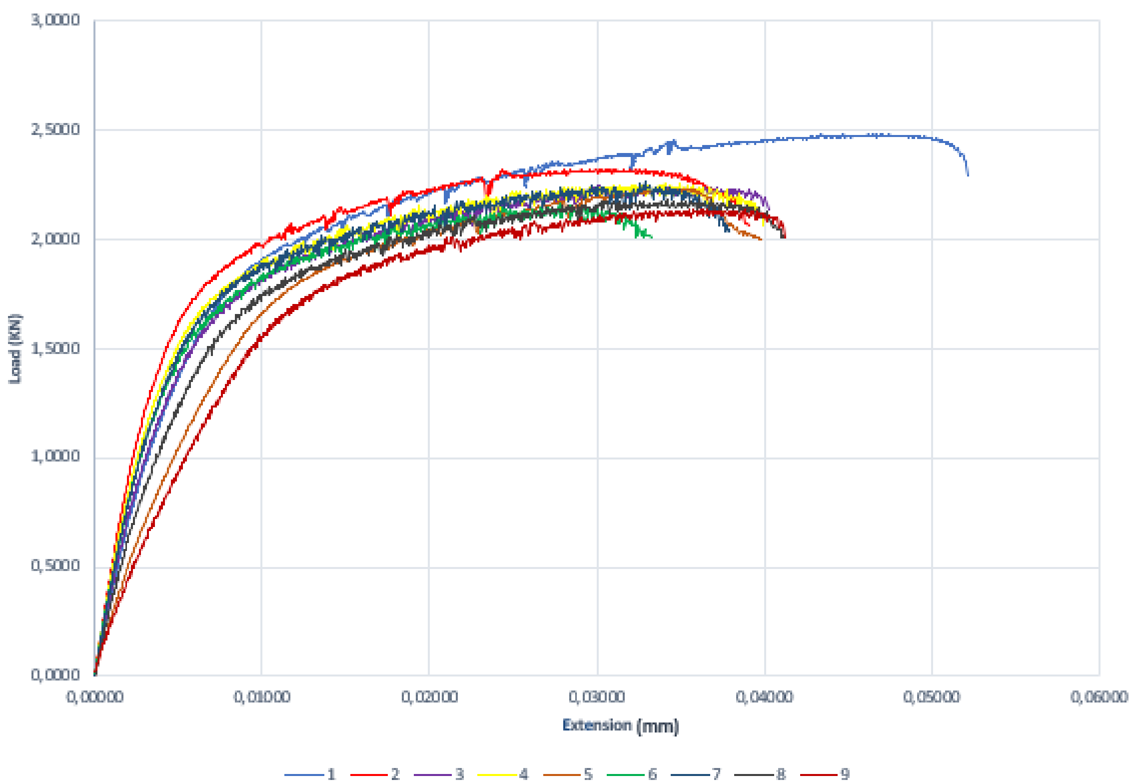

Figure 17. Load-Extension curve of all tests

7.2 Analysis of Variance (ANOVA)

The statistical method known as the analysis of variance (ANOVA) will be used to determine the impact of the parameters. A number of experiments which includes systematic change of the parameters and combining of those multiple variations for every parameter under consideration must be carried out in order to collect sufficient data for numerical computation. In order to acquire reliable data collection for analysis, an effective experiment design has to be established. In order to determine the impacts of each parameter as well as to illustrate how they interact with one another; an entire factorial design is developed. The study's final goal is to create a predictive model using linear regression to forecast the mechanical properties derived from a particular set of parameters, followed by a response surface that emphasizes the values of the crucial parameters for optimum weld tensile strength, and finally validation tests.

ANOVA is a statistical technique used in manufacturing for reliable process and quality control [24]. It enables the effective interpretation of experimental data. The findings of the tensile tests conducted on the welded coupons in relation to the variables represented by V for speed, G for shielding gas, and P for laser power as well as the results, that indicate the mechanical durability of the welds. ANOVA tables and regression equation definition are generated using the Minitab™ software application. The table including information related to numerical analysis, including the sum of squares (SS), the mean sum of squares (MS), and the degree of freedom (DoF), summarizes the findings of the ANOVA.

According to the findings, **figure 18** shows the most important variables to control to enhance mechanical performance. The F-value and p-value, which are used in hypothesis tests to check the consistency and applicability of the results taking those factors into account, are also included in Table 10. This table reveals that the speed parameter is the most significant one, contributing 55.20% and having a P-value of $\alpha = 0.005$, which is less than the 0.05 value that is generally regarded as the P-value threshold for defining the probability of rejecting the null when the hypothesis is true [25].

It is also obvious that the speed value has a negative impact on the weld's mechanical strength as increased speed tends to diminish the weld's mechanical resistance. This outcome is typical for aluminium laser welding and can be explained through the fact that a slower welding speed lengthens the time that the weld is exposed to the beam. This compensates for the heat loss caused by the aluminium's high conductivity and reflectivity because the linear energy becomes much more significant, leading to a greater weld depth [26], [27]. The shielding gas is the second important factor, contributing 38.41% of the total and having a P-Value of 0.007. The mechanical qualities of the welds are also negatively impacted, which means that the stronger the weld, the lower the shielding gas must be. With a value of 6.11% in contribution, the laser power makes up the least amount of the parameters in the ANOVA table. The ANOVA analysis performed on the laser welding data has provided valuable insights into the factors affecting the welding process and its outcomes. The study aimed to investigate how different variables influence the quality and characteristics of laser-welded joints. Figure.19 illustrates how increasing speed tends to reduce the weld's mechanical resistance. However, a speed of 5 m/min, a shielding gas of 10 L/min, and a laser power of 2900 W produce the best tensile strength. This combination avoids the plate from overheating at higher laser power levels in laser welding of AA 6061-T6.

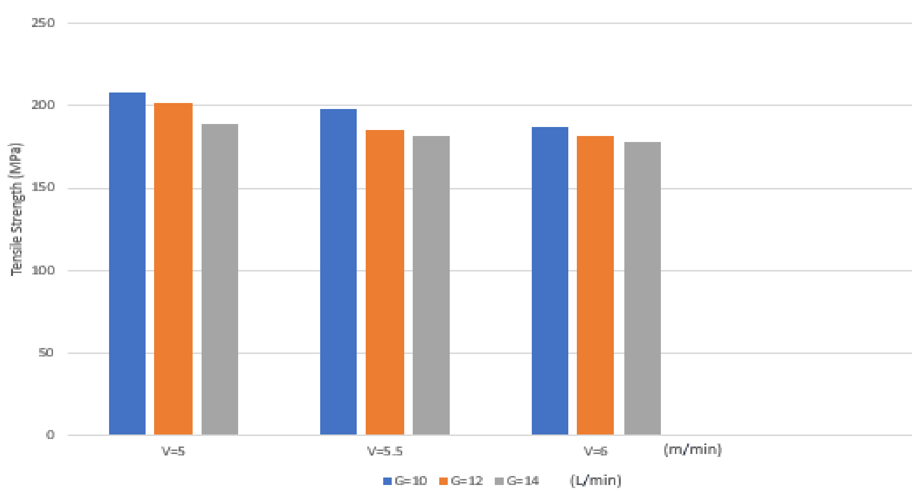

Figure 18. Tensile Strength for test power values

Table 10. ANOVA Table for Tensile Strength Results

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
G	2	319,396	38,41	319,396	159,698	139,95	0,007
P	2	50,809	6,11	50,809	25,404	22,26	0,043
V	2	459,049	55,20	459,049	229,524	201,14	0,005
Error	2	2,282	0,27	2,282	1,141		
Total	8	831,536	100,00				

S	R-sq	R-sq(adj)	PRESS	R-sq(pred)	AlCc	BlC
1,06823	99,73%	98,90%	46,215	94,44%	*	30,77

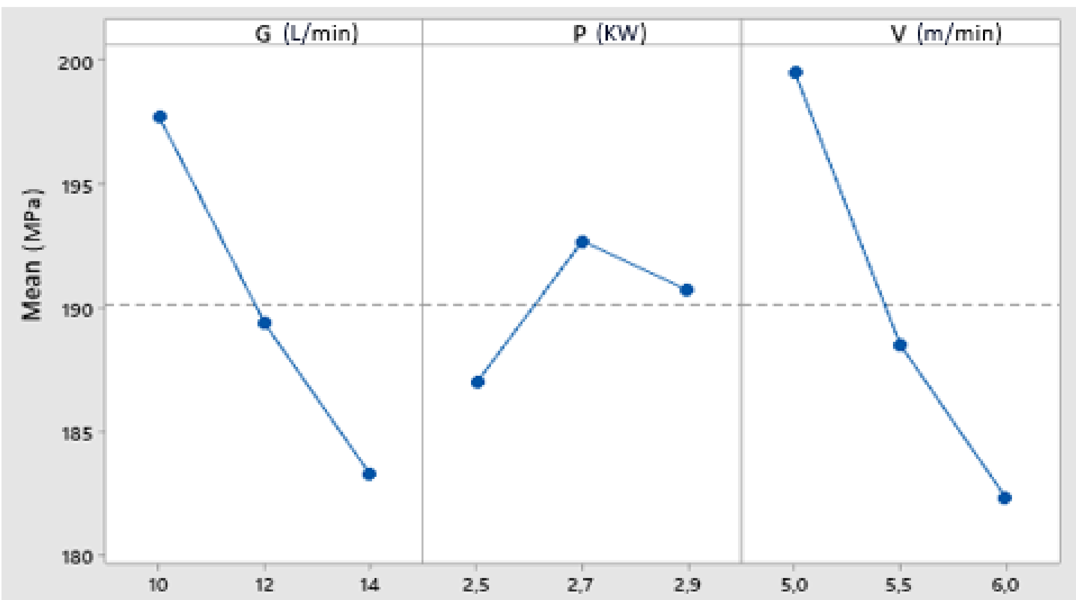

Figure 19. Mean effects of parameters on average Tensile Strength.

7.3 Microstructure

Before being examined with a scanning electron microscope (SEM) to look for weld defects, specimens for microstructure analysis go through preparatory methods for micrography that include cutting the parts with a rotary saw machine, covering the cut samples with epoxy coating, and polishing them. In **figure 20**, the whole weld cross section is visible for certain experiments. Evidently, typical wine-glass-shaped weld metals with full penetration were created. The fast heating and cooling during the laser welding process resulted in the dendrites that made up the WM's microstructure, which can be observed in **figure 21** and was noticeably thinner compared to the BM (**figure 22**). **Figure 23** illustrates the microstructure at the fusion line shows that the only element influencing the transition seen between materials was the heat generated during welding. There were typical columnar crystals that were parallel to the fusing line. This is because columnar crystals tend to grow in the direction that releases heat most quickly, which has to be perpendicular to the isotherm, and since the average growth of columnar crystals is anisotropic, varying in different crystallographic orientations [29]. Because the fastest cooling orientation in laser welding is perpendicular to it, the columnar grains near to the fusion line advance perpendicular to it. Due to the relatively localized nature of the heat and the fact that only a small fraction of the sample had obvious microstructural changes, the microstructure of the heat affected zone (HAZ) was comparable to that of BM.

An important area of research in materials science and engineering is the HAZ in microstructure laser welding. Laser welding is now a typical high-speed, low-heat input welding technology in several industries. However, the laser beam's increased temperature frequently alters the microstructure of the material welded, which in turn alters the material's mechanical properties. The grain structure in the heat-affected zone is changed by the heat produced by the tool, with grains nearer to the tool contact area sustaining more heat than grains much further away. This region is not mechanically deformed. The grain structure may be altering in the HAZ because to this heat.

According to Chowdhury et al. [30], there is uncertainty about the recrystallization that is occurring in the HAZ because the presence of freshly equiaxed grains indicates only partial recrystallization in the HAZ, even though the presence of certain larger grains indicates that the grains have really been recrystallized in the area. Tool contact in the TMAZ forced the grains to bend plastically even though Prangnell and Heason [31] discovered that the grains are really not recrystallized in this zone. Latest strain-free nucleation sites develop as a result of the material becoming strained due to the smaller grain size. 64 As a result, the microstructure of the various zones of the FSW weld joint changes according to the rates of recrystallization and grain growth.

The most prevalent welding flaw in laser welding of aluminium alloys is porosity, which influences the material's properties [32]. Based on the research on laser welding of aluminium alloy, the porosity problems can now only be minimised by modifying the proper parameters. This remedy is particular, not general. Porosity is a significant issue when welding aluminium alloys. It is simple to cause stress concentration, which lowers the joint's structural strength.

The aluminium alloy laser welding seam has two types of porosity: process porosity and hydrogen porosity [33-35]. The main cause of hydrogen porosity, which is often regularly round or oval, is hydrogen. Keyhole collapse following welding results in process porosity. Process porosity has an erratic form.

In the standard Al alloys, a notably high porosity has been discovered during fusion welding. For instance, the cause for the high porosity in the welded joints of Al alloys was mostly attributed to the naturally occurring small pores in the BM [36], as a result of the microscopic holes floating and developing or coalescing in the welding pool as seen in **figure 24**. When welding at these faster speeds, shielding gas impacts may contribute more to the formation of the porosity seen in **figure 25**.

The following [37-39] are the main causes of porosity development in the welding seam. The solubility of hydrogen decreases significantly when liquid aluminium alloy being cooled and crystallised into a solid aluminium alloy. The front end of the molten pool solidifies and crystallises, blocking the hydrogen that is dissolved at high temperatures and forming porosity. Bubbles are difficult to float when the weld metal's rate of solidification increases.

The high thermal conductivity as well as solidification characteristics of aluminium alloy make it difficult for bubbles to escape. The molten pool density of the aluminium alloy is low, and the bubbles float slowly.

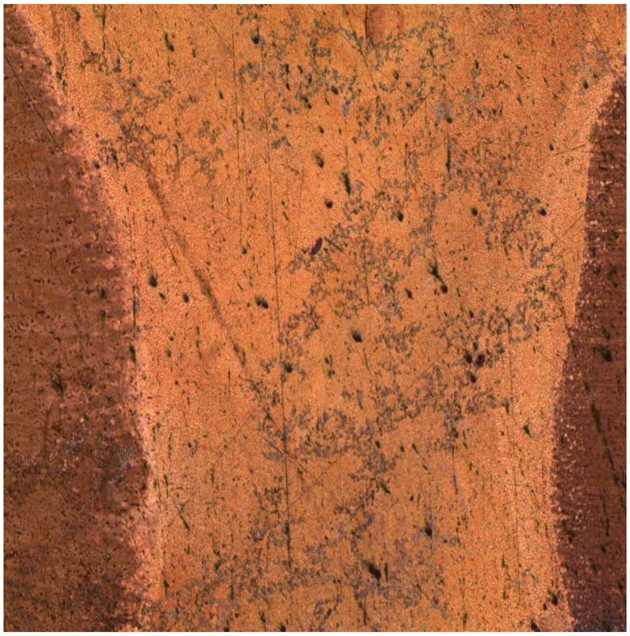

Figure 20. Weld cross section of sample 1

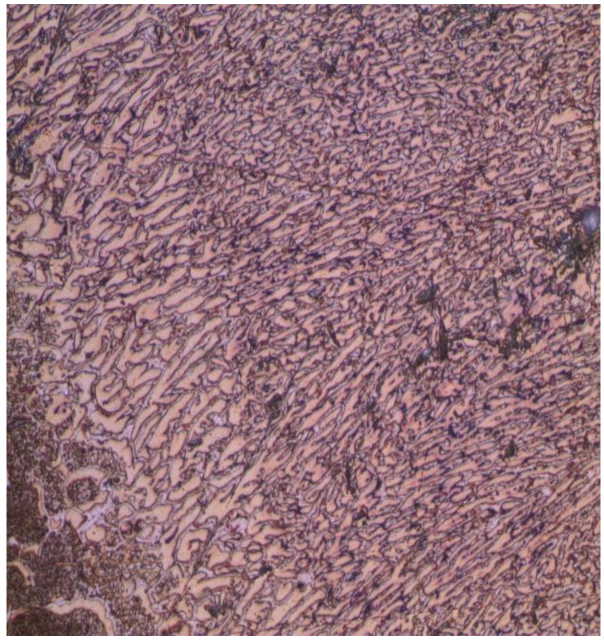

Figure 21. Dendrite observed in sample 2

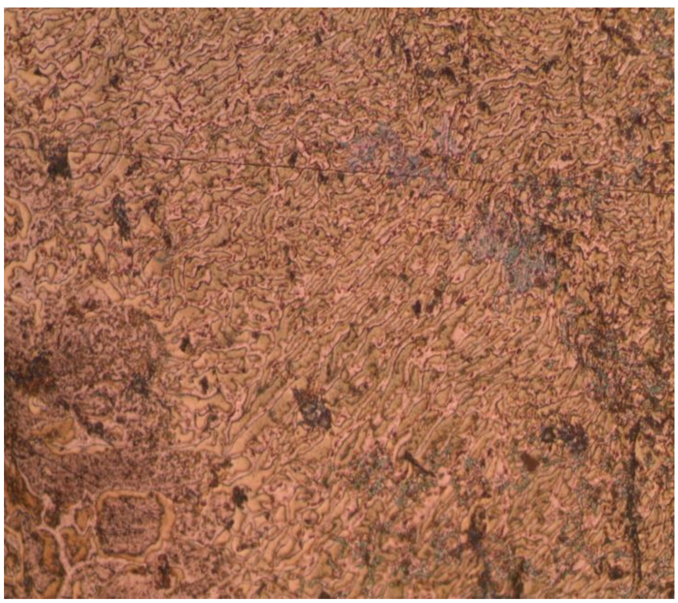

Figure 22. Dendrite observed in the base metal

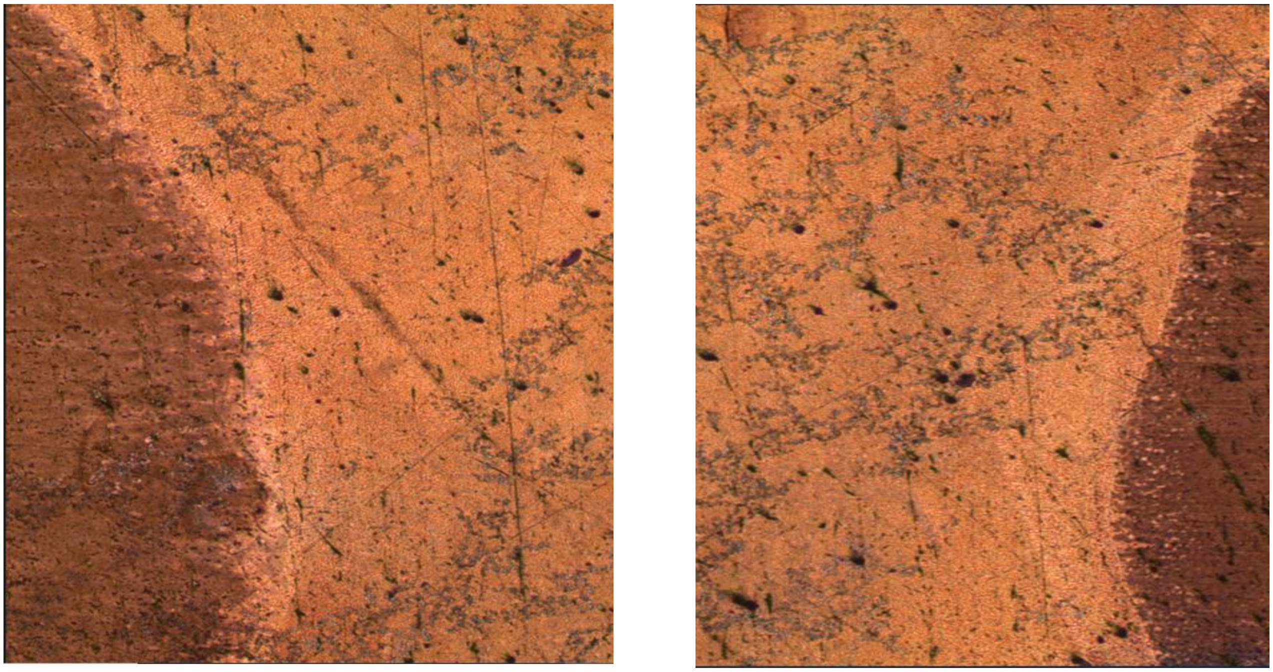

Figure 23. Microstructure at the fusion line of the sample 3

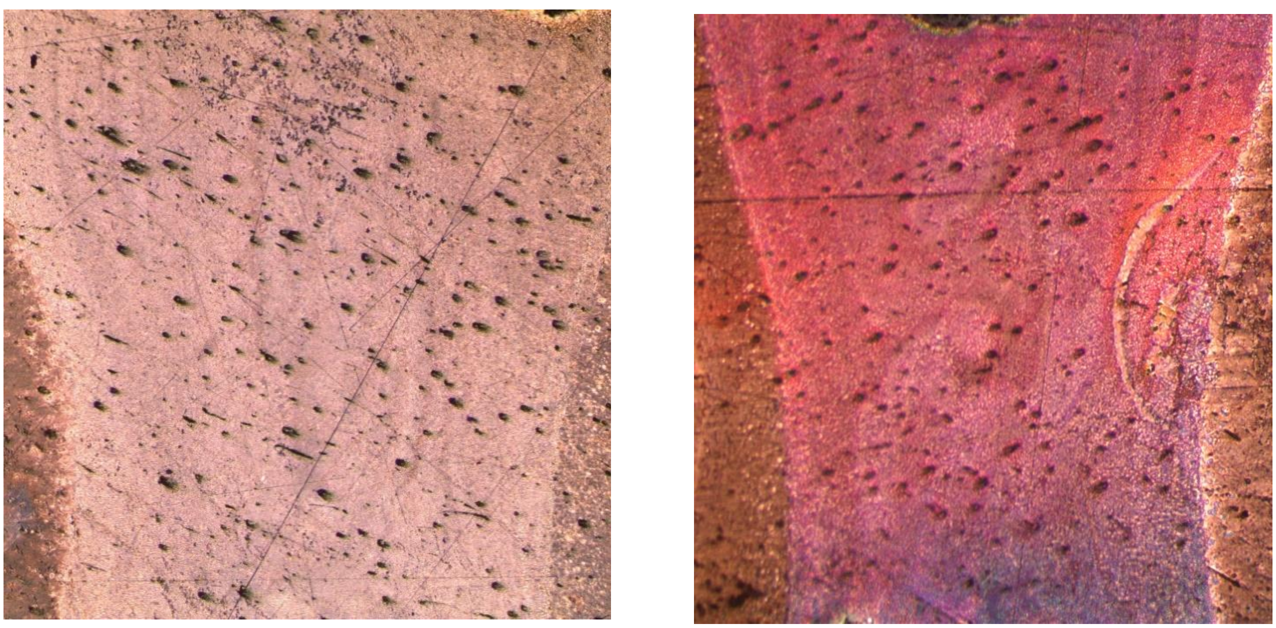

Figure 24. Microscopic holes observed in the welding pool in samples 5 and 6

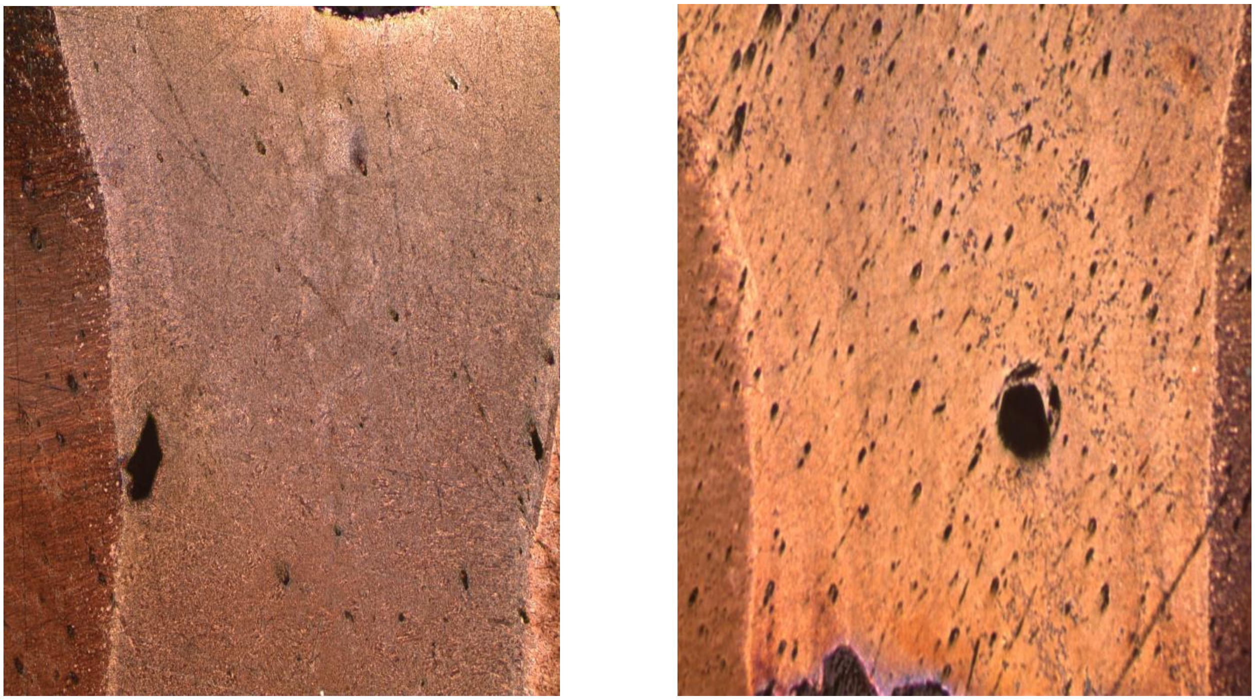

Figure 25. Formation of the porosities seen in the samples 7 and 8

8. Conclusion

In this study, the laser welding technique was used to weld the 2 mm-thick 6061-T6 similar Al alloys. As wrought aluminium alloys are used more frequently in the automotive, aerospace, and other industries, laser welding is going to be a vital joining method for aluminium alloys. Al alloy laser welding is a very immature and unreliable technology. Before laser welding becomes widely used, the industry will undoubtedly demand a predictable, repeatable, regular, and reliable welding technology. As a shielding gas, argon was used successfully for all welding operations. The samples were subjected to tensile and macrostructure testing after welding procedures were completed in 9 distinct tests. The parameters of the experiment were speed of welding, laser power and the gas flow rate.

First, the melt pool was shielded from oxidation by the argon shielding gas, which also ejected oxygen. An oxidation-related cracking weld resulted. Additionally, the weld's colour was altered by the shielding gas. A poor weld quality was caused by the shielding gas in a high-power density. Weld spatter and porosity were noticed. Additionally, the inclusion of argon improved the tensile strength before being saturated. Maximum tensile strength at 2.8 kW and 10 L/min argon flow rate served as the indicator of the outcome. By accelerating the welding process and increasing gas flow, the tensile strength was reduced.

Furthermore, it is difficult to control the outcome of the laser welding process. The weld outcome was used to modify the laser's settings. When welding speed is reduced, the microstructure's pores become smaller. This can be clarified through the simple fact that due to quick solidification, gas bubbles created by the circulation of molten metal while welding are prevented from rising to the surface.

As the welding speed slows down, shorter, and coaxial grains develop in place of the HAZ's elongated, thin columnar grains. The heat input, which changes with welding speed, is to blame for this. Tensile tests revealed that all samples separated from the weld metal. This occurs because of the notch effect produced by the weld metal's pores. Increased welding speed has a detrimental impact on tensile strength since it is directly proportional to a rise in pore count.

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CHAPITRE 3 : OPTIMISATION DES PARAMÈTRES DE SOUDAGE PAR LASER OSCILLANT POUR LES ALLIAGES D'ALUMINIUM DISSEMBLABLES 6061-T6 ET 5052-H32

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1. Résumé du troisième article

Cette étude a examiné le soudage par laser de plusieurs configurations utilisant des alliages d'aluminium dissemblables (6061-T6 et 5052-H32). Des alliages d'aluminium de 2 mm d'épaisseur ont été assemblés par soudage laser par oscillation. Grâce à l'effet de brassage, l'oscillation du faisceau a amélioré les morphologies de soudure et favorisé la production de grains équiaxes dans la zone de fusion. L'oscillation du faisceau est une méthode de pointe du soudage laser qui améliore considérablement la qualité de la soudure. Afin d'obtenir un processus de soudage répétable de haute qualité pour les alliages d'aluminium, cette étude examine les effets de l'amplitude, de la puissance du laser et de la distance focale sur le soudage par faisceau laser oscillant en utilisant un plan factoriel complet de trois variables et trois niveaux, suivi d'une analyse de la variance (ANOVA). Cette amélioration est évaluée à l'aide d'outils numériques basés sur des tests préliminaires dans lesquels chaque paramètre est modifié indépendamment dans une plage spécifique. Les résultats des tests de traction montrent que l'amplitude, suivie de la puissance du laser, a l'impact le plus significatif. Pour certains composants, la microstructure des soudures au laser a été examinée. Les résultats ont montré que les cristaux en colonne se développaient généralement perpendiculairement à la ligne de fusion et que la microstructure du matériau soudé (WM) était nettement plus fine que celle du matériau de base (BM).

Mots-clés: *Soudage par laser, alliages d'aluminium, laser oscillant, test de traction, ANOVA, microstructure.*

2. Contributions

Ce troisième article, intitulé « Optimization of oscillating laser welding parameters for Dissimilar Aluminium Alloys 6061-T6 and 5052-H32 » fut rédigé par son premier auteur Anas Ghazi Jerniti et a réalisé, avec Joys S.Rivera, presque toutes les recherches, les tests et l'étude sur les effets des paramètres du soudage laser. Abdessamad a été bien présent dans ce travail en effectuant certains tests et analyses. Enfin, Noureddine Barka a participé dans la révision et a également contribué à l'amélioration de la méthodologie et la rédaction de cet article.

3. Titre du troisième article

Optimization of oscillating laser welding parameters for Dissimilar Aluminium Alloys 6061-T6 and 5052-H32.

4. Abstract

This study investigated the laser welding of several configurations using dissimilar aluminium alloys (6061-T6 and 5052-H32). Aluminium alloys measuring 2 mm thick were joined using laser oscillation welding. Due to the stirring effect, the beam oscillation enhanced the weld morphologies and encouraged the production of equiaxed grain in the fusion zone. A cutting-edge method of laser welding that significantly improves the quality of the weld is beam oscillation. In order to achieve a repeatable high-quality welding process for aluminium alloys, this study investigates the effects of amplitude, laser power, and focal distance on oscillated laser beam welding by employing a complete factorial design of three variables and three levels, followed by an analysis of variance (ANOVA). This improvement is evaluated using numerical tools based on preliminary tests in which each parameter is varied independently within a specific range. The outcome shows that the amplitude, followed by laser power, has the most significant impact. For some components, the microstructure of laser welds was examined. The results demonstrated that columnar crystals typically grew perpendicular to the fusion line and that the microstructure of the welded material (WM) was substantially finer than that of the base material (BM).

Keywords: *Laser welding, aluminium alloy, oscillating laser, tensile test, ANOVA, microstructure.*

5. Introduction

The use of materials with positive impact to reduce the Greenhouse gas emissions is one of the green deals for economic development in the world [1]. The top contributors of greenhouse gas emissions are electricity generation, transportation, and industry [2]. Therefore, the solutions of materials in transportation industry are a very important subject to develop in the world, and for that innovate the manufacturing processes of materials in transportation is key. Aluminium alloys have an important application potential and increasing use in transportation such as the automotive industry, aerospace applications, maritime industry, and the railway industry with the objective of lighter weighting and reduce the energy consumption, having a direct impact in emissions reduction in all the productive chain of these industries [3]– [6].

Recently, automotive industry had a decisive role in the economy of developed country, it must be used properly and optimize as much as possible to grow more and more every year. Automotive manufacturers have already promoted combinations of different advanced materials to prove that they are able to apply their potential to reduce weight, as some methodologies of design represent an effective and efficiency approach for light-weighting [7], also to reduce fuel consumption and automation associated emissions. In automotive industry, environmental requirements are very strict and are getting tougher regarding the harmful emissions while meeting higher safety requirements. To complete these requirements, weight reduction has a critical role. That is why lightweight manufacturing is the most term used and developed in the recent research activities, and new manufacturing processes are discovered over the years related to innovative low cost and this become one of the main objectives in sheet metal forming.

There are some special stages in automobile manufacturing which offer the possibility of changing from conventional steels to lighter materials such as aluminium alloys, which is one of the best choice of materials for light-weighting as it is able to reduce vehicle weight by 20 to 30% compared to other steel sheet metals [8], [9]. This become one of the most serious challenges for producing lightweight cars, as hybrid components of aluminium alloys and steel grades are truly essential in modern designs.

In addition, due to the increasing global competition between the different automotive industries, low-cost manufacturing which is connected to lightweight is one of the main objectives for many companies [10], and it can be increased sometimes with lightweight technologies due to new processes and equipment. **Figure 26** presents life cycle energy assessment for aluminium and steel used in automotive closure panels [11].

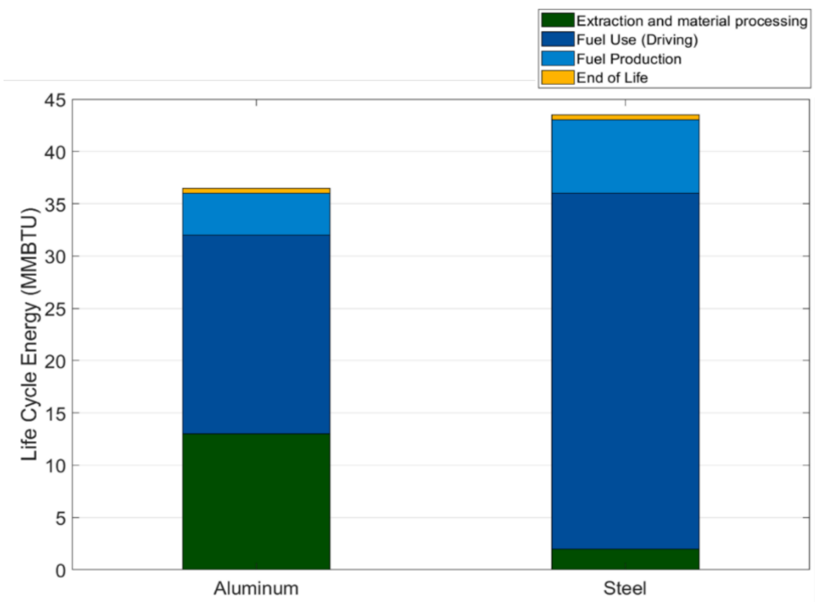


Figure 26. Life Cycle Energy assessment pe amount of aluminium and steel used in closure panels. Fuel (gasoline)

Among the most profitable and efficient processes in this field, laser welding technologies are used for its superiority regarding conventional processes and has many advantages including smaller heat affected zones compared to spot welding [12], higher energy efficiency, higher speeds, and can also be bound with gases to increase the efficiency of the process and minimize the oxidization of surfaces. The welding of dissimilar materials is a technical topic that is of great practical importance, and as a promising strategy to produce lightweight, economical, and environmental structures has become more and more widely used in the automotive industries.

The pursuit of more optimal lightweight and high-performance structures can be achieved by combining different materials into a hybrid multi-material structure [12]. The different properties of different materials are used together to have a greater flexibility and to achieve the required product performance. F. Fetzer and Al. found that increasing the amplitude on laser welding results in cracks reduction and an increase in welding width for aluminium [13]. Zhimin Wang et Al. found that welding oscillation increase the average tensile strength on aluminium laser welding, it associated to the refinement of grain size [14].

However, Laser welding depends on several parameters. The main sense of this work is to determine the optimal laser welding parameters involved in joining dissimilar materials. In this article, we will study dissimilar material in laser welding, which is a big challenge constantly being considered within engineering. To distinguish the most important process parameter in the current welding process conditions, analysis of variance (ANOVA) technique is used to achieve the optimal joint quality and nature of joints in the welded tests, also to observe the process parameter that most affects the acquisition of the highest value of stress and hardness and to obtain the total percentage of impact for each parameter. Also, Stronger mechanical performance was achieved by establishing the microstructure and overall quality and performance of the joints.

Finally, some parts have been inspected with laser ultrasonic technique which is the most commonly used techniques to inspect welding defects [15], [16]**.** The machine is occupied with a fiber coupled laser ultrasonic head, it contains generation and detection lasers and an interferometer to insure completely non-contact operation. Despite the fact that ultrasonic technique has been extensively utilised to assess welded connections, it is frequently highly challenging to properly carry out sheet metal scanning because of the existence of geometric structure, which contributes to the drawback of non-destructive testing.

6. Experimental procedures

6.1 Materials

Oscillating laser Beam welding have been done in dissimilar aluminium joint, the materials implemented in this study are the aluminium alloys 6061-T6 and 5052-H32. The weldability of aluminium alloys has been improved thanks to the combination of high-power density laser beam and the oscillating mode, it limits the heat-generated defects and enhanced the ductility of the AA 5052-H32 [17]. AA 6061-T6 has considerable strength to weight ratio and desired formability [18], with SI and Mg as their main components, he is strengthened by hardening precipitates [19]. Si can improve its fluidity and hot crack resistance, and Mg can enhance its specific strength. AA 5052-H32 has good mechanical properties, medium strength, machining performance and good corrosion resistance, this characteristic is shared by the two alloys, but the latter has poor weldability despite having a higher ultimate strength than 5052-H32 [20]. Due to this, both are frequently put together using different types of welding in order to benefit from each alloy's advantages and create a part that is more robust [21]. Both are widely used in automotive industry, aerospace industry and transportation industries [22], [23], with a successful application in naval and deep-sea applications. In tables 11 and 12 the nominal chemical composition and tensile strength properties of base materials are shown, respectively. To make the welding process the defined sheets dimensions were 150 mm x 75 mm, thickness 2.03 mm. The material was prepared to get best results in laser welding with acetone to remove surface contaminants.

Table 11. Nominal chemical composition of 6061-T6 and 5052-H32 Al alloys used in this investigation.

Material	Al (%)	Cr (%)	Cu (%)	Fe (%)	Mg (%)	Mn (%)	Si (%)	Ti (%)	Zn (%)	Others (%)
6061-T6	95.8 - 98.6	0.04 -0.35	0.15 - 0.4	<= 0.7	0.8 - 1.2	<= 0.15	0.4 - 0.8	<= 0.15	<= 0.25	<=0.15
5052-H32	95.7 -97.7	0.15 - 0.35	<=0.1	<= 0.4	2.2 - 2.8	<= 0.1	<= 0.25	-	<=0.10	<= 0.15

Table 12. Tensile properties of 6061-T6 and 5052-H32 Al Alloys used in this investigation.

Material	Tensile Strength, Ult (MPa)	Tensile Strength, Yield (MPa)	Elongation (%)
6061-T6	290	255	12
5052-H32	228	193	12

6.2 Design of Experiments

DOE gives the optimal combinations of values for input parameters to study their 6061Study, the defined input factors are focal distance, power, and amplitude; the process response is the tensile strength in welding. The Three factors analysis at three levels are defined for the experimental procedure, **table 13** shows factors and levels, and **table 14** shows the experimental design by Taguchi method in Minitab^{TM} for the experiments. Pure argon was employed as the shielding gas during the whole welding process, operating at a constant flow rate of 25L/min. Speed and frequency were also fixed as they have a significant impact to get a good welding, and their values are, respectively, 5m/min and 150Hz. These values were chosen based on the other parameters.

Table 13. Factors and Levels for Experiment.

Factors	Levels		
	1	2	3
Focal Distance (mm)	-2.0	0	2
Laser Power (kW)	2.5	2.7	2.9
Amplitude (mm)	1.0	1.5	2.0

Table 14. Experimental Design.

Experiment Number	Input parameters		
	Focal Distance (mm)	Power (kW)	Amplitude (mm)
1	-2.0	2.5	2.0
2	-2.0	2.7	1.5
3	-2.0	2.9	1.0
4	0.0	2.5	1.5
5	0.0	2.7	1.0
6	0.0	2.9	2.0
7	2.0	2.5	1.0
8	2.0	2.7	2.0
9	2.0	2.9	1.5

6.3 Welding and test plates

Both materials were cut for test according to recommended geometry by the Standard Test Methods for tension testing of metallic materials ASTM E8/E8M – 16A, in **figure 27** the specimen geometry for tensile tests is shown. In **figure 28** the welded plates and after cut process is presented. A robotized fiber laser welding (six-axis-robotic system FANUC M-710ic), using IPG Photonics YLS-3000 (Ytterbium Fiber Lasers) with 3kW maximum power, a wavelength of 1070 nm and a focal diameter of 0.45mm for LWBs was used to weld the two plates, getting a consolidated plate with 150 mm x 150 mm. In **figure 29** shows the welding robot used for the experiment.

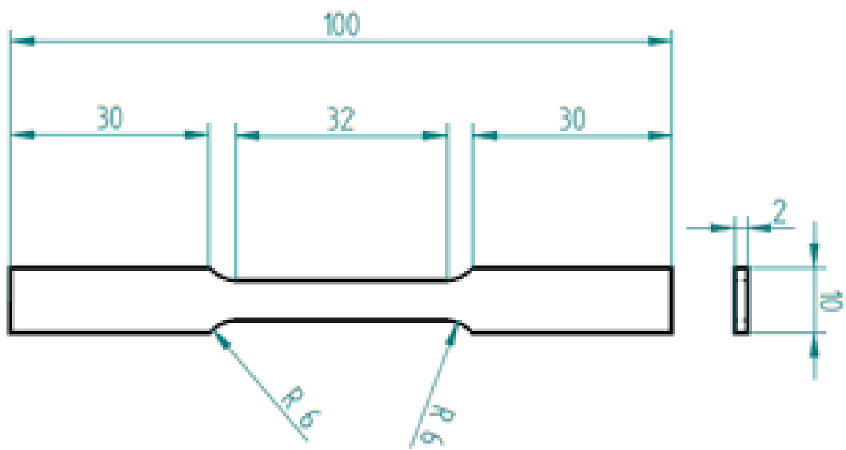


Figure 27. Test Specimen dimensions according to ASTM E8/E8M-16A

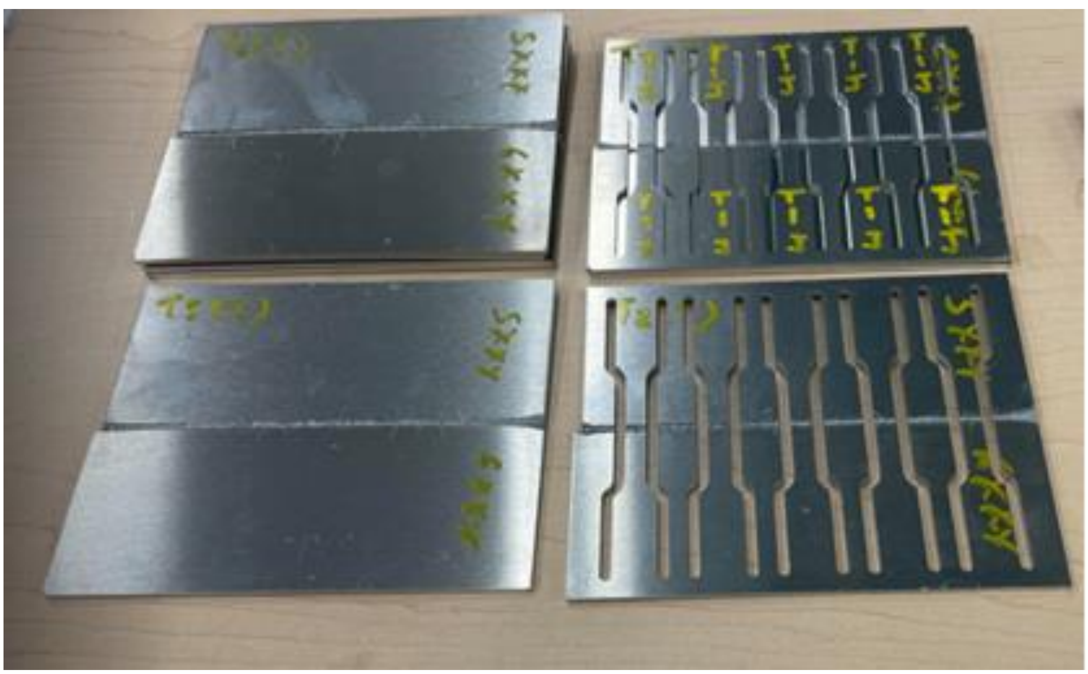


Figure 28. Left: Welded Plates. Rigth: Cutted samples

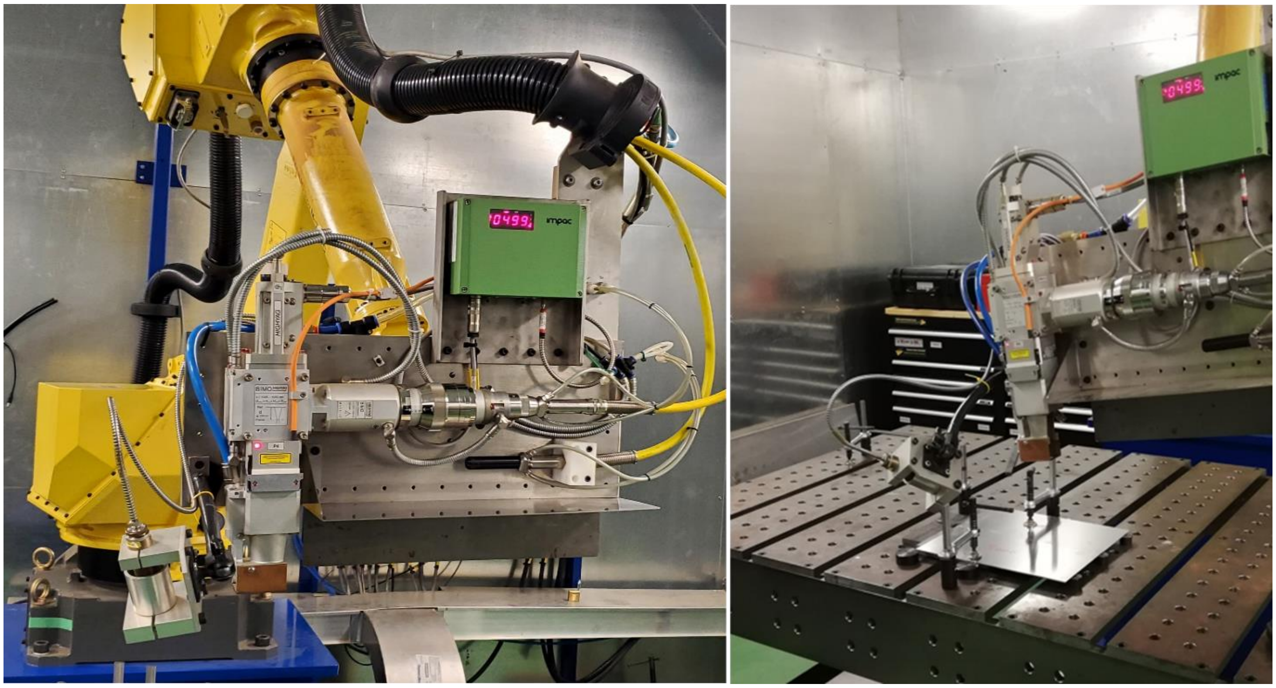


Figure 29. Automatic Fiber Laser System, six-axis-robotic system FANUC M-710ic with IPG Photonics YLS-3000 (Ytterbium Fiber Lasers).

7. Results and discussion

7.1 Tensile test

Tensile testing involves subjecting a material or component to a pulling force in order to determine its mechanical properties [24]. During the test, a tensile load is applied to the sample, which stretches the material until it breaks or deforms. The load and displacement of the sample are often measured and recorded. This method is commonly used to evaluate the strength and other characteristics of materials. **Figures 30, 31 and 32** show Tensile Strength-Elongation curves at three different values of focal distance (-2.0, 0.0 and 2.0mm). Elongation is a measure of a material's ability to stretch or deform before breaking and is used to assess the ductility of a welded joint [25].

The curves appear to have the same shape, as can be seen. Each curve's elastic zone exhibits a similar slope, indicating that the experiments did not affect the Young modulus. However, there is a variation between different trials in terms of Ultimate tensile strength, as seen in **table 15**. Test 1 shows the highest UTS of 206.9 MPa, and the weakest is test 3 with UTS of 180.2 MPa. A difference that can be anticipated as the parameter levels of tests 1 and 3 are really shifted. After rupture, the fracture path of the tensile samples reveals that the majority of the fractures happened in the fusion line, most likely as a result of flaws such undercuts, underfills, and root reinforcement that serve as stress concentration sites and start crack propagation. Tests 3 and 5 show that the failure occurred in the fusion line and deviated toward the fusion zone, which is consistent with the fact that those are the weakest welding conditions based on the findings of tensile tests. The significance of the defects produced during the welding process can be linked to the lowest tensile strength of test 3.

Table 15. Tensile Strength Results.

Test	Distance Focal (mm)	Power (kW)	Amplitude (mm)	Ultimate tensile strength (MPa)
1	-2.0	2.5	2.0	206.9
2	-2.0	2.7	1.5	188.5
3	-2.0	2.9	1.0	180.2
4	0.0	2.5	1.5	193.5
5	0.0	2.7	1.0	181.9
6	0.0	2.9	2.0	191.2
7	2.0	2.5	1.0	185.8
8	2.0	2.7	2.0	187.1
9	2.0	2.9	1.5	195.4

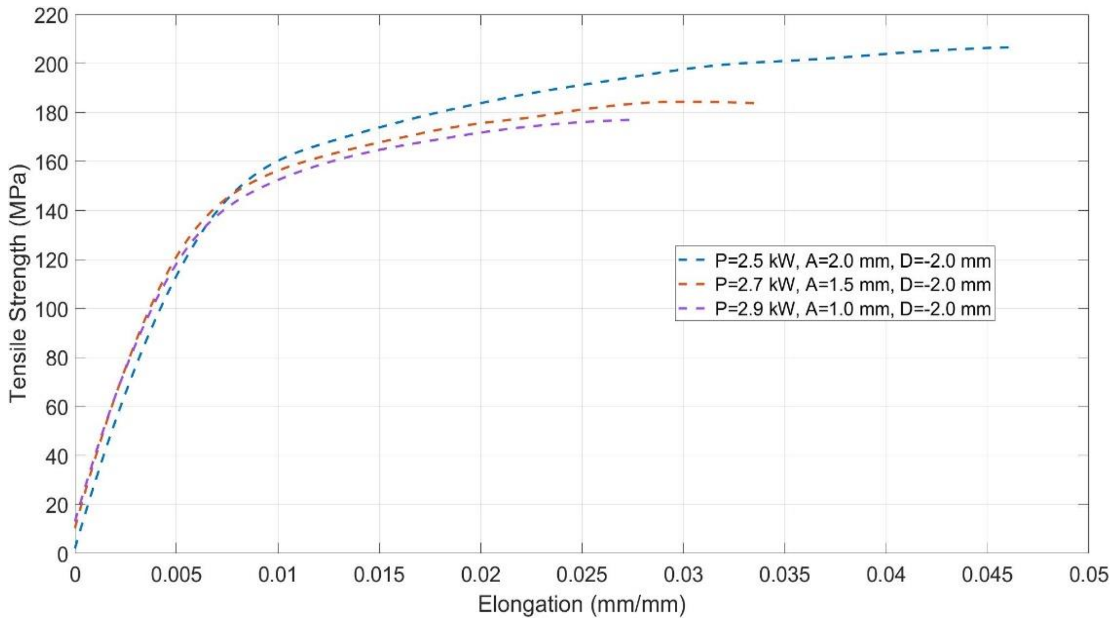


Figure 30. Tensile Strength-Elongation curve for Focal Distance -2.0 mm

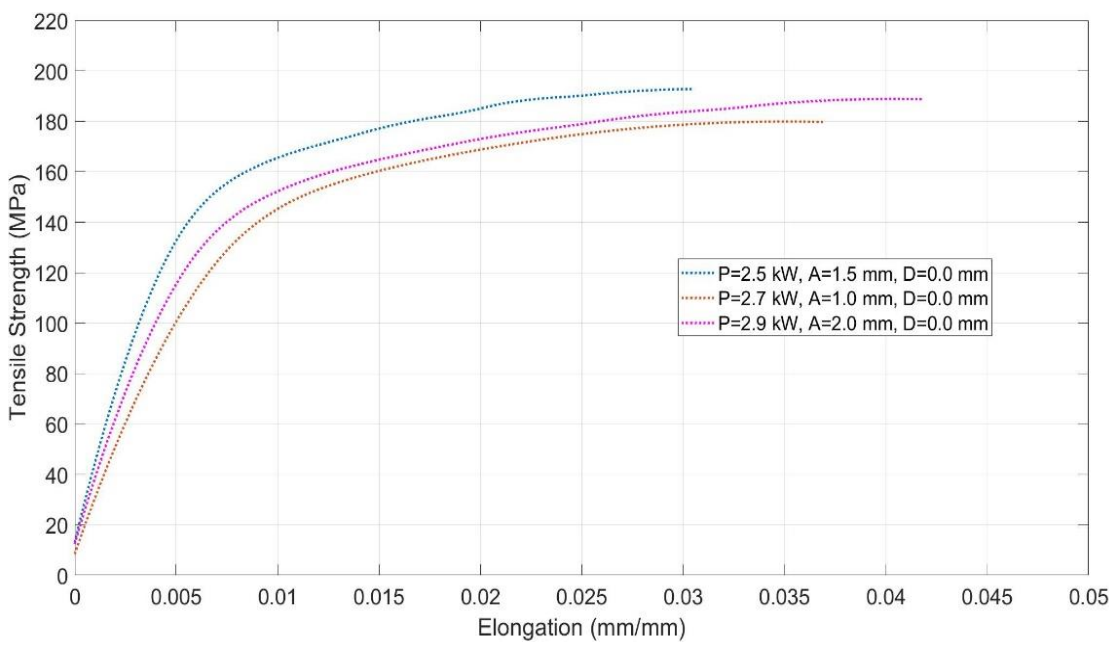


Figure 31. Tensile Strength-Elongation curve for Focal Distance 0.0 mm

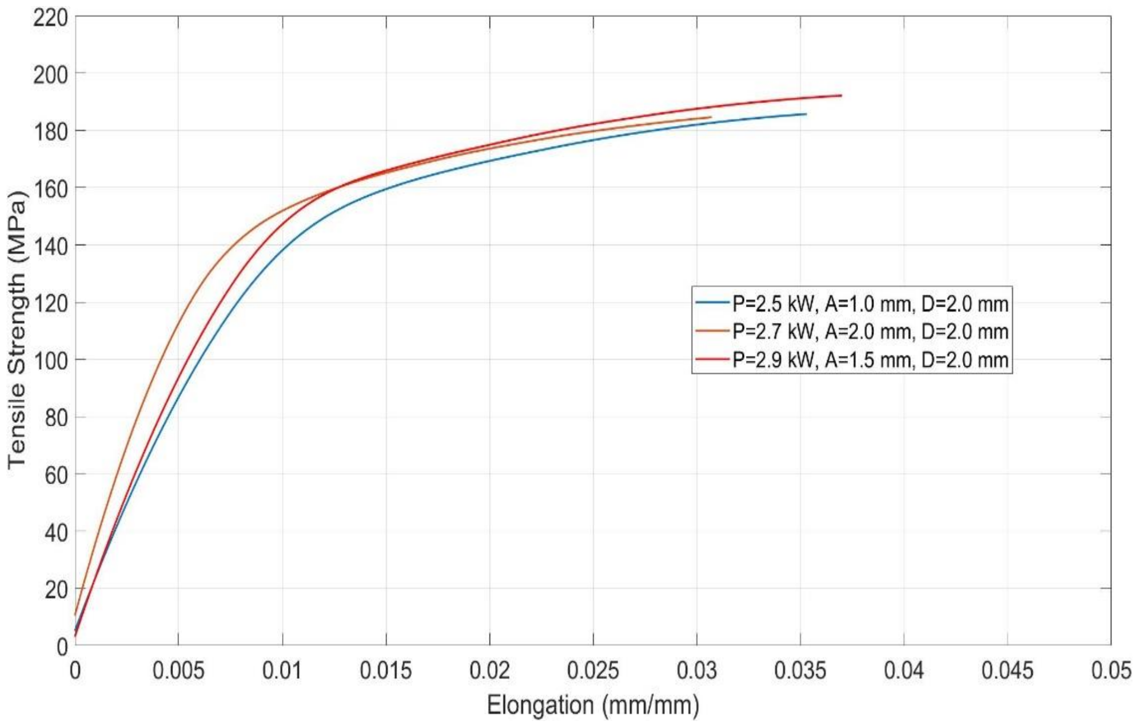


Figure 32. Tensile Strength-Elongation curve for Focal Distance 2.0 mm

7.2 Analysis of Variance (ANOVA)

Analysis of Variance is an effective statistical method that is widely used hypothesis testing and validation. It contains a rich applications field, and it has the flexibility to cover a larger number of experimental designs and procedures. Study and interpret ANOVA table for a given analysis helps to determine which of the parameters need control and which do not, to get an optimal expected output [26]. In this research, some terms such as Sum of squared Differences (SSQ), P-value, R-squared (R2) and Correlation (CORR) values for comparing models are keys to define interactions and influences of process parameters in responses. Minitab™ software tool is used to get ANOVA table and to define regression equations. In the following sections, the Influence of process parameters and their contribution percentage along factors interactions with respect to responses, welding Distortion and Forming Distortion are discussed. A linear regression model is then developed based on main process parameters and their interaction to predict welding and forming geometrical distortion.

The ANOVA analysis is based on the tensile strength results presented in **table 16**. **Figure 33** and **table 16** present that the most significant parameter to control to improve the mechanical performance according to work material and the input parameters is the Amplitude (A) with 31.92% effect contribution in the response, and with a P value of 0.004 that is lower than the recommended α= 0.05 value that is commonly used and accepted as the threshold for P value that defines the probability of rejecting the null, when hypothesis is true [26]. **Figure 33** show that increasing the Amplitude value has a direct impact on tensile strength values, reaching out 195 MPa at 2.0 mm; therefore, it is found that in the proposed process conditions increasing the amplitude values improve the mechanical performance of the dissimilar aluminium laser welding. Power (P) is the second parameter which impacted more the output with a contribution of 14.89% and a P-Value of 0.005. During welding, the heat input is typically determined by the laser power.

However, Focal Distance was found as the least effective parameter to be controlled in a similar process with just 8.66% of contribution on tensile strength results. This is confirmed by the results on **figure 33**, with a low variation in the process response with the set of focal distance values, with 3 MPa variation for the three defined levels (-2, 0, 2). Two parameters combinations are proposed in this study to verify if making a parameters group control have promising results to optimize the tensile strength performance, for that the Focal Distance-Amplitude and Power-Amplitude combinations is proposed. According to ANOVA results, the most effective combination that can help to optimize the response is Power-Amplitude with 26.6% of contribution and a P-Value equal to 0.005.

The most important process parameter from the calculate percentage is amplitude (mm) of about 31.92% which is the driving and most sensitive variable for a quality weld and tensile strength, It is expected that this result of an improved scrub action is efficiently distributed the oxides and contaminants of the interface, which, in turn improves the strength of the interface [22], followed by the combination of power (W) and amplitude of 26.16% due to the proportionality of the laser power to the heat input [23], and finally the combination of focal length (mm) and amplitude of 17.06% due to the increase of the temperature.

The results prove that the amplitude is the most significant process parameter which influences in joint strength. The amplitude it's directly related to the geometry of the welding, Wl and Ws are directly affected by the amplitude value. Although, Focal distance in the chosen conditions does not have an important impact in the mechanical performance. At last, we can see the effect of each parameter on average tensile strength in **figure 34**, as we found that an upper level of amplitude tends to strengthen the weld in term of tensile strength. While with a higher laser power, which is associated to a higher heat input, prone to weaken the tensile strength. The effect of focal distance is minor despite the results in Figure 34 showing that the other parameters are more significant terms of impact on tensile strength.

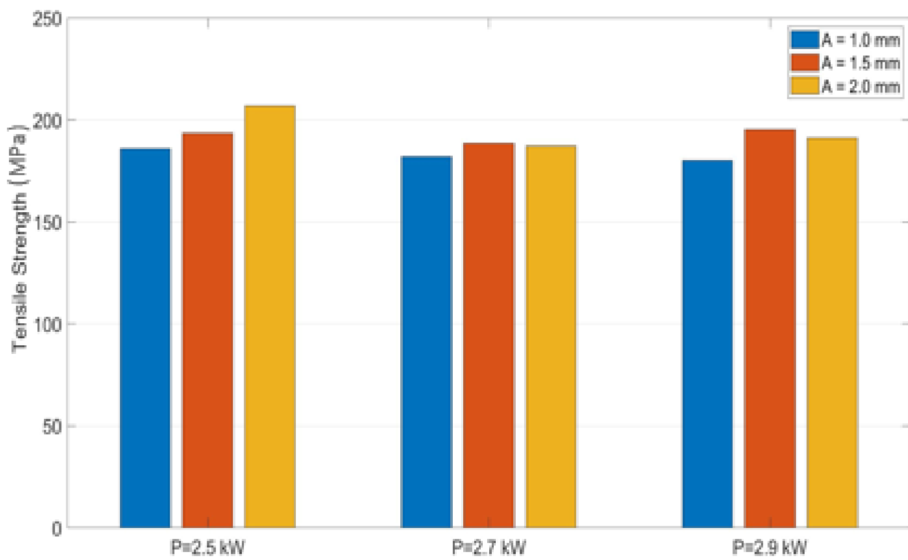


Figure 33. Tensile Strength for test power values

Table 16. ANOVA Table for Tensile Strength Results

Source	DF	Seq SS	Contribution	Adj SS	Adjus MS	F-Value	P-Value
Regression	5	1277.74	98.68%	1277.47	255.494	44.89	0.005
Focal Distance (mm)	1	112.11	8.66%	401.89	401.888	70.61	0.004
Power (kW)	1	192.72	14.89%	305.93	305.934	53.75	0.005
Amplitude (mm)	1	413.16	31.92%	371.46	371.462	65.27	0.004
Focal Distance*Amplitude	1	220.88	17.06%	440.23	440.233	77.35	0.003
Power*Amplitude	1	338.6	26.16%	338.6	338.6	59.49	0.005
Error	3	17.07	1.32%	17.07	5.691		
Total	8	7.35	100.00%				

Figure 34. Mean parameters impact on average Tensile Strength.

7.3 Microstructure

Hot tearing can be caused by the microstructure of the weld metal. Columnar grain structures are particularly prone to hot tearing [27], while fine; equiaxed grains can improve resistance to solidification cracking because they form a network of dendrites later in the freezing process, reducing the coherent temperature range [28]. Fine-grained materials are generally less likely to suffer from solidification cracking than coarse-grained materials due to their lower melting point segregates being distributed over a larger grain boundary area, and their ability to move and relieve local contraction stresses during freezing. Laser welding typically produces fine grain sizes due to its low heat input and fast cooling rate, and the addition of trace elements such as titanium and zirconium can further refine the solidification structure and reduce the risk of solidification cracking.

The microstructural characteristics of the fusion zones in welded aluminium alloys are strongly influenced by the welding technology, process parameters, and base metal composition [29]. Proper selection of process parameters during laser welding of aluminium alloys can help minimize the number of pores in the welded joint [29]. The morphology and microstructure of the fusion zone during laser beam welding of aluminium alloys are largely determined by the heat flow, which is controlled by travel speed, laser power and focus diameter [30]. The weld zones produced by laser beam welding of aluminium alloys are often divided into the fusion zone, heat affected zone, and sometimes partially melted zone. The high power density and low heat input of a laser beam welding system, combined with high cooling rates, affect the microstructure of laser welded joints, resulting in a narrow heat affected zone and fine-grained weld zone. During the solidification process of weld metal, the temperature gradient of the molten pool decreases and the nucleation of equiaxed dendrites can be initiated by nucleating particles in the center of the fusion zone. As the temperature gradient decreases, the formation of equiaxed dendrites increases.

Therefore, reducing the peak power density of the laser will lower the temperature gradient in the fusion zone and favor the formation of equiaxed dendrites [31]. The microstructure of welds plays a significant role in their resistance to solidification cracking and mechanical properties. Solidification cracking can be very damaging to the integrity of aluminium welds, as cracks are areas of high stress concentration that can lead to weld failures. This type of cracking in laser welded aluminium alloys is primarily caused by the inherent properties of aluminium alloys such as a high coefficient of thermal expansion, high thermal conductivity, and high solidification shrinkage. During solidification, the contraction of the weld generates tensile-compressive stresses in the weld zone that can lead to cracking. There are two main categories of cracking in aluminium alloy weldments: solidification cracking, which occurs in the weld's fusion zone, and liquation cracking, which occurs in the narrow partially melted zone due to tearing of the liquate [32], [33]. It has also been noted that pulsing the laser power can increase the risk of cracking in aluminium alloys due to the high cooling rates and rapid solidification of the fusion zone [31]. The aspect ratio (depth to width) can also affect the degree of cracking in the fusion zone of aluminium alloys; a larger aspect ratio increases the likelihood of cracking [34].

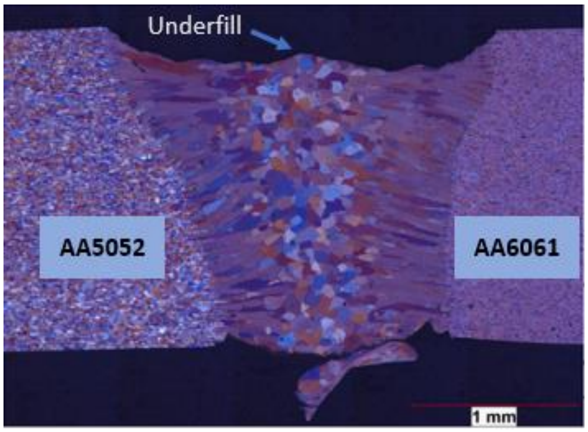
Other reported causes of solidification cracking in laser beam welding of aluminium alloys are listed in **table 17**. Solidification cracking can occur during or immediately after the solidification of weld metal when the alloy being welded passes through a temperature range where its ductility is very low. At this temperature range, cracking starts as the thermal tensile strains of the weld surpass its endurance strain limit [31]. As a result, when the cumulative strain surpasses the ductility limit, which is reflected by the distinctive ductility curves of particular alloys, cracking in the weld consequently occurs [35]. During solidification, the weld metal undergoes thermally induced deformation due to thermal contraction and shrinkage from phase transformation. These conditions (residual stress or strain) can open up connected dendritic arms in the mushy zone, and if there is not enough liquid flow to fill or heal the openings, solidification cracking will occur [36].

Table 17. Causes of cracking and their preventive measures in aluminium welds

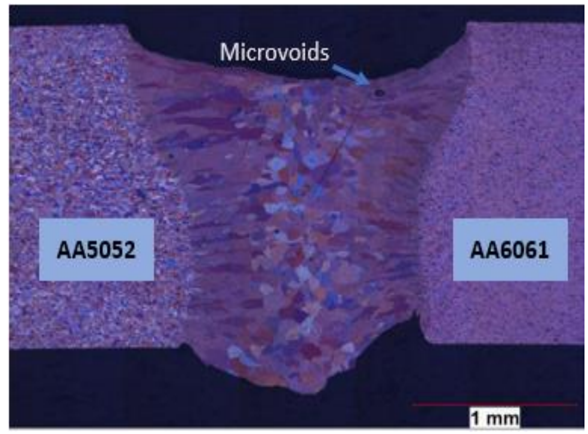
Types of Cracking	Causes	Thermal approach	Metallurgical approach
Weld metal solidification cracking [32], [33].	Increase in aspect ratio (depth/width) [34].	Dual beam laser welding [35].	The application of the appropriate filler metal to compensate for alloying elements that have been evaporated [40].
Liquation cracking [32], [33].	Residual stress [36].	Double-pulse laser welding [38].	Microstructural change attributed to thermal influence [31], [36].
	Parameters like the power density and overlapping factor in welding [31], [37].	Modification of cooling rate [39].	
	High cooling rate [31].	A decrease in the highest level of power density of laser [31].	
	Resultant Weld microstructure [31].		

Underfill, excessive penetration, and undercut were the geometrical flaws and defects found in the cross-sections of the welds in our investigation. Only five simple operations were used in this paper, all of which produced excellent results. **Figure 35** displays underfill imperfections as well as root reinforcement with excessive weld penetration in comparison to material thickness. According to ISO 13919-2 level B and level C standards, the maximum underfill depth and root undercut are, respectively, 0.1 mm (h0.05 t) and 0.2 mm (h0.1 t) for both aforementioned defect types [41]. **Table 18** displays the outcomes of surface underfill, root reinforcement, and undercut depths for several simples. Except for tests 3 and 8, which met level D, the majority of welding conditions satisfied the ISO 13919-2 standard's level C acceptance criteria for underfill depth. The test with the deepest underfill is test 8, which has welding circumstances with a 2.0 mm maximum amplitude and 2.0 mm maximum focal distance. All welding conditions satisfied level B acceptance criteria of the ISO 13919-2 standard for undercut imperfection at the root side, except for test 3, which met level C with a maximum undercut depth of 0.106 mm. Another break in the welds' cross-sections was the root excessive penetration.

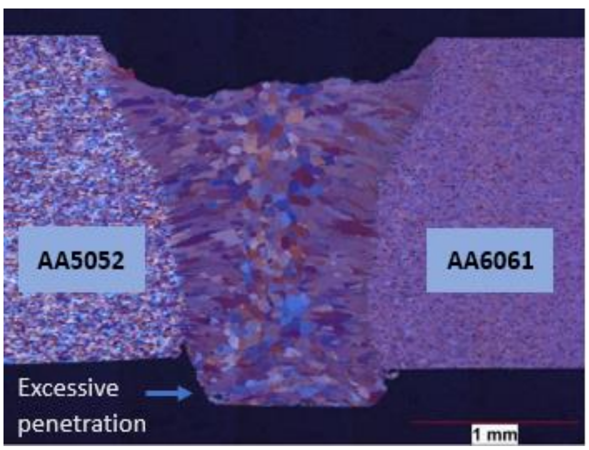
According to ISO 13919-2 level B, the excessive penetration height for all welding settings in this study was less than 0.5 mm (provided by h (0.2 mm+0.15t)), as shown in **table 18**.



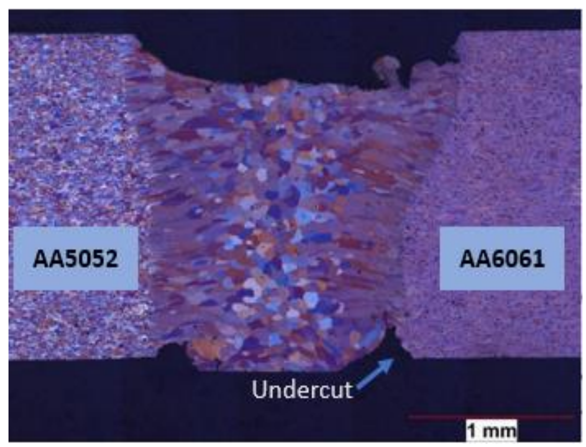
Test 2



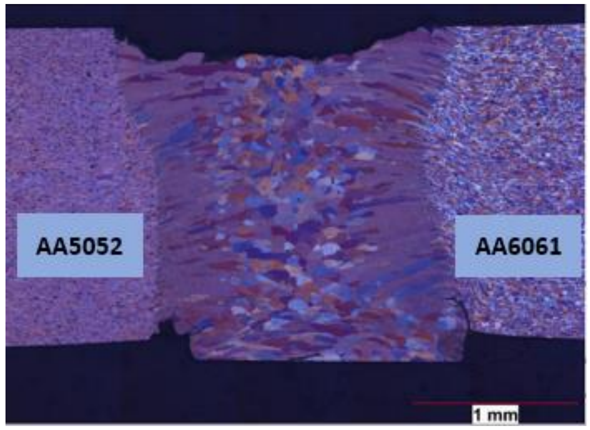
Test 3



Test 4



Test 8



Test 9

Figure 35. Cross-sections of tested specimens

Table 18. Defect quality level for each test according to ISO 13919–2 (D, moderate; C, medium; B, elevated)

Test	Measurements			Defect quality level		
	Underfill (mm)	Undercut (mm)	Root reinforcement (mm)	Underfill (mm)	Undercut (mm)	Root reinforcement (mm)
2	0.175	0.082	0.381	C	B	B
3	0.206	0.106	0.262	D	C	B
4	0.188	-	0.247	C	B	B
8	0.227	0.093	0.143	D	B	B
9	0.168	0.077	0.158	C	B	B

Additionally, smaller than 100 µm-diameter microvoids that are most likely caused by hydrogen porosity were seen in the weld seam at the fusion line and near the top or bottom surfaces. In the fusion zone for tests 8 and 9, which are represented respectively in **Figures 36** and **37** at high magnifications, microstructure reveals the presence of microcracks.

These intergranular microcracks, which form a weld fusion zone centre and root excessive reinforcement, are fewer than 100 micrometres long. These cracks are probably shrinkage solidification cracks that develop because of metallurgical variables and the degree of local strain produced during the solidification process's final step. Microcracks will develop along the grain boundary if there is insufficient liquid metal to fill the gap left by the thermal/shrinkage strain during solidification [42]. In our situation, the focal distance increases when the cracks begin to show. As discussed by Ma et al. [43], who state that heat enhances the ductility of Mg, favouring the crack inhibition, the level of laser power that determines the heat input can also influence the appearance.

Figure 36. Microcracks in fusion zone of test 8

Figure 37. Microcracks in fusion zone of test 9

8. Conclusion

The aerospace, marine, and other transportation industries, where there is a requirement for lightweight structures, are among the industrial areas where aluminium alloys are the most alluring options. Although the laser welding process has many advantages over traditional welding methods for industries, including a small heat-affected zone that reduces high energy efficiency, geometrical distortion, and faster welding speeds, it is still a complex process because of the physical phenomena involved and the challenges in monitoring and controlling it.

This study used oscillation approach to raise the average of our experiments to examine the effects of laser power, amplitude, and focal distance during laser welding of two different aluminium alloys, AA5052-H32 and AA6061-T6. The weld identification and optimization results enable the following conclusions:

The weld shape is greatly influenced by the oscillation's amplitude, and the results of the tensile test revealed that breakage occurred in the weld seam under all welding circumstances. The weld tensile strength was significantly impacted by the amplitude and power, as shown by the ANOVA. There is a discernible relationship between laser power and amplitude. The combined effects of the two parameters, which are characterized by the specific point energy, are used to interpret it.

Weld imperfection analysis reveals varying degrees of imperfection appearance in relation to the welding circumstances. In contrast to undercut, which is only noticeable for a few trial units, and root reinforcement, which is offered in the finest quality for all weldments, underfill is the most frequent imperfection. Without a doubt, there will be many challenging tasks to do in these new fields of laser welding applications.

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CONCLUSION GÉNÉRALE

Le soudage par laser est un procédé de soudage prometteur pour l'industrie, et les lignes de production dans de nombreux domaines industriels ont rapidement adopté cette méthode. Ce mémoire s'est penché sur les performances du soudage par laser dans divers contextes industriels. Bien que le procédé de soudage par laser présente de nombreux avantages par rapport aux méthodes de soudage traditionnelles, notamment une petite zone affectée par la chaleur qui minimise la distorsion géométrique, une grande efficacité énergétique et des vitesses de soudage plus rapides, il s'agit toujours d'un procédé complexe en raison des phénomènes physiques qu'il implique et des défis que posent sa surveillance et son contrôle. C'est pourquoi la recherche et la définition de techniques et de technologies de surveillance sont essentielles à la création de solutions fiables et durables.

L'objectif principal de ce mémoire était d'effectuer un certain nombre de recherches méthodiques et scientifiques afin de maîtriser l'application du procédé de soudage laser aux alliages d'aluminium AA6061-T6 et AA5052-H32. Dans cette optique, le premier objectif de ce travail était d'étudier et de décrire les meilleurs systèmes de surveillance, qui présentent des difficultés en termes de mise en œuvre, d'optimisation des paramètres du processus et de contrôle de la qualité du produit final. Le deuxième objectif était d'utiliser un plan expérimental structuré et des méthodes d'analyse statistique éprouvées pour examiner comment les différents paramètres du procédé affectaient la géométrie et la microstructure du cordon de soudure, qui à leur tour affectaient les propriétés mécaniques des matériaux de AA6061-T6 soudés. Le troisième objectif de cette recherche était d'examiner comment les différents paramètres affectaient la microstructure et la résistance à la traction des soudures dans la configuration bout à bout pour le soudage des matériaux dissemblables AA6061-T6 et AA5052-H32 et comparer les résultats des deux travaux.

Dans cette étude, une revue de la littérature sur les algorithmes et la surveillance intelligente, les configurations de détection, les approches de surveillance et les technologies liées au soudage au laser a été réalisée. Cette étude montre les techniques les plus efficaces pour la surveillance en ligne dans les applications de soudage par laser et suggère des approches technologiques qui peuvent offrir des solutions utiles à l'industrie.

Ensuite, une méthode de contrôle des propriétés mécaniques des plaques AA6061-T6 et AA5052-H32 en fonction des paramètres de soudage par laser a été proposée. La vitesse de déplacement du point focal, la puissance d'émission de l'énergie laser, la distance focale et la pression du gaz de protection sont les variables examinées dans les deux travaux. La contribution significative de cette étude est la formulation des critères de contrôle des paramètres de soudage laser pour une prédiction précise des caractéristiques mécaniques et de l'aspect de la microstructure. Pour la validation des formules, des résultats et des modèles, la complexité de ce développement nécessite la prise en compte du dispositif expérimental à l'échelle du laboratoire (cellule laser, machines de métallographie et machines d'évaluation des propriétés mécaniques).

Une stratégie structurée en trois étapes a été utilisée pour produire des modèles prédictifs précis et fiables. Pour déterminer les effets thermiques et métallurgiques des paramètres du processus sur la qualité de la soudure, un examen expérimental constitue l'étape initiale. Afin d'estimer les variations des attributs de qualité de la soudure, les expériences sont basées sur une conception Taguchi et réalisées à l'aide d'une source laser Nd:YAG de 3 kW, tout en tenant compte de tous les éléments connus pour avoir le plus grand impact sur la qualité de la soudure. L'ANOVA est utilisée pour évaluer les effets des facteurs pris en considération et leurs contributions à la variance des différentes qualités de soudure.

Les étapes de cette étude ont démontré que les paramètres de soudage, ainsi que les positions et les modèles de soudage, avaient un impact substantiel sur les caractéristiques mécaniques et la microstructure des plaques AA6061-T6 et AA5052-H32, ce qui se traduit par des attributs distincts pour le métal soudé. Le nombre de paramètres et le nombre de niveaux utilisés pour chacun d'entre eux ont été utilisés pour concevoir les expériences à l'aide de la méthode Taguchi.

La vitesse de soudage et le gaz de protection sont les facteurs qui ont le plus grand pourcentage d'impact sur les propriétés mécaniques des soudures de matériaux AA6061-T6, selon les résultats de la première étude. Les résultats des essais de traction effectués ont révélé que la résistance à la traction diminue à mesure que la pression et la vitesse du gaz de protection augmentent. Ce résultat est courant lors du soudage de l'aluminium au laser et peut s'expliquer par le fait qu'un soudage plus lent donne à la soudure plus de temps pour être exposée au faisceau. Afin d'examiner les défauts de la soudure, des images de la microstructure ont ensuite été récupérées.

Selon les résultats de la deuxième étude, parmi tous les paramètres choisis pour le soudage des matériaux dissemblables AA6061-T6 et AA5052-H32, l'amplitude de soudage apporte la plus grande contribution. Ceci est lié à l'effet significatif que ce paramètre a sur la quantité de chaleur apportée pendant le processus de soudage au laser. Les résultats des essais de traction ont montré que la résistance à la traction augmente et atteint une valeur maximale lorsque l'amplitude est augmentée tandis que la puissance est diminuée. Ensuite, les essais de microstructure ont permis de détecter et mesurer des divers défauts dans le soudage.

D'après les résultats, le soudage par laser est nettement supérieur aux techniques de soudage conventionnelles en termes de vitesse de soudage, de qualité de soudage, de liberté de conception et de réduction des distorsions.

L'étude a attiré l'attention sur certains inconvénients du soudage au laser, tels que sa sensibilité aux changements de qualité des matériaux et aux fluctuations de la distance entre la pièce et la source laser. En outre, les dépenses d'investissement initiales peuvent être importantes, mais elles peuvent être quelque peu compensées par des augmentations de production à long terme.

Ces résultats ont d'importantes applications industrielles, notamment dans les domaines de l'aérospatiale, de l'automobile et de la production de machines. Elles impliquent que le soudage au laser peut être utilisé pour créer des composants d'une qualité et d'une précision accrues, ce qui pourrait améliorer la longévité et la sécurité des produits finis.

Les orientations futures de la recherche pourraient inclure l'amélioration des connaissances sur les interactions entre les matériaux et le laser, le développement de nouveaux lasers et matériaux pour le soudage, et l'optimisation des paramètres de soudage afin d'améliorer l'application pratique du soudage au laser. En fin de compte, le soudage au laser pourrait devenir une technique de soudage courante pour les applications industrielles, à condition que les restrictions actuelles soient supprimées et que les procédures et technologies connexes continuent à progresser.

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