INSPECTION GÉOMETRIQUE D'ALLIAGES D'ALUMINIUM SOUDÉS AU LASER

Exploration, modélisation et optimisation des techniques d'inspection avec et sans contact – Alliages 5052-H32

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Composition du jury :

Abdelrrazak El Ouafi, président du jury, Université du Québec à Rimouski

Noureddine Barka, directeur de recherche, Université du Québec à Rimouski

Sasan Sattarpanah Karganroudi codirecteur de recherche, Institut technologique de maintenance industrielle

Vahid Sabri, examinateur externe, Mouvement Desjardins

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RÉSUMÉ

L'inspection géométrique est un procédé qui se vulgarise petit à petit grâce à l'avancement technologique et aux innovations des récentes années. Ce procédé est une étape majeure dans le cycle de vie d'une pièce après sa fabrication. Il permet de s'assurer de la qualité de la production et le respect des différentes normes de fabrication. Néanmoins, beaucoup reste à faire pour parfaire l'utilisation des techniques d'inspection géométriques, afin d'avoir un procédé rentable et efficace. Le but de cette étude est d'explorer les différentes méthodes d'inspection géométriques et leur combinaison avec le processus de soudage laser et d'optimiser cette approche pour une application sur l'assemblage de divers alliages d'aluminium. Pour mener à bien cette étude, des analyses ont été faites concernant l'efficacité de l'inspection avec contact et celles sans contact mais également sur les résultats donnés par la variation des paramètres de soudage sur les alliages d'aluminium, et finalement, voir l'effet des paramètres sur la planéité, la dilatation et la torsion des alliages pour trouver les valeurs optimales des paramètres, pour avoir une soudure qui respecte les normes. Cette démarche part de l'hypothèse que le soudage laser déforme les pièces à l'assemblage. À cet effet, plusieurs séries d'expérience ont été faites dans le cadre de la recherche en faisant varier les paramètres liés à l'oscillation, la densité de puissance et la vitesse de déplacement du laser pour disposer de données satisfaisantes pour pousser l'analyses en profondeur. Des outils statistiques tels que l'ANOVA sont utilisés à ce propos, précédés d'une planification d'expérience faisant appel à la méthode Taguchi et un design factoriel complet. L'optimisation est faite à l'aide d'outils numériques qui sont des méthodes itératives et algorithmiques aidant à trouver les valeurs optimales et à repérer un modèle de prévention et prédiction pour les recherches futures. Les résultats de l'étude ont montré l'efficacité des différentes approches d'inspection, en mettant en avant l'apport des paramètres du soudage laser. Les conclusions de la recherche ont également pointé l'aspect rentable et préventif des techniques utilisées grâce aux modèles produits qui rendent possible la compréhension des résultats antérieurs et permettent de prédire les résultats futurs.

Mots clés : Inspection géométrique, Aluminium, CMM, Inspection laser, Soudage laser, Taguchi, ANOVA, Prédiction

ABSTRACT

Geometric inspection is a process that is becoming increasingly popular thanks to the technological advances and innovations of recent years in some specific applications. This process is a major step in the life cycle of a part. It ensures the quality of production and compliance with various manufacturing standards. Nevertheless, much remains to improve the use of geometric inspection techniques in order to have a cost-effective and efficient process. The purpose of this study is to explore the different geometric inspection methods and their combination with the laser welding process and to optimize this approach for application on the assembly of various aluminum alloys. This study analysis was made on the effectiveness of the inspection with and without contact, but also on the results given by the variation of the welding parameters on the aluminium alloys. The research is assumed to see the effect of the parameters on the flatness, the dilatation and the torsion of the alloys to find the optimal values of the parameters and to have a welding, which respects the standards. This approach is conducted on the assumption that the laser welding deforms the parts during assembly. To this end, several series of experiments have been conducted in the research by varying the parameters related to the oscillation, the density of power and the speed of movement of the laser to have satisfactory data to push the analysis in depth. Statistical tools such as ANOVA are used for this reason, preceded by experimental planning using the Taguchi method and a full factorial design. The optimization is done using numerical tools, which are iterative, and algorithmic methods helping to find the optimal values and to find a prevention and prediction model for future studies. The results of the study showed the effectiveness of different inspection approaches by highlighting the contribution of laser welding parameters. The research findings also pointed to the cost-effective and preventive aspect of the techniques used, with models produced that make it possible to understand past results and predict future results.

Keywords: Geometric inspection, Aluminium, CMM, Laser inspection, Laser welding, Taguchi, ANOVA, RSM, Prediction

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ANOVA	Analysis of variance
ASME	American society of mechanical engineers
CAD	Computer aided design
CAI	Computer aided inspection
CCD	Charged coupled device
CMM	Coordinate measuring machine
DCS	Design coordinate system
DMIG	Département mathématiques, informatique et génie
FE	Finite elements
GD&T	Geometric dimensioning and tolerancing
ICP	Iterative closest point
IoT	Internet of things
MCS	Measurement coordinate system
NDT	Non-destructive testing
SS	Sum of squares
UQAR	Université du Québec à Rimouski

LISTE DES SYMBOLES

A	Amplitude
Adj MS	Adjusted mean square
Adj SS	Adjusted sum of squares
Al	Aluminium
DF	Degré de liberté
f	Fréquence
Hz	Hertz
J	Joule
kW	Kilowatt
m	Mètre
Mg	Magnesium
P	Puissance du laser
R-sq(adj)	Coefficient de détermination ajuste
R-sq(pred)	Coefficient de détermination prédictive
R-sq	Coefficient de détermination
SD	Écart type

Seq SS	Somme des carrés séquentielle
V	Vitesse de soudage
W	Watt
Wt%	Pourcentage de masse
x	Coordonnée à l’abscisse
y	Coordonnée à l’ordonnée

INTRODUCTION GÉNÉRALE

1. CONTEXTE ET GENERALITES

L'inspection est le processus le plus important dans le cycle de vie de la production et la fabrication d'un produit. De nos jours, le développement technologique ne cesse d'accroître ce qui permet de créer des pièces très complexes pour pouvoir répondre aux différents besoins des milieux industriels, notamment dans le domaine de l'automobile, naval et l'aérospatial qui sont des plus demandeurs. Ce contrôle de qualité permet de s'assurer que les pièces répondent à des critères prédéfinis par le bureau de recherche et que ces dernières s'alignent avec les attentes du cahier de charge. Dans un domaine où le temps de fabrication ne cesse de diminuer, l'inspection des pièces reste le processus le plus long ; il a souvent besoin d'une intervention manuelle. Certaines inspection dans le domaine aérospatiale comme chez Bombardier prennent 60 à 75 heures d'opération[1, 2]. Pour cela, différentes méthodes d'inspection sont apparues pour réduire non pas le temps du processus d'inspection mais aussi son coup. Les méthodes d'acquisition de données, avec et sans contact, ont connu l'apparition de l'inspection assistée par ordinateur qui a créé un grand changement dans ce domaine, elle lui a permis de prendre une tout autre grandeur. Ce processus est utilisé après la fabrication des pièces mais aussi après leurs assemblages, pour donner le produit final. Étant l'élément métallique le plus répandu dans la croute terrestre et l'un des métaux les plus exploités dans le monde avec le fer, on rencontre souvent l'aluminium dans les différents processus de fabrication et d'inspection[3]. Petit à petit, il prend la place de l'acier dans l'automobile, la légèreté des alliages 2XXX et 7XXX est aussi demandé dans le milieu aérospatial. Par ailleurs, la résistance à la corrosion des alliages 5XXX et 6XXX rende possible son utilisation dans le milieu naval.

Aussi faut-il rappeler que l'aluminium possède une densité de 2.7 g/cm^3 presque trois fois plus légère que l'acier. Il a un aspect très écologique. En effet, Modaresi et al.[4] ont mené une étude en proposant quatre scénarios pour le remplacement de l'acier par l'aluminium dans les automobiles. L'un des scénarios présente une diminution d'émission de gaz à effet de serre de 9 à 18 gigatonnes entre 2010 et 2050. Cette étude montre clairement la solution qu'incarne l'aluminium dans le virage vers une économie verte. Tous ces aspects montrent, donc, que l'aluminium est un matériau incontournable dans l'industrie manufacturière ; il a toutes les propriétés nécessaires pour substituer des métaux qui traditionnellement ont une place importante mais qui deviennent de plus en plus obsolète à cause des enjeux existants mettant en péril la viabilité de leur utilisation dans le futur. Il est donc important de trouver des moyens efficaces pour l'assemblage précis de l'aluminium qui nous permettra d'exploiter le potentiel de ce métal et d'ouvrir la possibilité à de nouvelles applications dans des domaines divers.

2. INSPECTION GEOMETRIQUE

L'inspection de pièce est considérée comme un procédé de maintenance et de contrôle de qualité des pièces après leur fabrication, leur assemblage et première inspection d'article. Il nous permet de savoir si le produit final répond aux attentes du cahier de charge et s'il s'aligne avec les tolérances prédéfinies dans la création du modèle. L'avancement technologique des méthodes d'usinage et de fabrication nous permettent maintenant de produire des géométries très complexes avec beaucoup de détails. En parallèle, pour répondre à ces exigences, différentes méthodes d'inspection sont disponibles pour s'adapter avec les différentes géométries : textures, formes et autres caractéristiques des pièces fabriquées. Cet avancement, notamment celui des technologies embarquées et l'industrie 4.0, a ouvert la possibilité à l'implémentation de l'inspection assistée par ordinateur dans ce processus de contrôle de qualité. Cette fusion a permis l'apparition de nouvelles méthodes plus développées qui consomment moins de temps et surtout moins d'argent. Cette évolution a vu le jour surtout avec le développement constant que connaît le domaine de fabrication et d’assemblage où les pièces sont devenues de plus en plus complexes, elles sont fabriquées très rapidement, comparées aux plages horaires dont ce processus avait besoin dans le passé.

2.1 Méthodes d’inspection

L’objectif reste le même mais les techniques pour y arriver diffèrent dépendamment des pièces à inspecter, de leur texture, leur forme et d’autres caractéristiques. En effet, on peut diviser l’inspection géométrique en deux grandes catégories : l’inspection avec contact et l’inspection sans contact. Comme leurs noms l’indiquent, la différence est dans la manière d’acquérir les données de la pièce à inspecter. Les scanners à contact sont apparus en 1933 par Abbot et Firestone et jusqu’à aujourd’hui le profilomètre tactile est toujours l’outil le plus utilisé dans le domaine de l’inspection. Cette technologie a évolué, certes, car les appareils sont basés maintenant sur une machine de mesure des coordonnées appelée CMM fixe qui permet à une gauge de se déplacer suivant 3 axes : chaque axe a une norme de référence intégrée. Un modèle de CMM fixe est présenté dans la figure ci-dessous. Le bras 1 est celui qui se déplace suivant l’axe Y, 2 se déplace selon Z, 3 est la gauge et le support des pièces à inspecter est représenté par le 4.

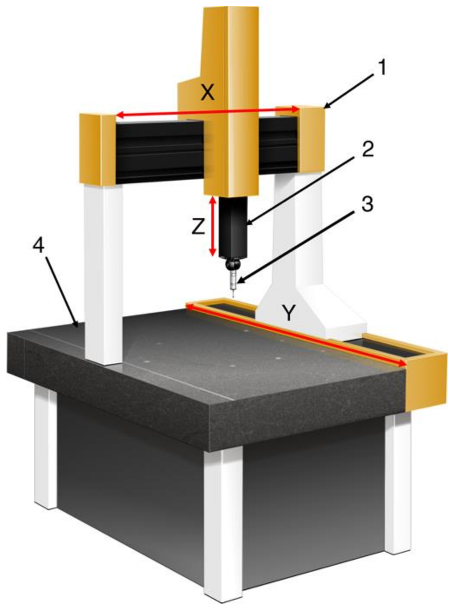


Figure 0.2.1: Exemple de CMM Renishaw

Ces CMM fixes sont très efficaces vu que les couleurs ou la transparence des pièces ne les affectent pas. Ils ont aussi une très grande précision et coûtent moins cher que certains scanners sans contact mais les quantités scannées sont très basses comparer au scanner laser. Leurs défauts se présentent dans la durée d'inspection des pièces, des contraintes dimensionnelles qui viennent avec l'appareil, mais aussi du fait que les CMM sont généralement fixes ce qui diminue leurs champs d'application.

Les scanners sans contact utilisent des lasers et de la géométrie optique pour acquérir les données géométriques (coordonnées 3D) des pièces à inspecter qui sont ensuite traduites sous forme de nuages de points. Ces nuages de points sont transférés à un ordinateur muni de logiciels adéquats pour les traiter, enlever le bruit et préparer un modèle pour la comparaison et l'inspection des déformations et imperfections qui peuvent apparaitre lors des différents processus de fabrication ou de l'assemblage. Ces scanners sont rapides, comparés au scanner avec contact fixe et beaucoup plus performants. Ils ont certes une précision plus basse que les CMM fixe et cela reste toujours très acceptable dans plein de domaines de fabrication et d'assemblage. Ils se différencient aussi par le fait qu'ils existent des scanners lasers portables ce qui a permis d'ouvrir de nouveaux horizons dans le domaine d'inspection géométrique de pièces.

2.2 Inspection assistée par ordinateur

Souvent lorsqu'on parle d'acquisition de données de nuage de points grâce à des scanners sans contact, on a recours à des ordinateurs et logiciels pour traiter ces données. Les scanners nous permettent d'acquérir des données sous forme de nuages de points. Ces nuages sont après traités et raffinés pour enlever le bruit du scan et ensuite pouvoir créer un modèle 3D du scan. Les modèles 3D créés à partir du scan sont par la suite comparés au modèle CAO de la pièce pour pouvoir définir les différentes imperfections de fabrication ou d'assemblage des pièces. Pour cela, plusieurs méthodes ont été développées. Étant donné que le modèle créé à partir du scan et le CAO ne sont pas sur le même système de coordonnées, on se doit de trouver un système de coordonnées commun et bien orienté pour pouvoir comparer les deux modèles. Ces méthodes de correspondance de modèles diffèrent l'une de l'autre. D'ailleurs, plusieurs paramètres causent cette différenciation. Premièrement, on peut diviser les pièces en deux sections les pièces rigides et non-rigides ; chacune de ces deux catégories connaît des méthodes de correspondance différentes. Ensuite, en ce qui est le cas des pièces non-rigides, ils existent des méthodes qui déforment le modèle scanné vers le modèle CAO puis d'autres qui déforment le CAO vers le modèle scanné, pour pouvoir s'adapter aux déformations causées par la pesanteur, les forces appliquées par les gabarits, etc… Ces méthodes seront présentées en détail dans le premier chapitre de cette étude, étant donné qu'il représente une revue de littérature du domaine d'inspection géométrique de pièces.

3. Soudage laser

Le soudage est un processus de fabrication dans lequel deux ou plusieurs pièces sont fusionnées ensemble au moyen de chaleur, pression ou les deux formant une jonction lorsque les pièces refroidissent. Le joint obtenu est appelé une soudure comme cela est défini par The Welding Institute (TWI). Le soudage est alors un moyen d'assemblage de pièces au moyen de différents phénomènes thermodynamiques. On remarque aussi que, à cette ère récente, différentes méthodes de soudage existent et on peut alors classifier ces procédés en différentes catégories selon le phénomène physique qui intervient ou la technologie utilisée. Parmi ces phénomènes, la technique la plus répandue est le soudage à l'arc qui consiste à utiliser un arc électrique qui va générer de la chaleur pour faire fusionner les matériaux entre eux. Il existe aussi des techniques de soudage qui font intervenir des phénomènes thermoélectriques telles que le soudage par résistance. C'est une technique qui tire profit de l'effet Joule qui est la manifestation thermique de la résistance électrique qui se produit lors du passage d'un courant électrique dans tout matériau conducteur. Cette technique est très répandue dans l'industrie automobile pour l'assemblage des carrosseries.

D'autres techniques sophistiquées existent également telles que le soudage par faisceau électronique ou le soudage par friction malaxage qui utilise la chaleur générée lors du frottement pour réaliser l'assemblage. Il est à noter que la méthode d'assemblage la plus utilisée pour les alliages 5052-H32 est le soudage par arc. Une technique qui commence à prendre de plus en plus de place n'est autre que le soudage laser. LASER étant acronyme de Light Amplification by Stimulated Emission of Radiation qui veut dire amplification de la lumière par une émission stimulée de radiation. Cette technique utilise l'énergie du faisceau laser pour obtenir la chaleur requise, pour faire fondre les matériaux et les assembler. Cette technique peut être expliquée par trois phénomènes physiques : l'absorption, l'émission stimulée et l'émission spontanée.

Pour exploiter ces phénomènes physiques et mettre en œuvre l'émission de faisceau laser pour réaliser le soudage, trois composants sont nécessaires, ils constituent les bases des équipements laser :

- un milieu amplificateur, également appelé source laser, il constitue la partie qui sera excitée pour générer les émissions de photons. Il définit les propriétés du laser et peut être sous forme de divers états (solide, gaz...) dépendamment de la matière utilisée

- une source d'énergie, c'est la partie qui va fournir l'énergie nécessaire pour exciter le milieu amplificateur. La source peut également être de divers types mais les plus utilisés sont des sources d'énergie optique et électrique. L'excitation externe des atomes est appelée pompage développé par Alfred Kastler en 1966.

- une cavité résonnante a pour rôle de recycler les photons et de les émettre de manière unidirectionnelle à travers une combinaison de miroirs avec des propriétés différentes selon le besoin et les contraintes de l'équipement laser.

Pour le soudage laser, plusieurs types de source laser peuvent être utilisées dépendamment de leurs caractéristiques relatives aux besoins du soudage comme le coût des équipements, la qualité de laser, les propriétés des matériaux à souder, la configuration de soudage, etc... On peut trouver alors le laser CO_2, le laser YAG, le laser diode, le laser disque ou encore le laser fibre. Ils se différencient chacun par la source du laser, la longueur d'onde et leur puissance moyenne.

Tous ces types de laser ont chacun des avantages et des inconvénients. Le laser CO_2 est l'un des premiers types de laser à être utilisé pour le soudage laser. Ce type de laser est notamment reconnu pour être capable de fournir une très grande puissance à moindre coût. Néanmoins, sa grande longueur d'onde élevée limite son utilisation, premièrement, en raison de son incapacité à être transporté par fibre optique réduisant sa versatilité. Deuxièmement, certains matériaux sont très réflectifs par rapport au laser CO_2 ; c'est particulièrement le cas pour les métaux avec une grande réflexivité comme le magnésium, l'aluminium ou encore le cuivre. Pour remédier à cela, des lasers à faible longueur ont été développés comme le laser Nd : YAG. L'arrivée de ce type de laser a permis une exploitation plus avancée des fibres optiques rendant le laser plus versatile, en plus d'élargir la panoplie de matériaux qui peuvent être soudés. Sa seule limitation réside dans la puissance qu'il peut fournir. Aujourd'hui, d'autres types présentent de meilleures caractéristiques comme le laser disque qui combine à la fois versatilité et puissance. Malgré tout, l'accès aux plus récentes technologies laser n'est pas encore vulgarisé en raison des coûts plus élevés par rapport aux lasers CO_2 ou Nd:YAG.

4. PROBLEMATIQUES

Malgré le fait que l'inspection géométrique des pièces connaît différentes méthodes et de multiple processus, il y a encore beaucoup d'avancement à faire dans ce domaine. En effet, en ce qui concerne l'inspection avec contact, avec une machine CMM par exemple, ce procédé ne peut être applicable pour toutes les pièces fabriquées. Les machines à contact ont des limitations dimensionnelles, suivant les différents axes de déplacements des bras. Dans certains cas aussi, on a besoin de scanner une pièce après son montage chose qui n'est pas toujours faisable. Un défaut apparaît lors de l'inspection de pièces non-rigides comme celles utilisées pour le domaine aérospatial où un scanner avec contact peut causer des déformations, certes minimes, mais d'une grande importance dans ce domaine qui requiert de la haute précision, ce qui affecte alors le scan. Ces imperfections et ces défauts peuvent être réglés par des scanners sans-contact, puis c'est la toute la beauté de ce processus post-fabrication. Mais, comme tout domaine dans la vie rien n'est parfait, les scanner sans-contact connaissent des limitations. En effet, on trouve que la caractéristique réfléchissante de certains métaux affecte les scanner laser. Le bruit est aussi un critère important à prendre en considération, lors d'une inspection avec un scanner laser. On a souvent recours à des logiciels pour raffiner les nuages de points acquis suite à l'inspection. Les pièces non-rigides créent aussi certains problèmes, le fait qu'elles soient flexibles, facilite leur déformation sous l'effet de la pesanteur. Pour contrer ce problème, on a recours à des gabarits d'inspection qui permettent aux pièces de prendre leurs formes d'assemblage pour les inspecter. Ce processus est très couteux en matière d'argent et de temps ; car ces gabarits sont propres à chacune des pièces à inspecter et l'inspection est faite par sections que l'on se doit de reconstruire après, en utilisant un logiciel pour traiter les nuages de points.

Malgré le fait que le soudage laser représente une technique de choix pour joindre des pièces en aluminium d'après les nombreux avantages offerts par ce procédé, beaucoup d'amélioration reste encore à développer en raison des propriétés de ce métal lui conférant une réputation de métal difficile à souder. Il possède, en effet, une très grande conductivité thermique qui fait en sorte que la chaleur qui a pour but de générer la fusion se dissipe très vite au contact du métal. De ce fait, le soudage au laser de l'aluminium requiert une grande énergie pour compenser cette perte de chaleur. Une autre problématique est la qualité de la soudure. Pour certaines pièces, un peu épaisse, on remarque que l'on n'a pas une bonne pénétration du faisceau laser pour la soudure ce qui nous oblige à utiliser une gauge pour créer un espace entre les pièces à souder. Ce processus d'assemblage crée aussi des imperfections sur la surface des pièces qui doit être prise en considération lors de la mise en place du protocole d'inspection pour la machine CMM. Après plusieurs recherches, nous n'avons pas trouvé de travaux combinant le procédé de soudage laser et celui de l'inspection soit avec CMM ou scanner laser. Cependant, en misant sur les différents paramètres du soudage laser et les différentes combinaisons possibles entre ces derniers cela va nous permettre d'atteindre des assemblages qui répondent aux critères prédéfinis.

5. OBJECTIFS

L'objectif de ce mémoire est donc d'explorer les deux grandes catégories d'inspection, avec CMM et avec laser, en combinant ce processus avec le soudage laser afin d'optimiser le procédé pour mieux comprendre les résultats antérieurs et être capable de prédire les résultats futurs. Pour atteindre ces objectifs, il est nécessaire de passer par des sous-objectifs qui correspondent à des étapes spécifiques du projet de recherche.

Le premier objectif se présente comme une approche littéraire du domaine d'inspection. Il a pour but de présenter les différentes avancées de ce processus de maintenance, les nombreuses méthodes développées et aussi l'effet de la révolution de l'industrie 4.0 sur ce dernier. Cet objectif est essentiel pour l'exploration et les recherches futures que l'on vise.

Le second objectif vise à étudier la dilatation et la torsion causé par la variation des paramètres du soudage laser, notamment la puissance de soudage et l'oscillation du faisceau, sur des pièces épaisses munies de trous grâce à un scanner CMM fixe, pour définir les bonnes soudures et chercher les combinaisons de paramètres qui peuvent nous fournir les meilleurs résultats grâce à un modèle de prédiction.

Le dernier objectif a pour but d'étudier la planéité de plaques d'alliages d'aluminium grâce à un scanner sans contact. Un de ces objectifs est de savoir l'effet des paramètres sur le procédé ainsi que les résultats qui en découlent et dégager une tendance à partir de cette analyse pour pouvoir améliorer le procédé. Les travaux d'optimisation vont permettre de trouver les paramètres optimaux pour avoir la meilleure soudure selon les critères d'évaluation qui ont été admis dans cette étude c'est-à-dire la planéité.

6. METHODOLOGIE

La première phase du travail consiste à déterminer les avancements effectués dans le domaine de l'inspection. En effet, le premier article est sous forme d'une revue de littérature qui regroupe la majorité des travaux réalisés dans le domaine de l'inspection, en présentant les différentes méthodes d'acquisition de données développées au court des années. Une présentation des normes de fabrication suivant GD&T et ASME Y14.5 est aussi nécessaire pour le domaine de l'inspection géométrique des pièces. L'implémentation des ordinateurs et la rencontre de ce domaine avec la révolution industrielle 4.0 nous a poussé à chercher les techniques développées et les algorithmes produit pour la correspondance des éléments scannés et des designs réalisés avant la fabrication. Cette phase est considérée comme une synthèse qui nous permet de mieux diriger nos explorations et nos expérimentations futures.

La seconde phase est l'exploration ayant pour but d'inspecter des pièces d'un alliage d'aluminium 5052-H32 soudées grâce au processus laser. Dans une première étape, l'inspection se fera au moyen d'une machine CMM pour calculer les variations des distances et des angles. Ensuite, dans un deuxième lieu, on utilisera un scanner laser pour étudier la planéité. Pour cela, plusieurs séries de soudage au laser seront réalisées, en suivant un plan d'expérience bien établi pour obtenir des résultats fiables pour les analyses qui suivent. Le plan d'expérience tient compte de toutes les combinaisons possibles entre les différents niveaux de paramètres, c'est-à-dire un plan factoriel complet. Les travaux de soudage seront exécutés en suivant ce plan en utilisant la machine de soudage laser disponible au sein du département de mathématiques, informatiques et génie à l'UQAR et les résultats obtenus sont les distances entre les trous, les angles et la planéité. Une fois les résultats obtenus, des outils d'analyses statistiques comme l'ANOVA seront appliqués pour déterminer l'effet des paramètres sur les pièces soudées. Le soudage laser et l'inspection géométrique avec CMM et scanner laser se feront à l'UQAR dans les différents laboratoires de l'université.

La dernière phase des expériences est orientée vers l'optimisation du procédé sur un soudage dissemblable. L'optimisation commence par l'exploitation des résultats de l'exploration en définissant des plages de paramètres qui seront utilisés pour la construction du plan d'expérience. Une matrice Taguchi sera utilisée pour l'établissement du plan d'expérience en raison des avantages qu'elle présente notamment en termes d'économie de temps et de coût tout en ayant des résultats fiables et exploitables. Les résultats sont constitués par les distances, les angles et la planéité grâce aux inspections faites dans notre laboratoire de métrologie. Des techniques statistiques comme l'analyse de la variance seront menées pour connaitre l'importance et l'effet des paramètres sur les pièces soudées qui sont la densité de puissance exprimée par la puissance, l'amplitude d'oscillation et la fréquence. L'analyse statistique permettra de proposer un modèle de prédiction permettant une estimation de la qualité de la soudure à partir des paramètres. Le modèle servira à une analyse numérique destiné à trouver les valeurs de paramètre qui vont donner le meilleur résultat de soudure pour optimiser le procédé. Des outils d'optimisation déterministiques, itératives et algorithmiques usant d'outils informatiques tels que Minitab et Matlab seront préconisés à cet effet.

7. ORGANISATION DU MEMOIRE

Le premier chapitre du mémoire consiste à mieux comprendre le processus d'inspection géométrique. Ce chapitre présente les différentes méthodes existantes, les travaux et recherches antécédents réalisés dans ce domaine par différents chercheurs et les résultats trouvés par ces derniers. L'étude se présentera sous forme d'une revue de littérature permettant une meilleure compréhension du sujet et des lacunes rencontrés dans des travaux antérieurs. Elle nous présente aussi une ouverture pour l'implémentation dans l'industrie 4.0.

Le second chapitre aborde une approche expérimentale de la combinaison du procédé de soudage laser et celui de l'inspection géométrique avec CMM. À cet effet, le deuxième chapitre se focalise sur l'effet du soudage laser, sur dilatation des alliages d'aluminium et la torsion causée par ce processus. La combinaison de ces deux processus n'a pas été rencontrée dans des études antérieurs ; ce qui fait de ce chapitre une découverte expérimentale. Les résultats de cette étape de la recherche permettent de mieux comprendre les effets des paramètres de soudage sur les alliages d'aluminium et nous présentent un modèle préventif et prédictif pour le processus de soudage.

Le troisième chapitre utilise le même alliage d'aluminium pour le soudage laser mais le processus d'inspection géométrique change car on a eu recours au scanner laser pour cette étude. Le but de ce travail était de mesurer la platitude des plaques d'aluminium 5052-H32 et voir l'effet des paramètres du soudage laser sur ces dernières. Étant donné que pour cette étude on a eu recours à des plaques minces, le scanner laser était le plus approprié pour ne pas causer d'autres déformations avec le scanner à contact. A l'instar du chapitre précédant, des analyses numériques sont menées accompagnées d'une approche algorithmique pour achever l'optimisation et déployer les meilleures combinaisons de paramètres.

La dernière partie du mémoire constitue une synthèse des résultats obtenus dans les chapitres précédents. Elle propose une conclusion générale sur l'efficacité du soudage laser mais aussi l'efficacité des deux procédés d'inspection géométriques utilisés. Elle présente aussi les avantages et les lacunes délivrées par ces techniques. Le dernier chapitre ouvre également les possibilités qui peuvent encore être explorées pour le soudage laser de l'aluminium et son inspection géométrique.

CHAPITRE 1
INSPECTION INTELLIGENTE : CADRE CONCEPTUEL, SCENARIOS INDUSTRIELS ET PERSPECTIVES D'AVENIR

I. Houban[1], N. Barka[1], S. S. Kanganroudi[1],and A. Aminzadeh[1]

University of Quebec at Rimouski, Rimouski (Qc), Canada

Cet article a été retenu comme un chapitre du livre « Sustainable manufacturing 4.0 : Pathways and practices »

1.1 Résumé en français du premier article

Un des procédés les plus couteux en question de temps et d'argent dans le processus de fabrication et assemblage est l'inspection des pièces et le contrôle de qualité de ces dernières pour voir s'ils répondent aux attentes du cahier de charge. Les techniques d'inspection diffèrent, on peut trouver alors des CMM avec contact et d'autres sans contact dépendamment des pièces à inspecter. L'implémentation des ordinateurs dans ce domaine a ouvert de nouvelles possibilités surtout pour les scanners laser ; car il est possible de raffiner les nuages de points, comparer un élément scanné à son modèle CAO etc… Ce premier article est une revue de littérature regroupant la majorité des avancements effectués dans le domaine de l'inspection géométrique des pièces et son évolution grâce à l'implémentation des ordinateurs et du IoT dans le cadre de l'industrie 4.0. On parle aussi de l'évolution des normes d'inspection et des tolérances essentiellement GD&T et ASME Y14.5.

Ce premier article, intitulé : *« Computer-aided-inspection in the era of industry 4.0 : A systematic literature review »* fut essentiellement rédigé par son premier auteur Ilyasse Houban. Le premier auteur a également écrit les parties concernant l'état de l'art et a fait les recherches nécessaires pour cette revue de littérature. Noureddine Barka et Sasan Sattarpanah sont à l'origine du projet de recherche et ont contribué à l'amélioration de la rédaction pour la version finale. Ahmad Aminzadeh a apporté son aide et son expertise en ce qui concerne l'intelligence artificielle.

1.2 Titre du premier article

Smart inspection: conceptual framework, industrial scenarios, and future perspectives

1.3 Abstract

Nowadays, computer-aided inspection (CAI) is used to cope with increasing complexity in part manufacturing and the difficulty of physical access to certain workplaces. Therefore, manufacturing companies adopt automated CAI methods to increase the efficiency of the control quality activities. This study aims to capture the current state of the art of literature related to rigid and non-rigid inspection with a focus on the intelligent factory based on CAI. This investigation is a road map in different methods developed and how precise this kind of inspection can be. This paper presents a systematic literature review in the computer-aided inspection field with an extensive assessment of the included studies. After analyzing the relevant papers and industrial documents in detail, we derive deep insights into the different methods developed to inspect parts based on their physical aspects. This study will contribute to the computer-aided inspection field providing methodologies that will make the human intervention useless at one point. Finally, the digital twins' model has been proposed for an industrial application based on industry 4.0.

1.4 Nomenclature

CAD: Computer aided design

CAI: Computer aided inspection

DCS: Design coordinate system

DT: Digital twins

MCS: Measurement coordinate system

CMM: Coordinate measuring machine

ICP: Iterative closest point

CCD: Charged coupled device

GD&T: Geometric dimensioning and tolerancing

ASME: American society of mechanical engineers

IoT: Internet of things

NDT: Non-destructive testing

1.5 Introduction

1.5.1 State of the art

Metal manufacturing faced such an evolution these recent years that made possible the creation of such complex parts to answer the needs of many different industrial sectors among automobile and aerospace which are the most demanding. These parts are posited complex by their geometric details, features, and innovative shapes. In addition, like every manufactured part, they need to go under the quality control process that consists of dimensional and geometrical controls to make sure that the part corresponds to the specifications that were indicated before the manufacturing and that to ensure the functionality of the product. Manufacturing companies give significant importance to this process that makes them maintain in the competitive markets by producing high-quality parts [1]. However, in the modern era where the industries reduced so much their manufacturing time, the inspection of the parts is the most time-consuming and usually needs human intervention. Even though research on rigid parts inspection reduces the cost and operation time of the inspection by digital tools, the inspection of non-rigid parts remains still an important challenge. For example, some inspection setup for non-rigid parts in Bombardier Aviation™ as a giant industrial company demands 60 to 75 hours of operation [2–4]. Therefore, an accurate inspection in a short period became a necessity for manufacturing companies and that without omitting the cost. And the highlight of this evolution was the appearance of the Computer-Aided Inspection (CAI) allowing for easy 3D scanning of a product to create a digital replica of it stored as a point cloud. The CAI opened doors for a new way of inspection, less time and money consuming, reducing the human intervention by a large margin. A novel method of real-time 3D scanning of aluminum 5052-H32 laser-welded blanks as semi-flexible parts' inspection based on lean manufacturing concept has been already presented by our research team [5]. Finite elements analyses and simulations are also applied in non-rigid inspections to define the influence of process parameters in laser material processing and optimization of objective functions based on genetic algorithm and metaheuristic approaches [6–8]. The CAI uses advanced data acquisition methods instead of traditional and tactile tools such as calipers, optical comparators, and gauges. The CAI methods can create a point cloud of inspection surfaces using contact or contactless CMM to fulfill the inspection that is most of the time non-destructive. Back in time, the quality inspection was usually done by using micrometers, calipers, gauges, optical comparators, and manual Coordinate Measuring Machines (CMM), but those processes are slow and require a lot of programming and planning before beginning to function. They also need contact with the fixture and can be a redundant and tedious process to double-check practical errors. Over the past few years, digital data acquisition devices have been advancing drastically and rapidly such as 3D optic and laser scanners [9, 10] along with computational algorithm and calculation developments made possible the use of computer-aided inspection (CAI) methods. In this regard, 3D data acquisition devices make it possible to obtain the coordination of points on the inspection surfaces of parts by scanning the surface of parts during the inspection process. From obtained point clouds a scan mesh is generated, simplified and optimized using mesh smoothing and decimation methods [11, 12]. The objective of the scan mesh is to represent the geometrical shape of the part in the most accurate way with the least required data volume which can be translated to the mesh size.

CAI methods help to make an automatic time-saving inspection by both applying tolerancing methods and computational meshing tools. Those methods make it possible to compare the computer-aided design (CAD) model and the scan mesh in a common coordinate system to define the geometrical deviations that appears on the surface of the parts during the manufacturing process. An issue related to this inspection is the coordinate system. In fact, the CAD model is in the Design Coordinate System (DCS) and the scan data is in the Measurement Coordinate System (MCS), and the registration methods developed in the computer aided registration are required to align the two models in a common coordinate system.

Depending on the type of inspecting parts such as simple or complex geometry, rigid or non-rigid behavior, industrial applications, and tolerance requirements, different computer-aided methods can be found. On one hand, rigid registration is applied for rigid parts to align the scan model in a free state with respect to the CAD model. On the other hand, non-rigid parts know a more complicated registration as the geometrical deviation of parts can exceed the tolerances due to the compliance of the parts in a free state. This complication opens the door to two categories of non-rigid part inspection: physical fixtures inspection methods and fixtureless non-rigid registration methods. Operational limits and drawbacks of using fixtures encouraged industrial sectors towards using fixtureless inspection methods that firstly appeared in 2002 [13]. Figure 1.5.1 shows a framework hierarchy for automated inspection using a 3D scanner. Here, rigid and non-rigid parts have been discussed in detail then a novel digital model is presented for parts' inspection in industrial application.

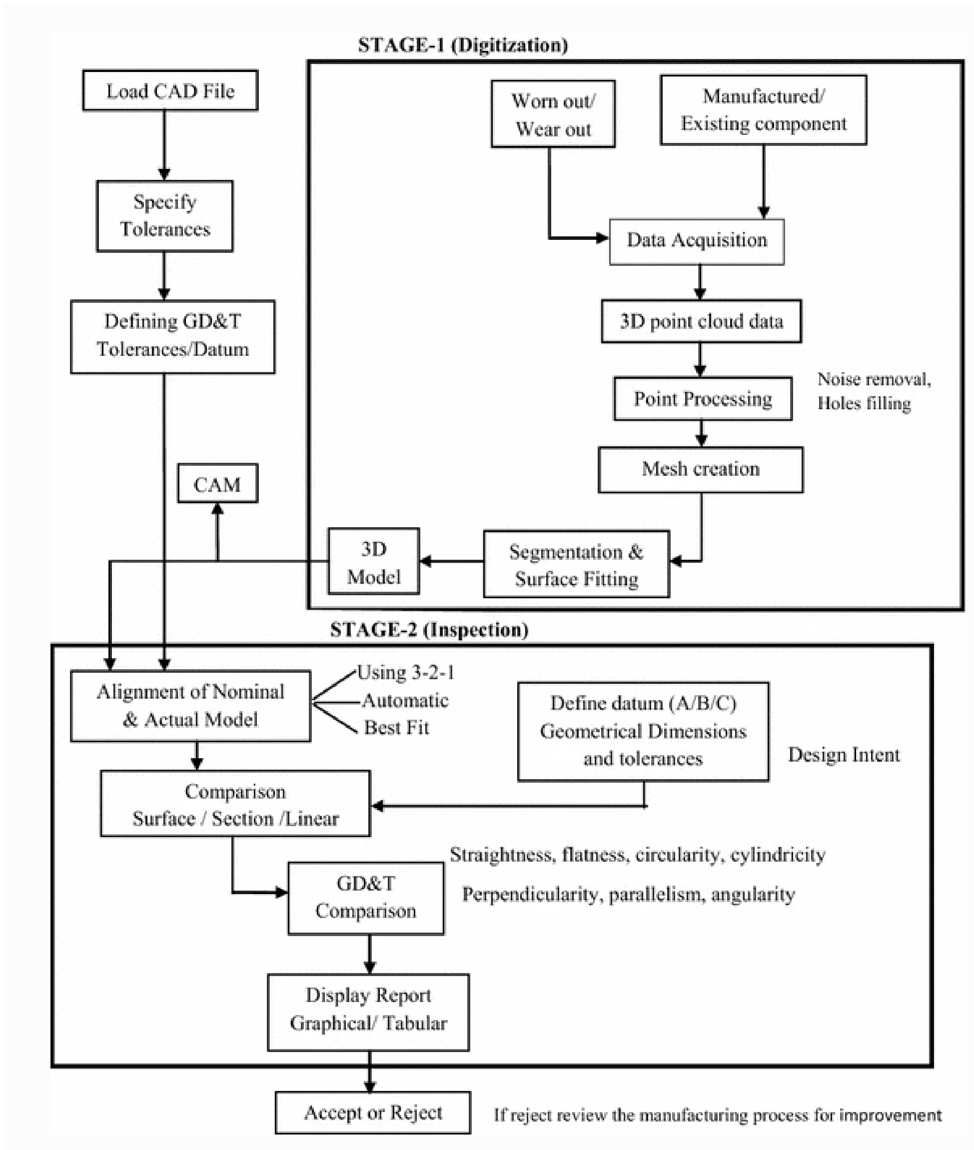


Figure 1.5.1: Framework hierarchy for automated inspection using a 3D scanner [14]

1.5.2 Data acquisition methods

The technical drawing of each manufactured part goes under a lot of investigation and steps before its validation and acceptance from the engineers to make sure that any misunderstanding of the parameters has been cleared. It is the first step in the manufacturing process. This is done to make sure that the final product will respond to the different dimensional and geometrical criteria defined such as the dimensions, angles, precision sought for each part of the workpiece, etc. Even though all those actions are taken to make sure that the manufacturing of the part will be as precise as we can, we can't omit the importance of the measurement and data acquisitions of the workpiece to make it possible to validate the manufacturing work. Thus, the biggest issue the modern manufacturing field is facing is that the traditional measurement and data acquisition methods require human intervention and skillful operators, and most of them are time-consuming. Some methods were developed to increase the efficiency of the 3D topography of surfaces like the spiral sampling [15] but with the increasing demands of customers that not only expect higher quality, lower price, and higher performance, but they also require the earliest delivery of product, better and less time-consuming methods had to be chosen.

Developments in 3D scanning technology allow creating a digital scan model from a physical object. The developed measuring systems and specific scanners can be categorized as contact and non-contact . Contact CMM knew their beginning in 1933 by Abbot and Firestone's [16]. The tactile profilometer is still the most common roughness measuring device in mechanical industry and has been upgraded over time. Those scanners are based now on Coordinate Measuring Machine (CMM) technology that can be controlled either manually or automatically by a program. These devices consist of a probe that can move along three axes, where each axis has a built-in reference standard (Figure 1.5.2.a). The contact CMMs are very reliable as they are not sensitive to colors nor transparency and they have high accuracy and cost less than some contactless scanners. However, the data acquisition by these devices is slow and the probe contact can affect certain non-rigid parts making an unwanted deformation during the scan process [17]. Non-contact scanners use lasers and optics (e.g., using charged-coupled device (CCD) sensors presented in Figure 1.5.2.b) to digitally capture the geometrical shape of a part as point clouds. Unlike contact scanners, those devices are fast whereas there is no physical contact between the scanner and the workpiece. The accuracy of data acquired by non-contact scanners is slightly lower compared to contact scanners but nonetheless that accuracy is quite acceptable for industrial inspection applications. As revolutionary as they may seem like, non-contact scanners also have some limitations and disadvantages. The transparency, reflectivity, or even the color of the surfaces can affect the data acquisition of these devices. The limitations of non-contact scanners can be reduced by applying temporary non-reflective paints to make the scan more reliable [18]. These limitations can add noise in the acquired point clouds for which the robustness of relevant inspection methods needs to be validated.

a) b)

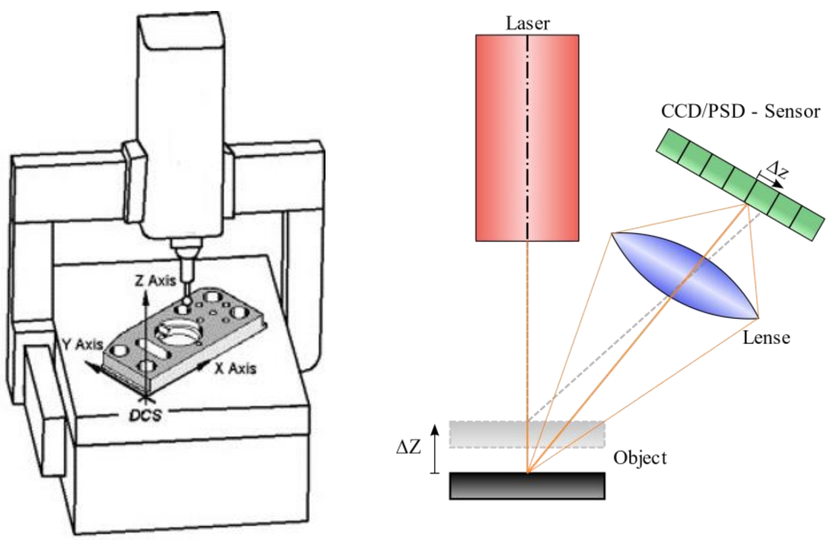


Figure 1.5.2: a)Contact scanner based CMM[19] b) Principle of a laser triangulation sensor[20]

1.5.3 Quality control based on 3D geometrical inspection

Nearly every industry, at various levels, is required to use quality control. Regardless of the type of industry or activity, each company needs to evaluate its production quality to improve its production, remain competitive, and sustain a sound reputation. Quality control is not only about eliminating the defective parts but also ensuring a comprehensive evaluation of the commercialized product's quality. Inspection tasks may be classified into the following three broad categories [21] wherein typical tasks are listed for each category.

- Gross inspection: This is the first step of inspection as it is done with the bare eye to obtain diagnostic information of the workpiece. It's done by comparing the visual form of a workpiece to its CAD model [22].
- Dimensional and geometrical inspection: In this step different dimensions of a workpiece is measured to verify if they respond to the tolerance requirements [23].
- Micro inspection: This step inspects the manufacturing quality of the workpiece to verify the integrity of the parts such as the surface roughness and porosity [24].

Quality control is a crucial activity in the life cycle of mechanical products, especially in the zero-defect manufacturing approach. To this end, parts and assemblies must be inspected to ensure that they meet their specifications. Inspection results also provide valuable information about the behavior of manufacturing processes. For example, a hole out of tolerance may indicate that a cutter is worm out and must be replaced. Tolerancing is a technique to ensure part interchangeability by controlling the geometrical dimensioning variation that exists in manufactured parts. The tolerances come off by specifying a range within which a dimension is allowed to vary. In other words, tolerancing ensures the functionality of parts and the quality of production. According to the literature, tolerancing can be expressed as the following [25]:

- A direct tolerancing method, which includes the limit dimensioning and plus/minus tolerancing.
- General tolerancing notes, to generally address tolerancing for all dimensions.
- The Geometric Dimensioning and Tolerancing (GD&T), to verify the conformity of manufactured parts with the specification defined at the design stage.

Geometric Dimensioning and Tolerancing (GD&T) is a core aspect of inspection and control quality. Basically, GD&T is a system credited to Stanley Parker who developed the concept of "true position". The purpose of geometric dimensioning and tolerancing is to define and communicate engineering tolerances. It makes it possible to define the allowable variation by describing the nominal geometry of CAD and engineering drawings using symbolic language. In the manufacturing and production industry, GD&T is widely applied in the manufacturing field for workpieces with complex shapes in different industrial disciplines. Generally, all types of industrial parts could be categorized as rigid and non-rigid parts. This separation opens the door to different specifications and tolerancing methods. Tolerancing methods for non-rigid parts must take into consideration, compliance and permissible displacements of those workpieces during the inspection and assembly process. Firstly appeared in 1996 [26] for advanced vehicle manufacturing, the tolerance analysis for non-rigid parts evolved in time. In this context, the profile tolerances are assigned to free-form surfaces of parts to control surface variations. These profile tolerances can be defined with reference to datum(s) known as related profile tolerances. Related profile tolerances are applied for cases that involve the assembly of free-form surfaces with other geometric features [27]. Once tolerances are allocated, the geometrical and dimensional requirements need to be verified on the part in an inspection process. Figure 1.5.3-1 illustrates a categorization of particular specification methods used for the geometric dimensioning and tolerancing of non-rigid parts.

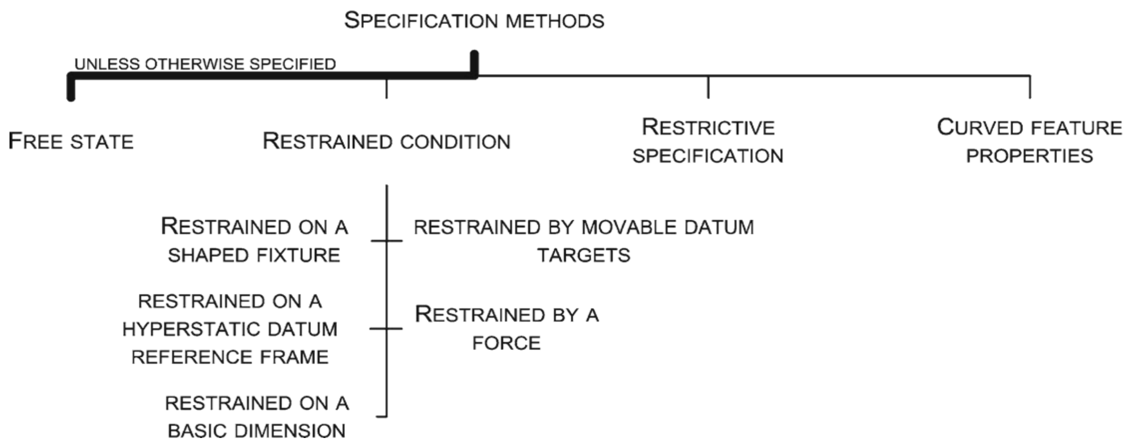


Figure 1.5.3-1: Categorization of the particular specification methods used for the geometric dimensioning and tolerancing of nonrigid parts [28]

In the automation era, manufacturing standards such as ASME Y14.5 and ISO-GPS were developed to have a better and common state and interpretation of GD&T. Also, the American Society of Mechanical Engineers (ASME) established rules, definitions, requirements, defaults, and recommended practices to make that possible. They state that workpieces and parts should be evaluated in a free state which is represented by the symbol Ⓕ in drawings. However, an inspection of non-rigid parts must take into consideration the compliance and deformation of these parts. As a result, specific requirements, based on ASME Y14.5 and ISO-GPS standards, for geometric dimensioning and tolerancing of non-rigid parts were developed as depicted in Figure 1.5.3-2.

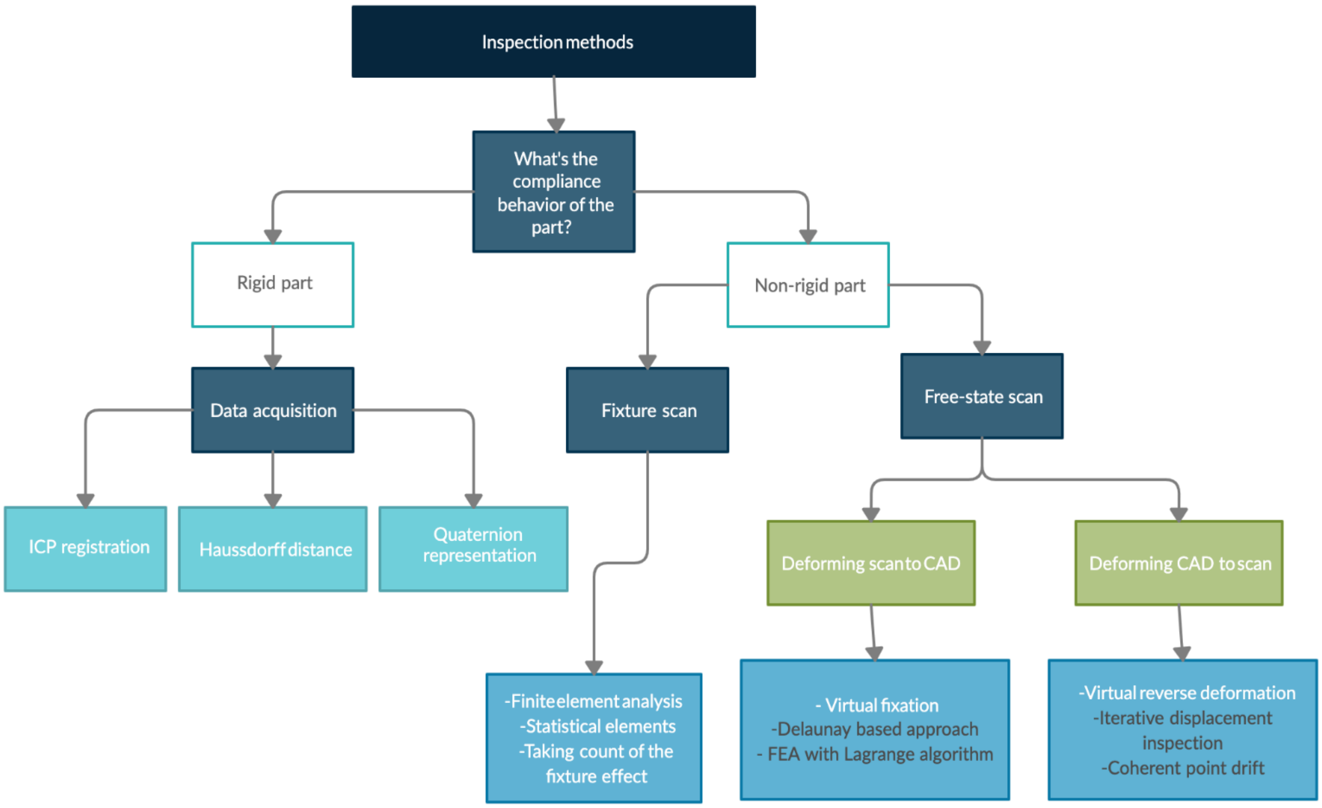


Figure 1.2.3-2: Graphical representation of existing inspection methods

This kind of graph can be an example of the basic works that can be implemented in the a 4.0 inspection that aims for an intelligent inspection. A graph like this will be implemented to the cloud and depending on the compliance behavior and all the different parameters of inspection, the right machine and inspecting method will be chosen. This is a new aspect that will be presented in the upcoming parts of this article.

1.6 CAD model and scan data registrations

The main objective of computer-aided inspection (CAI) is to make it possible to compare the computer-aided design (CAD) model with the data acquired from methods cited in the previous section. Workpieces being categorized by rigid and non-rigid, different registration methods have been developed to make it possible to inspect every part. In fact, rigid registration is the primary step in computer-aided inspection for non-rigid parts. The rigid and non-rigid registration methods are discussed in detail in the following sections.

1.6.1 Rigid registration

The main goal of rigid registration is to bring the CAD and the scan models as close as possible in a common coordinate system without deforming both models [2]. It uses an optimal transformation matrix to translate and rotate the models without making any changes to their shapes. Historically, CAI firstly appeared in 1992 by Besl and McKay [29], the Iterative Closest Point (ICP) algorithm is one of the most robust and efficient rigid registration methods. Although different methods appeared over the years such as those described by Li and Gu in 2004 [19] or Savio in 2007 [30], ICP is still widely applied in different domains, for example for the inspection of an aircraft [31], it has its place among the most reliable and statistically robust methods of registration. Figure 1.6.1 shows the result of an ICP algorithm when applied on CAD and scan models of a workpiece that are not in the same coordinate.

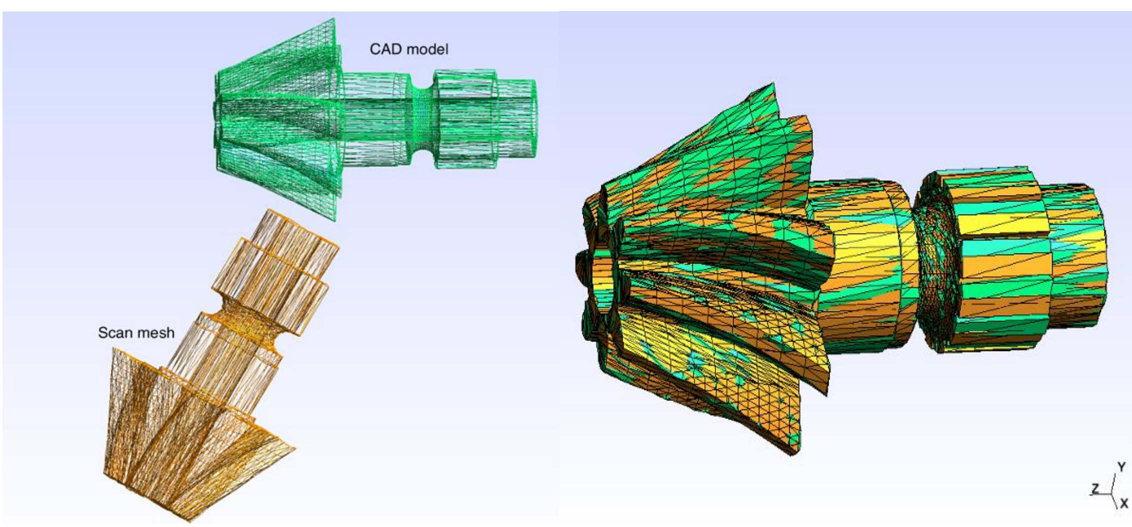


Figure 1.3.1: Result of ICP applied on a CAD(green) and its scan (orange)

The ICP algorithm can be applied using the four following steps:

- Match each point from the point cloud set to the closest point in the reference set (CAD).
- Estimate the combination of rotation and translation to find the transformation matrix.
- Transform the source points using the obtained matrix.
- Iterate (re-associate the points).

The transformation matrix that combines translation and rotation in the ICP registration is estimated and calculated at each iteration to minimize the distance between the two models. The main metric used in this algorithm is the Hausdorff distance [32]. It measures the distance between the CAD mesh and the point cloud data acquired by the scan. It can be explained as the maximum distance between every point of a non-empty set to some point of another non-empty set. We can illustrate that in Equation 1.6.1 where d_H *(X,Y)* is the Hausdorff distance and *(X,Y)* are the two non-empty subsets.

$$\boldsymbol{d_H}(\boldsymbol{X},\boldsymbol{Y}) = \mathbf{max}\,\{\boldsymbol{sup}_{\boldsymbol{x}\in\boldsymbol{X}}\boldsymbol{inf}_{\boldsymbol{y}\in\boldsymbol{Y}}\boldsymbol{d}(\boldsymbol{x},\boldsymbol{y}), \boldsymbol{sup}_{\boldsymbol{y}\in\boldsymbol{Y}}\boldsymbol{inf}_{\boldsymbol{x}\in\boldsymbol{X}}\boldsymbol{d}(\boldsymbol{x},\boldsymbol{y})\} \qquad 1.6.1$$

An algorithm, as strong as ICP and as used as it, has definitely been subject to a lot of improvements and upgrades. The evolution of the different fields where ICP is being used had made it clear that we can’t use the same algorithm that appeared nearly three decades from now. The ICP has been modified and developed to decrease the calculation time first in 1995 [33] by proposing a robust method applying random sampling of the point clouds. The algorithm knew also the minimization strategy [34] or minimizing the metric error of the transformation. An improvement in the search of the closest points by using corresponding points from previous iterations of the ICP and only searching in a small neighborhood near those points made a huge improvement in the processing time of the algorithm [35]. The registration process also has been improved by some techniques to accelerate the process and upgrade efficiency [36]. Color registration has been also implemented to improve the efficiency of the transformation of the sets [37], although not all the scanners can acquire the colors from the workpieces, this variant of the algorithm can't be ignored. The ICP knew many more improvements and many variants for the algorithm have been investigated [34].

1.6.2 Non-rigid registration

The rigid registration, being the first step in the process of registration, is not enough and not a reliable method to be applied on non-rigid workpieces as they have so much more parameters to bear in mind. Considering the flexible deformation of parts in a free state, the comparison between CAD and scan models cannot identify defects and estimate their size on the scan model. To resolve this problem, CAI methods for non-rigid parts are used to distinguish between the defects, such as geometrical deviations and distortions with respect to the CAD model, and the flexible deformation due to the compliance of non-rigid parts. As already mentioned, conventional dimensioning and inspection methods for non-rigid parts set up over-constrained inspection fixtures to compensate for the flexible deformation of these parts and to ensure that the measurement setup properly represents the assembly functionality of the part.

Before presenting the non-rigid registration and its methods, a better understanding of the compliance of non-rigid parts is required. The definition of compliant behavior (compliance) for non-rigid parts is related to the material and geometrical flexibility of parts. In fact, the higher compliance value of parts implies the higher flexibility of these parts. Therefore, the flexible deformation of non-rigid parts in a free state is due to the compliant behavior of these parts. Considering the notation of finite element ana1ysis, $[K]\{u\} = \{f\}$, the comp1iance (C) is defined in Equation 1.6.2.

$$C = \{u\}^t\{f\} \qquad 1.6.2$$

Where $\{f\}$ is the force vector, $[K]$ is the global stiffness matrix and $\{u\}$ is the disp1acement vector. The flexibility is defined as the inverse of stiffness ($[K]^{-l}$) according1y.

Due to the behavior of the non-rigid parts, it is clear that their compliance will affect the inspection process. The deformations caused by their weights will get in the way of the registration of the workpieces. This way the inspection process will be simpler, and we can register the workpiece the same way we do with a rigid part. However, several downsides exist in using fixtures such as their time-consuming set-up process, considerable acquisition and operation expenses, limitations of standard fixtures in some scenarios. The companies find themselves in the obligation to design and manufacture costly conformation jigs to try to recreate as much as possible the assembly state of the parts. Those disadvantages made it obvious that fixture registration was not the best solution in the long term even if it is currently widely used. Researchers have tried to avoid the use of those fixtures by numerically deforming the data acquired by the scan until it matches the CAD or vis-versa. Thereby elastically deforming the data to reach an optimal assembly shape while avoiding any manufacturing defects of the jigs. The fixtureless CAI methods are classified into four approaches as I) automated vision inspection, II) metric characteristic, III) boundary reconstruction and IV) simulated displacement. Fixtureless inspection of non-rigid parts can be performed by non-rigid registration methods c1assified as simulated displacement. These methods are essentially based on compensating for flexible deformation of non-rigid parts in a free state by virtual displacement. The core idea of the fixtureless methods is to enable a comparison between the scan and CAD models by virtually compensating for the flexible deformation of the part whereas leaving the defect areas intact.

1.7 Intelligent factory based on computer-aided-inspection (CAI)

In the context of industry 4.0, inspection is a fundamental stage towards sustainable manufacturing in industrial applications. In fact, the importance of this process has already been mentioned above as it turns physical parts into information to make it possible for manufacturers to evaluate the quality of the parts made and their conformity to specifications pre-defined on the CAD model. Inspection is among the main contributors to the value of a product. The main concern of industry 4.0 being time management and cost reduction, planning every task is then critical to assure the best results. As a matter of fact, inspection planning is popping out as a key element for the upgrade of inspection 4.0. Many advanced methodologies for sampling strategy design have been thought of as the current practices, in general, see the operator as the main actor, and this is due to the lack of information circling both at a system level and for the machine during the measurement. Intelligence and mostly artificial intelligence (AI) is needed to optimize the sampling strategies. From those methodologies, we can name the Point Distribution, Choice of sample size, and Path planning and probe configuration [38]. Figure 1.7 shows, as an example, inspection planning in the coordinate measurement system.

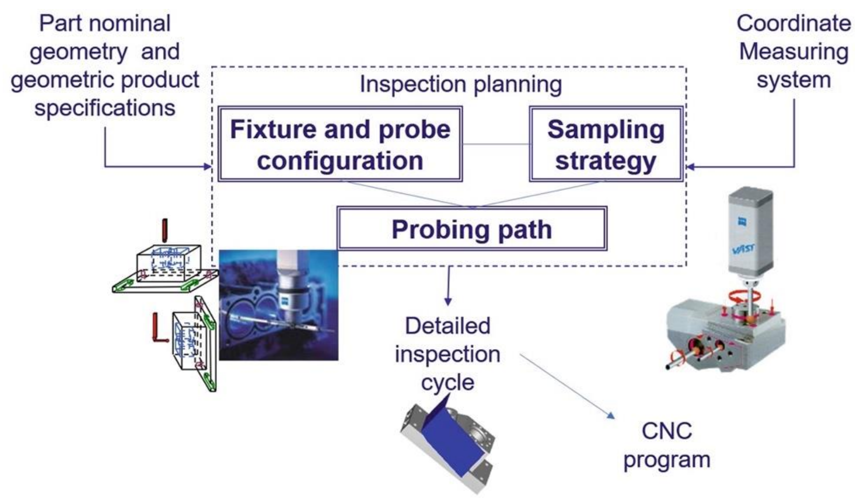


Figure 4: Inspection planning in coordinate measurement system [38]

Reducing the human intervention in the era of industry 4.0 gave way to the implementation of industrial robotic arms with server computers, sensors, and actuators in a way it can be useful in any field, making it possible for the automation of non-destructive testing (NDT) [39]. The process of data acquisition can be very redundant and human intervention can make mistakes and is for sure not as precise and accurate as a robotic arm controlled by a computer. A part can be sent to the NDT facility with some basic information about the piece, the data will be collected automatically and the best way of scanning/inspecting (type of probe, pathway, registration method) will be exported from the database and the robotic arms and computers will apply the pre-defined sequences of actions to inspect the part. Basically, these elements are the foundation of an intelligent factory in the concept of industry 4.0.

1.7.1 Digital twins (DT)

First and foremost, scanning inspection is among the main contributors to value not only for a product but also for a whole factory. As being said, it is definitely one of the key processes to upgrade during the era of industry 4.0 as this revolution's goal is to automate the traditional manufacturing and industrial practices using modern smart technologies. Human intervention is being less and less required as it was mentioned above for its time-consuming tasks. Recently, a numerical solution has been presented on product life-cycle management at the University of Michigan Lurie Engineering Center as Digital twins (DT) [40]. There is a correlation between CAI and DT model. In this regard, Airbus A350™ is an example of advanced aircraft which is entirely based on a 3D digital mock-up. This technology is facilitating a significant decline in progress time and development. Generally, the first stage is to generate a virtual version of the asset that is known as a digital twin. Figure 1.7.1 illustrates a basic representation of how DT can help manufacturing factories. A twin model manages data in an extra robust approach for operators to easily identify essential simulation, reports, device history, and results. Also, by providing a virtual interpretation of the product lifecycle it permits to make better decisions and predict problems. Basically, the digital twin concept is based on 3 steps, 3D definition, 3D in context, and 3D as a service. The first step includes using the best technology & process to obtain the real-world and create a 3D definition by generating point clouds via 3D laser scanning. Then, the 3D model should be capable of evolutions, a variety of revisions, and structures of the asset or product. Finally, the model should be customized with 3D functionalities to recommend services to each actor of the product lifecycle in a way that will improve operational outcomes.

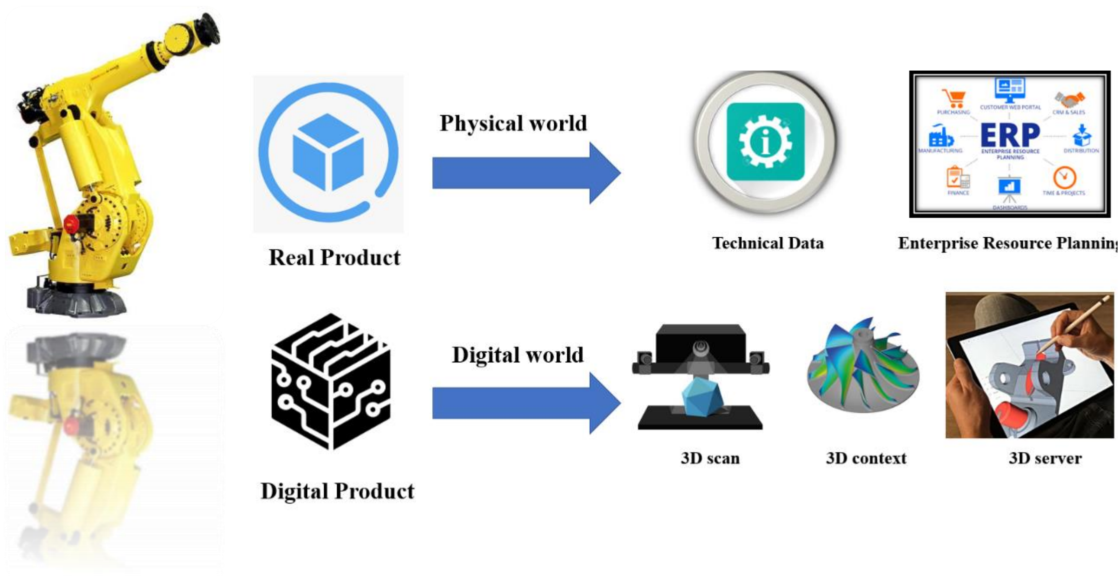


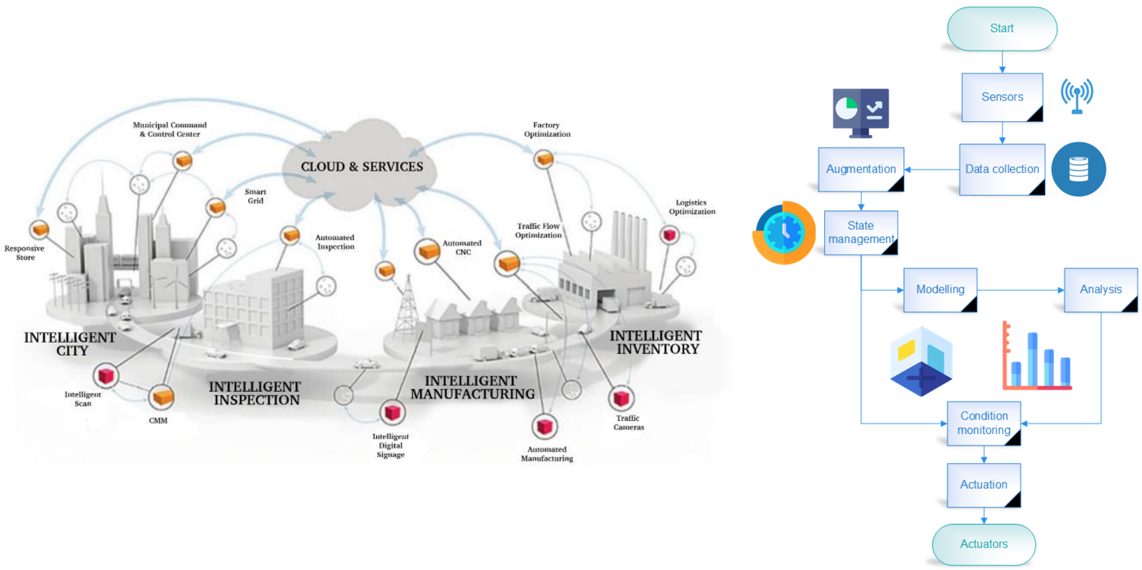
Figure 1.7.1: A general model of digital twin

The digital twin can be utilized to any asset, equipment, or machine in a factory or complete factory [41]. The real idea of Digital Twin began from product lifecycle management (PLM) earlier than new technologies such as the Internet of Things, Smart Manufacturing, and Industry 4.0. Twin's structure has multiple elements to simulate states and then future circumstances of the manufacturing process. In current trends, sensors play a key role to collect any sort of data in real-time conditions. The smart network software has been developed and tried to visualize physical plants in the digital world. Incidentally, networks are diverse from various wired and wireless networks. Now, the digital twin has major questions related to a user persona, value chain, its supporting data model, inputs, user interfaces, benefits, and supporting business models. It is worth mention that the current factory system simulation is based on four stages namely machine states monitoring, forklift movements, constraint management, asset position and orientation. All these data should be transmitted by a real-time network connection which provides whole information for different types of the value chain in manufacturing sectors. In this regard, in our model internet of things is considered as the core of data transmission from all the units.

1.7.2 The internet of things (IoT)

The industry knew such a development lately in all its different aspects and with the upcoming 4.0 revolution being one big step towards the future many technologies had to keep up with its pace. One of the key elements of industry 4.0 development is the internet of things. It may be described as the network of physical objects. The internet itself was one of the greatest achievements of humankind as it made it possible to connect people all over the globe and made access to information so much faster and easier. Due to its importance, it seems that anything related to the internet may just be as beneficial to the development of modern technologies. The internet of things (IoT) serves the same purpose as the "common" internet as it connects objects that are embedded with software, sensors, machine learning, real-time analytics, and multiple other technologies for the purpose of exchanging data with other devices and systems over the cloud. The cloud being a non-physical network to gather the information and made for storage, it is also easy to access, and the follow-up can be done in a matter of seconds. The most common example of IoT is smart houses; it's an environment that you can control by a single device. A smartphone can turn off the lights open the windows or heat up the oven with clicks. It seemed futuristic at first, but it became reality in no time. Now imagine all the machines of a factory controlled from a distance with a single device and with machine learning those machines can also be automated and gain autonomy at some point. With this kind of technology, the privacy and security of the industry can also be upgraded. In the industry, all the modern machines have sensors that acquire so much information in a very short time but mostly those machines are not related one to another and it takes time to gather all the information of a factory. Apart from that, some tasks are redundant, take a lot of time and human error can affect the results a lot because the appearance of robots in different steps of the industry became so much important to its development. IoT can make it one step further as it can make the usage of machines and robots so much more efficient and precise. New opportunities and possibilities will surely be available thanks to IoT as it is a new field that knows no barriers or limitations due to the aspect of the internet being so vague and limitless.

An example of an intelligent factory will be presented to give an idea of how things might evolve later. We will separate a product life into 4 different steps and explain how the IoT can revolutionize that. The inventory, the manufacturing, the inspection, and then the customer. Thanks to IoT a cloud network will connect all those different steps assuring constant feedback, information storage, and communication. Firstly, the design of the product will be made responding to the demands of the customer and then sent to the network. A small check in the inventory will be the next step to see the availability of the raw materials that will be sent to the manufacturing process. The design that had already been analyzed made it possible to extract a manufacturing protocol that will be sent to the machines to create the product. The next step will be the inspection and like in the manufacturing process the data collected will dictate which kind of inspection methods and tools will be used to acquire the best scan possible. The material, rigidity, and size of the product are the most important factors in this step. After the inspection, the data is analyzed, and if everything checks, the product is sent to the customer. All these steps are automated without any need for human intervention. The time-consuming and repetitive aspect of some actions will be reduced this way and the human error will be completely erased. At this point, the only human work that is left might be the maintenance of the different machines but even that can be at some time delegated to robots as sensors will send the information to the cloud of a failing part in a machine. Figure 1.7.2 is a representation of the basics of industry 4.0 in sustainable manufacturing.



(a) (b)

Figure 1.7.2 : a) Digital factory based on industry 4.0 concept [42] b) Digital Twin Data flow from Device.

1.8 Conclusion

This study proposed a systematic review of the works done in the field of 3D geometric inspection and its importance in the manufacturing industries. The methods cited in this review englobe aspects of inspection in the era of industry 4.0 with the criteria towards different fields and types of parts. Inspection, as a core of quality control, is one of the most important steps in the production cycle of a part. In this regard, its development is not to be neglected. As we move more towards industry 4.0, the implementation of its ideas should be part of the development of dimensional and 3D geometrical inspections that already exist. To this end, the data of a manufactured part is acquired and compared to its CAD model to verify whether it meets the assembling and functional requirements without any human intervention. A fully automated and intelligent inspection 4.0 in its industrial use is in its way wherein an automated factory with the least human intervention is the main goal. Finally, a digital twin's model has been proposed for an industrial application based on industry 4.0 answering the question that can it be possible at some point to use artificial intelligence to delegate redundant inspection works to machines expecting feedback from them as well as an auto-maintenance at some point?

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CHAPITRE 2
UNE NOUVELLE APPROCHE EXPERIMENTALE POUR EXPLORER ET OPTIMISER LE SOUDAGE AU LASER DE L'ALLIAGE D'ALUMINIUM 5052-H32, BASEE SUR LA MESURE CMM ET SON ASPECT METROLOGIQUE

I. Houban[1], N. Barka[1] and S. S. Kanganroudi[1]

University of Quebec at Rimouski, Rimouski (Qc), Canada

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2.1 Résumé en français du deuxième article

Plus léger et plus résistant à la corrosion par rapport à d’autres alliages métalliques, l’utilisation d’un alliage d’aluminium permet de réduire la consommation d’énergie et de fournir un véhicule plus durable pour l’industrie automobile et même l’industrie navale où l’alliage d’aluminium 5052-H32 est présent dans différentes pièces. Mais le soudage de l'alliage d'aluminium reste un réel problème en raison de sa conductivité thermique élevée, de son faible point de fusion ainsi que de sa grande réflexivité. Cependant, une technique innovante telle que l'oscillation du faisceau laser est proposée pour surmonter ces difficultés en distribuant la grande quantité l'énergie du laser requise pour le soudage de l'aluminium et en limitant les dommages qui pourraient survenir. La puissance du laser, la fréquence et l'amplitude sont étudiées pour évaluer leurs effets sur les distances entre les trous fait sur les pièces et l’angle entre ces deux dernières à l'aide d'un plan factoriel complet à trois facteurs et à deux niveaux suivi d'une analyse de la variance (ANOVA). Le résultat révèle que l'amplitude possède l'effet le plus influent suivi de la fréquence, et finalement, la puissance

du laser. Une augmentation de l'oscillation d'amplitude tend à pousser les pièces loin de l’autre. Une interaction importante est trouvée entre la puissance du laser et le soudage dans les analyses statistique. Une optimisation utilisant la méthode de surface de réponse à partir des paramètres de soudage a permis de déterminer que la meilleure soudure pouvait être obtenue par une bonne combinaison des paramètres de soudage.

Ce deuxième article, intitulé *« A new experimental approach to explore and optimize laser welded aluminium alloy 5052- H32 based on CMM measurement and metrological aspect »* fut essentiellement rédigé par son premier auteur Ilyasse Houban qui a également réalisé toutes les expériences et travaux de laboratoires requis pour l’acquisition des données dans les locaux du DMIG de l’Université du Québec à Rimouski, le soudage laser par contre a été fait grâce à l’aide du deuxième et troisième auteurs. Le premier auteur a également écrit les parties concernant l’état de l’art ainsi que l’interprétation des résultats à travers des travaux d’inspection géométrique et de traitement de données qui ont abouti aux résultats finaux optimisés. Noureddine Barka est le second auteur de cet article. Il est à l’origine de ce projet de recherche en proposant l’approche et la méthodologie pour aborder la problématique. Il a également contribué à l’amélioration de la rédaction pour la version finale. Le troisième auteur de l’article est Sasan Sattarpanah Karganroudi a apporté son expertise du domaine d’inspection et de soudage laser.

2.2 Titre du deuxième article

A new experimental approach to explore and optimize laser welded aluminium alloy 5052-H32 based on CMM measurement and metrological aspect

2.3 Abstract

Laser welding, a critical joining technique for aluminium alloy, is widely used for fast and precise part welding, as the evolution of the automotive field and the aerospace one requires more efficient results in this era. Regarding the importance of the welded parts and its performance, a precise part inspection is required to make sure that the welded pieces match the requirements and are in the tolerance zone. In this study, two same parts of aluminum 5052 H-32 are laser welded using different parameters and some features were added to the parts to measure specific deformations caused by the laser welding process. Then after welding, a geometric inspection is made by using a Coordinate Measuring Machine (CMM) that make it possible to acquire all the needed data from the different parts. The results are analyzed using Analysis of Variance (ANOVA) and Response Surface Methodology (RSM) to determine the main effect of process parameters, also the best combination of welding parameters that minimizes the residual stress and the deviation angle between the two parts. Results imply that a good joining of the parts must be achieved and the deviation and the distance between the features must be minimized. This study provides a good exploration and a complete process from laser welding to inspecting the effect of the different parameters of that joining technique.

2.4 Nomenclature

ANOVA: Analysis of variance

AA : Aluminium alloy

Adj MS: Adjusted mean square

Adj SS: Adjusted sum of squares

CAD: Computer aided design

CMM: Coordinate measurement machine

d: Distance

DF: Degree of freedom

f: Frequency

mm: Millimetre

Mg: Magnesium

MS: Mean square

P: Laser power

R-sq(adj): Adjusted coefficient of determination

R-sq(pred): Predicted coefficient of determination

R-sq: Coefficient of determination

S: Standard deviation

SS: Sum of square

W: Watt

2.5 Introduction

The aluminium is a metal with many interesting properties to the modern manufacturing and helps a lot the technological improvements in different fields. In fact it has a good mechanical resistance, corrosion resistance combined with low density [1]. It's a very revolutionary material if used in the right way. Another aspect of this metal is its lightweight compared to other metals. In fact this aspect is advantageous to many industries and mostly the transportive one since those properties make it possible to lessen the weight of the vehicles and reducing in the same time the energy consumption without affecting the lifetime of it [2]. Aluminium alloys are largely used in different fields also as the combination of it with different materials opens the possibility for many applications. It is indeed used in marine, aircrafts, general sheet metal work, heat exchangers, fuel lines and tanks, flooring panels, streetlights, appliances, rivets and wire [3]. The cast alloy designation makes it easier to define which the properties of each aluminium alloy. In fact, the first digit defines which is the principal alloying element for our case 5xxx means magnesium, H3 means that this alloy is strain-hardened and stabilized and the last digit 2 refers to the degree of the strain hardening. The 5052-H32 is then a strain-hardened and stabilized alloy that has Mg and Mn as its main alloying elements [4]. All those properties cited make it clear for the choice of material used for our study. Nevertheless, despite looking like such a complete material and being versatile it also comes with its difficulties and restraints especially at the assembly level [5]. A part gets usually assembled to make a finite product, it is an important step for the production and must be well performed. The assembly has a big impact on the product quality [6] as a poor assembly usually means unsatisfied customers. Many assembly types exist in the modern manufacturing era and the main ones would be the mechanical assembly, the welding assembly and rivet assembly. Each type responds to a different need, a permanent assembly would require welding or rivets and a semi-permanent or one that needs adjustments one would mostly require a mechanical assembly. By looking at this and the different fields that we aim for we directed this study to welding assemblies as we want permanent and watertight assemblies. Spot welding is a kind of welding assemblies that we omitted in this study which does not give satisfying results due to the low resistivity of aluminium or MIG which causes high thermal distortion [7]. Also, the high reflexivity and the conductivity of the aluminium makes it a challenge as a lot of energy would be required due to the dissipation caused by the material properties [8, 9]. But for this study laser welding will be applied on our aluminium alloy part. In fact many studies have proposed several ways to weld aluminium with laser and get the best results [10]. Laser welding is one of the latest developments in the field of part joining as it is one of the most efficient and precise techniques that offers a lot of possibilities compared to the other welding methods. It is quite different from other fusion welding techniques from both equipment and operation standpoints. It uses a laser beam to join the parts together, many joints exist but for our experimentation we are going for a butt joint welding. This technique is also more versatile as we can reach our requirements just by changing the different parameters as the speed of the beam, the pulse and also the frequency to get to the penetration that we are aiming for [11]. The introduction of the oscillation of the laser beam really changed the way laser welding has been used. In fact, when the oscillation follows a certain pattern, it restrains the properties worsening of the aluminum when it is welded. This comes as a result of the limitation of the heat generated due to energy distribution [12] and a limitation of alloying elements loss [13].

Geometric inspection is the last step of the cycle of manufacturing as it makes it possible to acquire all the data from the scanned piece and compare it to our original CAD to see how good or bad of a result we have got. This field can be divided to two main scanners, contact CMM and non-contact scanners.

Contact CMM knew their beginning in 1933 by Abbot and Firestone's [14]. The tactile profilometer is still the most common roughness measuring device in mechanical industry and has been upgraded during over the time. Those are based on *Coordinate Measuring Machine* (CMM) technology that can be controlled either manually or automatically by a program. These devices consist of a probe that can move along three axes, where each axis has a built-in reference standard. The contact CMM are very reliable as they are not sensible to colors nor transparency and they have a high accuracy and cost less than some contactless scanners. But on the other side, the data acquisition from those devices is slow and the probe contact can affect certain non-rigid parts making an unwanted deformation during the probing process [15]. Non-contact scanners use lasers and optics to digitally capture the geometrical shape of a part as point clouds. The precision of the data acquired by contactless scanners is lower compared to contact scanners but nonetheless that precision is quite acceptable for common inspection applications. As revolutionary as they may seem like, the non-contact scanners also have some limitations and disadvantages. The transparency, reflectivity or even the color of the surfaces can affect the data acquisition of those devices. Those limitations can be reduced by applying temporary non-reflective paints to make the scan more reliable [16]. These limitations can add noise in the acquired point clouds for which the robustness of relevant inspection methods needs to be validated. The requirements of our study and our research work made us choose the fixed CMM for this article.

The machine we will be using is Coordinate Measuring Machine from Mitutoyo. It is a contact scanner as it uses a probe to measure the dimension of the part. After acquiring all the data thanks to the CMM, we will apply an ANOVA analysis to explain all the results and the different effects of each of the welding parameters on the final parts to try to find the best combination. To the best of authors' knowledge, no research works have thoroughly combined both the laser welding technique and a CMM inspection to discuss the results of aluminum welded parts.

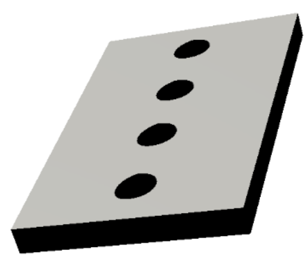

Figure 2.5-1: Parts before welding

The part used for this experimentation is 180x60x4.76 aluminum alloy 5052-H32 sheet with 4 equal holes as shown in Figure 2.5-1, they will be welded as shown in the next section. There are different parameters that will be taken in consideration to weld the pieces together like the power, the amplitude and the frequency. After that the welded parts will be placed on our Mitutoyo CMM for the data acquisition, the setup of the different steps of this work will be presented in the experimentation part.

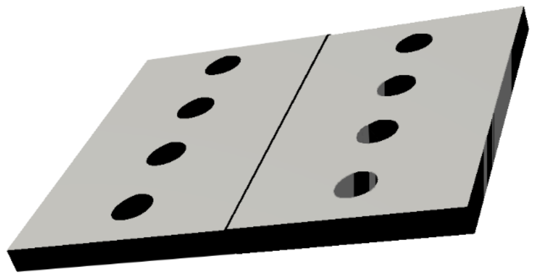

Figure 2.5-2: Parts after welding

In this research, an experimental method is adopted, and results are explored using ANOVA to analyze the effect of laser welding parameters on the deviation angle and different distances between features of 5052 H-32 alloy parts. This statistic approach is planned, to perform most precisely yet with the optimum number of tests. This proposed statistical approach is developed in progressive steps. The first step is to prepare an experimental plan and set a design of experimentation of the welding process to get the most interesting results. The second step is to take the welded parts to the metrology lab where we will geometrically inspect them using a CMM to extract all the data possible and needed for the ANOVA analysis which will be the last step. Based on ANOVA analysis, Response Surface Methodology (RSM) and main effects of parameters on each result are being extracted. The ANOVA method had been chosen for this study as it is so powerful to predict future results and have a better understanding of past events [17] and the RSM is here to present a the relationship between the parameters and the outcome [18]. This study is executed to achieve an optimized combination for the laser welding of alloy 5052 H-32 and also to make it possible for the combination of laser welding with CMM inspection. The feasibility and effectiveness of the proposed approach led to an accurate and reliable statistical model for predicting the deviation caused by laser welding. This article is formed as follows: Section 2.6 presents the methodology of our experimental tests based on laser welding and its related parameters with a presentation of the metrology setup used. Results of experimentation, statistical and RSM analyses, and deviation discussions are then reported in section 2.7 and section 2.8 (a section for the distances and another one for the angle). In the end, section 2.9 presents conclusions and ideas for future works in this field.

2.6 Experiment procedure

2.6.1 Materials and laser welding process

The laser welding experiments in this study have been performed on aluminium alloy 5052 H-32 that is widely used in the automotive field, the aerospace one and the naval. It is well known for its corrosion resistance against seawater and salt spray, a high fatigue strength and a good weldability. The chemical composition of aluminium alloy 5052 H-32 and its mechanical characteristics are presented in Tables 2.6.1-1 and 2.6.1-2 respectively.

Table 1.6.1-1: Aluminium alloy 5052 H-32 chemical composition in wt % [19]

Component	Al	Cr	Cu	Fe	Mg	Mn	Si	Zn
Content (%)	95.7-97.7	0.15-0.35	0.1	0.4	2.2-2.8	0.1	0.25	0.1

Table 2.6.1-2 : Mechanical and thermal properties of Alu 5052 H-32[19]

Yield strength (MPa)	Elongation at break (%)	Fatigue strength (MPa)	Melting point (°C)	Shear Modulus (GPa)
241	10	131	607-649	25.9

The welding machine is composed by an IPG Photonics YLS-3000 laser source which is Nd:YAG laser with wave length of 1070nm and BIMO High YAG laser head giving a laser focus diameter of 0.45mm. All those welding devices are mounted on a FANUC robot (Figure 2.6.1-1) which is a mechanical arm because laser welding is a dangerous process that requires the use of an automated workstation [20].

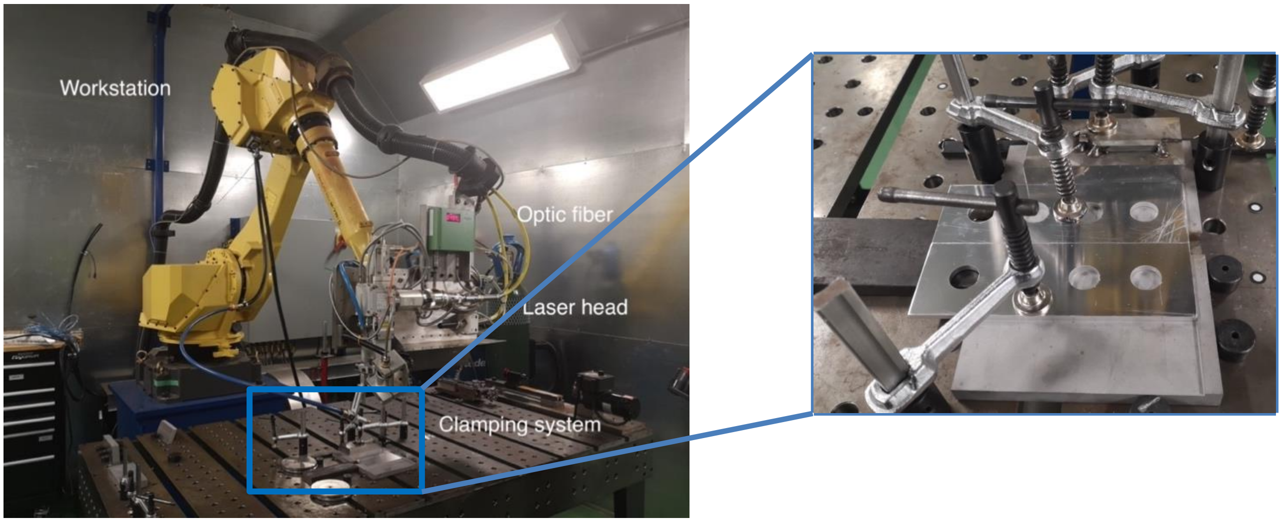

Figure 2.6.1-1 : Laser welding machine

All the part used in this experiment are made of Alloy 5052 H-32 with identical geometry of 180mm length by 60mm and with a thickness of 4.76mm. The four holes are also identical with a 20mm diameter and equidistant as shown in Figure 2.1.2. The holes serve a purpose as we want to study the distances between the centers of each hole with its symmetrical one in the welded part and also to see the difference of the deviation between the beginning and the end of the welding. The angle between the welded part will also be studied as the final piece tend to curve in the direction of the laser beam. A 0.05mm gap had also been instituted before welding to assure a good penetration of the laser beam because after many experiments, without the gap, the pieces tend to move towards each other and don´t allow a good penetration of the laser [21] Having here a 4.76mm thick pieces we went for 10% of the thickness while choosing our gap.

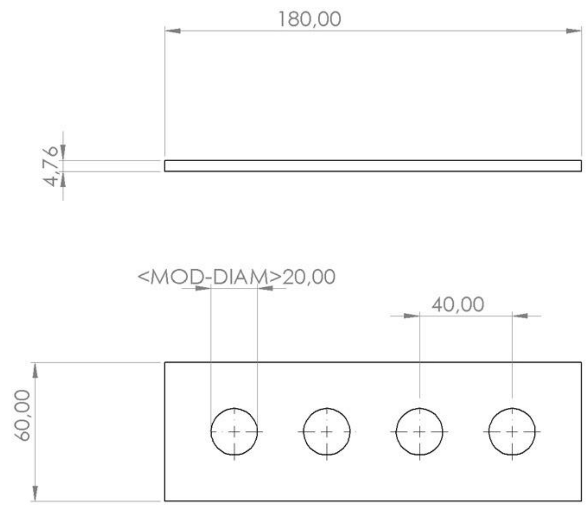

Figure 2.6.1-2: Dimensions of the 5052 H-32 alloy parts

After welding the parts together, we take them to our metrology lab to measure the different deviations and effects of the welding. To make a great geometric inspection that is a key step in our experiment, we used a CMM (Coordinate Measuring Machine) from Mitutoyo which is a really high-accuracy and low cost machine compared to other ones in the market [22].

2.6.2 Design of experiment

The experiment process for the laser welding followed a pre-designed protocol that was created after some testing on some parts to get the best results. The design of experiment is presented in Table 3 below and we mainly took as parameters the power of the welding, the frequency and the amplitude. The speed of the laser beam is kept constant and gap of 0.5mm has been created between the two pieces with a designated gauge. We should also note that we used a wobbling laser welding to get better results on our weld due to the high dissipation of the energy while using this aluminium alloy. The pieces are stabilized in the same way using fixtures and we created a protocol for our laser welding machine to assure that the beam hits the same spots on every couple of parts. The design of experiment presented below followed the Taguchi method as we have 3 parameters and 2 levels (each parameter takes 2 values which leaves us at the end with only 8 experiments). This factorial design of experiments helps a lot to get better results in fewer experiments [23]. The complete factorial design can also provide the effect of interaction between parameters which is very significant for this study as the considered parameters are related to the characteristics of the laser welding machine as described [24, 25].

Table 2.6.2-1: Taguchi design of experiment for 5052 H-36 aluminum alloy

Test	P (kW)	A(mm)	F(Hz)
1	2700	1	200
2	2700	1	500
3	2700	1,5	200
4	2700	1,5	500
5	2900	1	200
6	2900	1	500
7	2900	1,5	200
8	2900	1,5	500

The parts are welded on their sides as shown in Figure 2.1 to try to extract all the data possible from the features. In this article, the main effect that we are studying is the deformation of the surface of the parts and the deviation. That is why we defined the distances (d1, d2, d3, and d4) and the angle $\alpha 1$ presented in the figure below to discuss the welding results. The distance d1 marks the beginning of the welding and the d4 distance the end. Another angle had first made it way to the study being the orientation difference between the two parts but due to the thickness and the welding parameters this angle was shortly omitted for how insignificant it was.

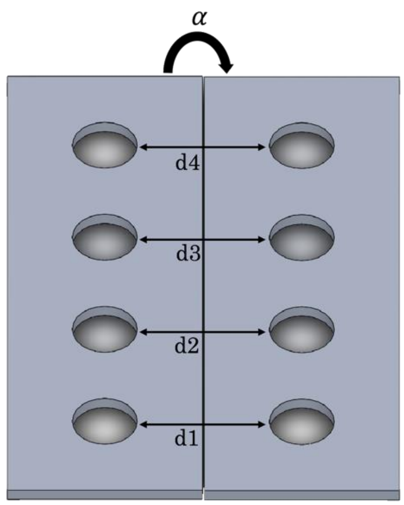

Figure 2.6.2-1: Parts after welding with distances and angle

The welded parts are then transferred from the laser welding lab to the metrology lab to acquire the data from the pieces. To scan them, we are using the Bright Mitutoyo CMM (Figure 2.6.2-2) paired with a single touch probe to extract all the data. The role of the CMM being detecting the placement of individual points, it required a software able to calculate and transform the data acquired from the points predefined in our protocol to dimensions. We chose the CMM over a laser scanning machine due to the priorities of the aluminium that makes the use of non-contact quite difficult. In fact the reflectivity of the material plays a big role in our choice of method of inspection.

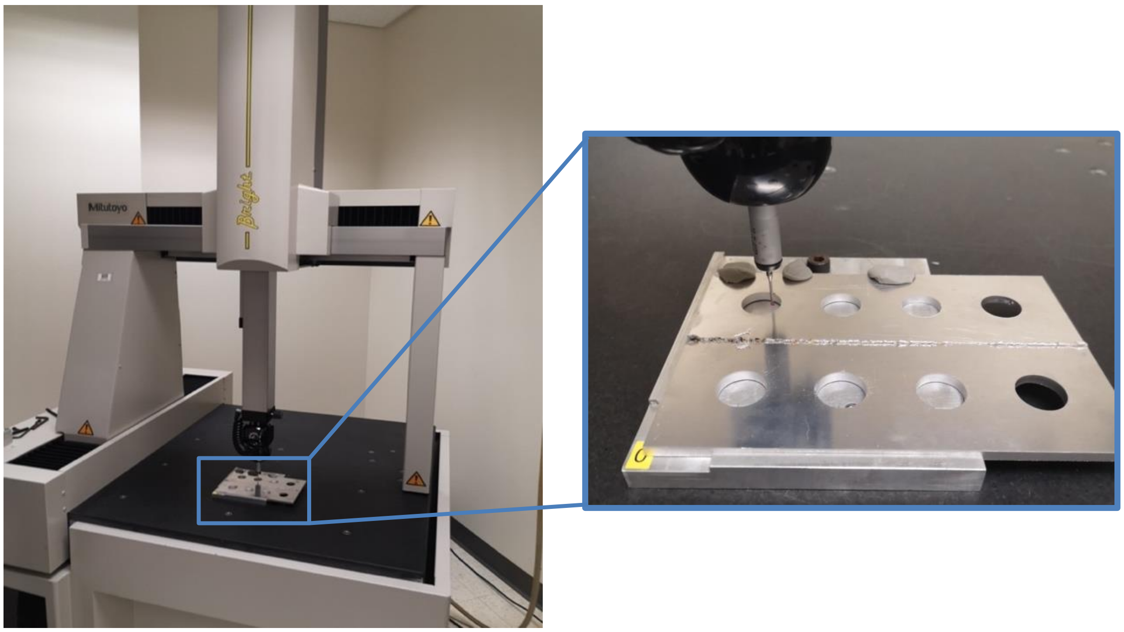

Figure 5: The Bright Mitutoyo CMM used for the experimentation

We used *MCOSMOS24*™ to calculate the data extracted by the CMM and it made it possible to interpretate the scan as it uses mathematical methods such as the Gaussian to calculate the diameter of the feature and get the coordinates of the center of the cylinders and after that calculates the distances. We also set a scanning protocol with *MCOSMOS24*™ and the welded parts were stabilized in the exact same position for every test. Doing so, it assured us of constant and reliable results for our experimentation. Also, the scan followed the direction of the welding, d1 being the closest distance to the welding start and D4 the closest to the end of the laser welding process. The results are presented below in Table 2.6.2-2.

Table 2.6.2-2: Presentation of the results

Test	**d1 (mm)**	**d2 (mm)**	**d3 (mm)**	**d4 (mm)**	**α1 (degree)**
1	60,155	60,156	60,291	60,503	180,984
2	60,164	60,139	60,181	60,326	181,606
3	60,333	60,289	60,355	60,506	180,814
4	60,253	60,205	60,222	60,426	181,129
5	60,445	60,337	60,357	60,504	181,144
6	60,233	60,212	60,288	60,46	180,672
7	60,158	60,122	60,215	60,379	181,147
8	60,095	60,096	60,188	60,393	182,172

We can already see some interesting results because in a perfect world the distance should all stayed at 60mm and the original angle between the two parts is 180 degrees. There are clearly some deviations and torsions that appeared as a result of the laser welding process and the change of the parameters. A discussion of those results will be presented below using the ANOVA analysis and some regression equations that we made. The RSM models will also be presented in the next part of this study.

In this study, to make a better presentation and discussion of our results we divided the work into two parts. The first part will discuss the analysis and the contribution of the parameters on the four distances that we already presented (d1, d2, d3, d4). And the second part will dive into the effects on the angle α1. In the two parts analysis of variance have been made, a regression equation and some plots will be presented for better explanations and visualization of the results. This division had been made to avoid repetition on this study. For sure all the distances don’t know the same effect but there are few similarities on the results found.

2.7 Effects of the parameters on distances

2.7.1 ANOVA results

Having results of an experiment is only the start of the study itself. As it already appears early on this study that the effects of welding on the two parts are considerable, we cannot stop at simple numbers on at table. In fact, to get deep down into the relation between the variables within the experiment, we require the use of an ANOVA method which is, as explained earlier, related to the variance. And more precisely the stepwise method is the one used in this study using Minitab™. This method starts with an empty model or includes the terms we specified to include in the initial model or in every model. Then, Minitab™ adds or removes a term for each step. We can specify terms to include in the initial model or to force into every model. Minitab™ stops when all variables not in the model have P-values that are greater than the specified [26]. P-values are an outcome of the ANOVA analysis that help us to determine if the analysis is usable or not.

As presented earlier, the distances presented in this study are the one between the same features on the different parts. And the results found in the second part of this article are being used for the ANOVA. Being a statistical method, that is based on the law of total variance, the variance is portioned into components attributable to different sources of variation [27]. In other word we are searching for the effects of the different parameters on the distances and with the ANOVA analysis we try to quantify those effects and calculate the contribution of each parameter on the deviation that occurred on the distances. The first step of this analysis is the ANOVA table that present the sources for each distance and those are the affecting parameters, The degrees of freedom (df) which is the number of independent variables in our regression model it's also the amount of information in our data. The sequential sums of squares (Seq SS) are measures of variation for different components of the model it is also used to calculate the p-value for a term. It also depends on the order of the terms that are entered into the model. The contribution is as clear as the name and it displays the percentage that each source in the variance analysis table contribute to the total sequential sum of squares [26] . The adjusted sum of squares is the same as the sequential one, but the order is not important. Adjusted mean squares measure how much variation a term or a model explains, assuming that all other terms are in the model, regardless of the order they were entered. Unlike the adjusted sums of squares, the adjusted mean squares consider the degrees of freedom. The F-value is the test statistic used to determine whether the term is associated with the response. And the p-value is a probability that measures the evidence against the null hypothesis [28]. Lower probabilities provide stronger evidence against the null hypothesis. In this case, the null hypothesis would be that all the distances are equal to the initial distance that we set in the manufacturing and that would be equal to 60. The results of the variance analysis for the four distances in this study are presented in Table 2.7.1-1 below.

Table 2.7.1: Analysis of variance for the distances

Distances	Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
	A	1	0,003121	3,44%	0,05881	0,058811	14,56	0,032
	$P \times F$	1	0,015285	16,84%	0,05467	0,054673	13,54	0,035
	$P \times A^2$	1	0,004883	5,38%	0,05986	0,059858	14,82	0,031
d1	$P \times F^2$	1	0,055356	60,99%	0,05536	0,055356	13,71	0,034
	Error	3	0,012116	13,35%	0,01212	0,004039		
	Total	7	0,090760	100,00%				
	A	1	0,002178	4,43%	0,034447	0,034447	27,32	0,014
	$P \times F$	1	0,008101	16,47%	0,030158	0,030158	23,92	0,016
	$P \times A^2$	1	0,004591	9,34%	0,035113	0,035113	27,85	0,013
d2	$P \times F^2$	1	0,030521	62,07%	0,030521	0,030521	24,21	0,016
	Error	3	0,003782	7,69%	0,003782	0,001261		
	Total	7	0,049174	100,00%				
	A	1	0,002346	6,70%	0,014611	0,014611	50,98	0,019
	F	1	0,014365	41,00%	0,003160	0,003160	11,03	0,080
	$P \times F$	1	0,000406	1,16%	0,006303	0,006303	21,99	0,043
d3	$P \times A^2$	1	0,014397	41,09%	0,015051	0,015051	52,51	0,019

	$P \times F^2$	1	0,002950	8,42%	0,002950	0,002950	10,29	0,085
	Error	2	0,000573	1,64%	0,000573	0,000287		
	Total	7	0,035037	100,00%				
d4	A	1	0,000990	3,11%	0,005728	0,005728	3891,30	0,010
	F	1	0,010296	32,30%	0,012202	0,012202	8290,11	0,007
	$P \times F$	1	0,000552	1,73%	0,004423	0,004423	3005,14	0,012
	$P \times A^2$	1	0,016419	51,51%	0,006773	0,006773	4601,61	0,009
	$P \times A \times F$	1	0,002804	8,80%	0,000615	0,000615	418,13	0,031
	$A^2 \times F$	1	0,000815	2,56%	0,000815	0,000815	553,70	0,027
	Error	1	0,000001	0,00%	0,000001	0,000001		
	Total	7	0,031877	100,00%				

After explaining each column of the ANOVA table, we get more in the details of it. The first thing we have to mention is the small value of the error for the four distances. A small error means that the majority of the variation is due to the parameters as they are the ones who contribute the most on our results. It also seems that the power of the welding and the frequency are the ones that affects the most the variation in d1 and d2. This also can be shown by the contribution percentage as we can see for d1 the majority of the variation is due to $P \times F^2$ as it has a contribution of 60.99% and $P \times F$ also contribute to the variation of d1 by 16.84%. The same observation can be seen on d2 as the same parameters affect this distance with a contribution of 62.07% for $P \times F^2$ and 16.47% for $P \times F$. For d3 it is a bit different as the frequency and the interaction between it and the amplitude plays a big role in the variation of this distance. In fact, the both frequency and the interaction frequency-amplitude contribute for a little bit over 40% in the variation. The distance that we defined as the end of the welding has it different. In fact, being the distance with the highest variation as we can see in Table 4 in the presentation of the results, all 3 of the parameters take visible action in the variation. The frequency contributes by 32.30% and the interaction $P \times A^2$ takes 51.51%. This analysis of variance makes it clear that a relationship between the parameters and the outcome exists. In fact, for all the distances and for each parameter, the p-value was smaller than 0.05 which is considered the significance level which means that our statistical results are reliable and the null hypothesis, in this case all the distance are equal to their initial value, can be rejected. The high F-value for the important contributors also implies that the relationship between output and input parameters is expressive. We can conclude by this analysis of variance that the parameters play an important role in the variation of the distances. A better visualization of the results found in this part will be found below on the model analysis and effects study.

2.7.2 Model analysis

The ANOVA analysis being such a powerful statistical method to analyze the data can also present us the regression equation for each distance. This kind of equation is used to find out the relationship between sets of data if it exists [29] and the existence of it has been proven in the analysis of variance in Table 5. The field of modelling is very wide and there are several ways to create models for phenomena or even series of experiments. For the collected data, the multiple linear regression was chosen because it is among the simplest in terms of calculation but presents a good reliability as shown by many researchers who applied it in their works [30, 31]. Data that fits into an equation like the regression one is very helpful to make future prediction possible or even giving indications for past events. The multiple linear regression equations are composed of an output calculated from the input parameters with coefficients calculated by the last mean square method. The model obtained for this study considers three parameters, the laser power, the frequency and the amplitude and the different interactions that appeared on the ANOVA table presented. The models will allow to predict approximations for the variation in distance for future experiments. The generated models are represented below:

$$d1 = 48.13 + 9.61\,A + 0.000016\,PF - 0.001384PA^2 - 2.318 \times 10^{-8}\,PF^2 \qquad (1.1)$$

$$d2 = 51.08 + 7.35\,A + 0.000012\,PF - 0.001060PA^2 - 1.721 \times 10^{-8}\,PF^2 \tag{1.2}$$

$$d3 = 55.578 + 4.789\,A - 0.00371\,F + 0.000006\,PF - 0.000694PA^2 - 6.977 \times 10^{-9}PF^2 \tag{1.3}$$

$$d4 = 59.0206 + 2.7445A - 0.008033F + 3 \times 10^{-6}PF - 0.000424PA^2 - 10^{-6}PAF + 0.001553A^2F \tag{1.4}$$

The interaction between the power and the square frequency cannot be omitted even if the value of the coefficient is small as it appeared to be a key factor in our study. Another important aspect of this model is its standard deviation and the R-squared. Those factors are the ones who can assure that our models are reliable or not. In fact, the R-squared is a statistical measure that represents the proportion of the variance for a dependent variable that is explained by variables in the regression model [32]. The adjusted R-squared is a modified version of R-squared that has been adjusted for the number of predictors in our model. In our study the values of both the R-squared and the adjusted R-squared are pretty high for the majority of the distances. Table 6 presents us the values of those criteria and it appears that for d2, d3, and d4, the R-squared is higher than 0.9 which shows a good reliability of the model and prevents it from overfitting.

Table 2.2.2: R-squared & standard deviation table

Source	Standard deviation	R-squared	R-squared adjusted
d1	0.0635493	86.65%	68.85%
d2	0.0355075	92.31%	82.05%
d3	0.01693	98.36%	94.27%
d4	0.0012132	100%	99.97%

The model presented make it possible also to predict the results for the same level of parameters that we set in our DOE in the previous section. The prediction of the results and the experimental outcome can be both presented in the same graph to compare the precision of our model. This comparison can be seen in Figure 2.7.2. The experimental outcome and the prediction on the same axis and the test number on the other present us the graph of the residual. In our case, we have an error varying between 0.0066 and 0.1861 for the first distance and with a mean error of 0.0979. The same observation can be made for the other distances as we have a mean of 0.0276, 0.1067 and 0.128 respectively for d2, d3 and d4. The maximum error percent is also very low in our case. Those results only reinforce the reliability of the model presented earlier and this can also be seen and demonstrated by the value of the goodness of fitting of our graph.

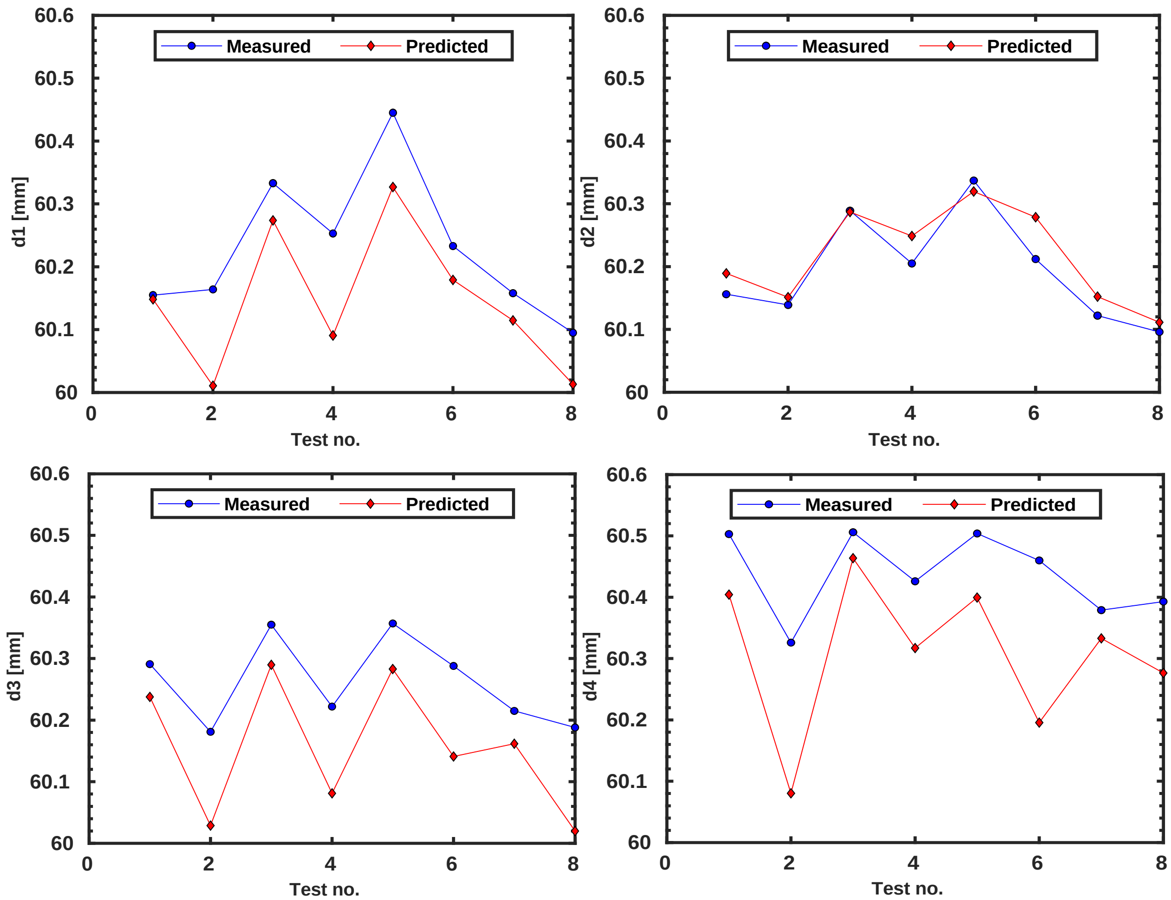

Figure 6: Experimental data vs Predicted value for the distances

2.7.3 Effects plots

To have a better visualization of the results presented in Table 2.7.1-1 for the variance analysis and to see the effects of each parameter on the outcome we required the use of the effects plots on Minitab™ to give a better understanding of the outcome of our study. A main effects plot is a plot of the mean response values at each level of a design parameter or process variable. One can use this plot to compare the relative strength of the effects of various factors. The sign and magnitude of a main effect would tell us the following:

- The sign of a main effect tells us of the direction of the effect, that is, whether the average response value increases or decreases.

- The magnitude tells us of the strength of the effect.[33]

The next figures present us an overview of the effect of the different parameters on the outcome of our study.

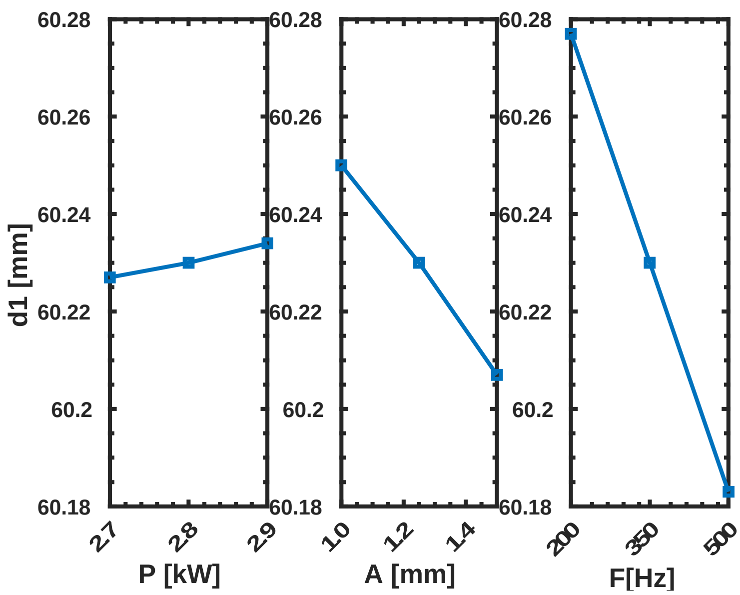

Figure 7: Effects plot for d1

The figure 2.7.3-1 shows us the effect of respectively, the power of the welding, the amplitude and the frequency, on the distance that we set in the beginning of the welding process. From the plot, we can see that a variation of 200 in the power only provoke a variation smaller than 0.02 of the distance. In other words, an increase of the power increases the distance. The amplitude and frequency are different, and their variation is more important on the outcome. The more both of those parameters increase, the more our distance have a small value. In fact, an increase of 0.5 of the amplitude knows a regression of the distance from 60.25 to 60.2. It also appears on the figure that the frequency effect plot is stepper, in fact the distance goes from 60.275 to 60.18 for a frequency that increases by 300. From this observation we can clearly see that the two main parameters that affects the distance are the amplitude and the frequency.

The results of the effects for the other three distances are presented in figure 2.7.3-2 and the same observation can be made. The main parameters that affect the outcome are both the frequency and the amplitude of the welding. When the frequency goes up from 200 to 500, the distance goes from 60.225 to 60.16, from 60.305 to 60.22 and from 60.475 to 60.4 for respectively d2, d3 and d4. The amplitude also plays an important role in the variation of the outcome as it always affects the distance by at least 0.05 each time. On another hand, the power of the welding is the weakest parameter of the variation of the distance is it affects it by 0.01 or not at all for some cases like d3. Note that for this study of the effect plots the mean of the data is the one considered in the calculation of the variation.

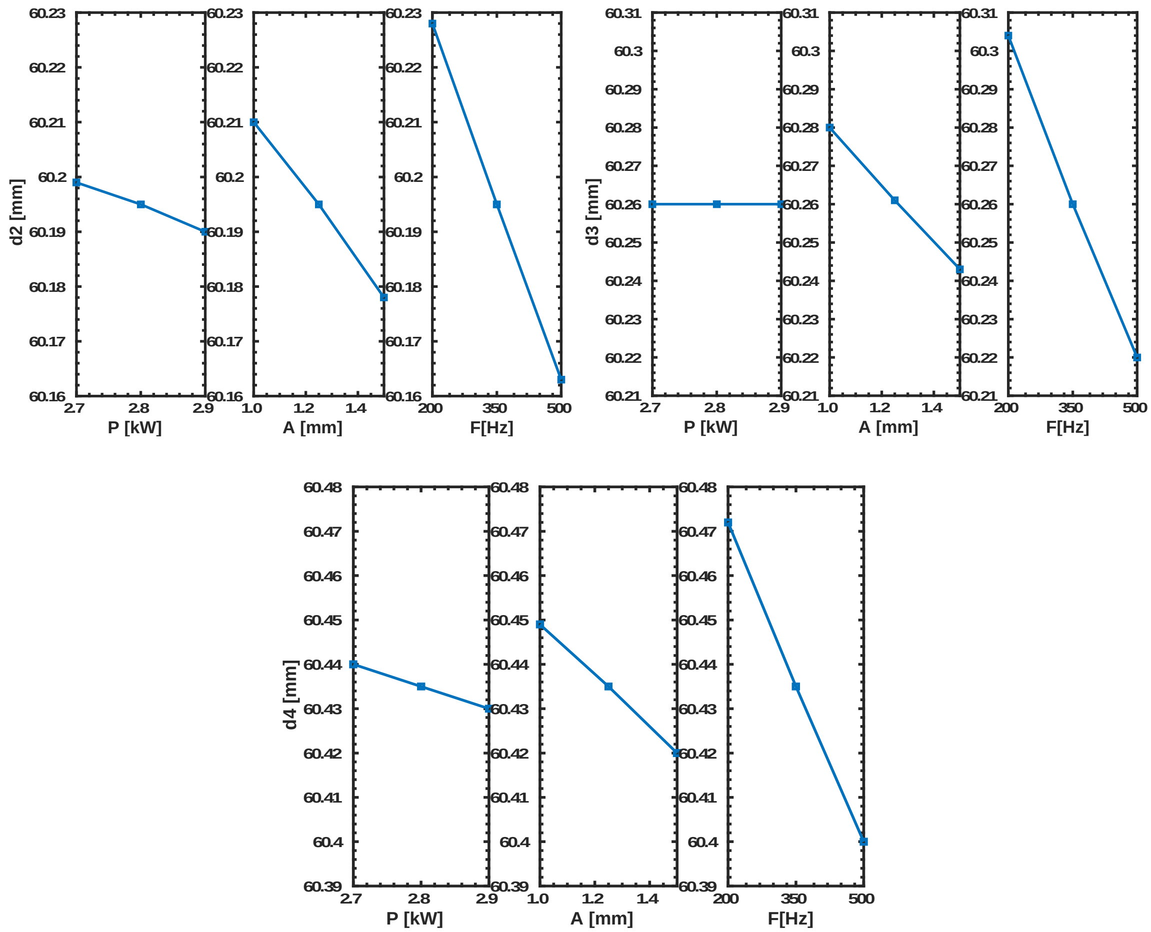

Figure 8-2: Effects plots for d2, d3 and d4

2.7.4 Response surface method

RSM is used for the modeling and analysis of problems in which a response of interest is influenced by several variables, with the objective of optimizing this response, CCDs are among the principal RSMs used in experimental design [34]. The RSM is also presented in this study as it is a powerful tool to come out with deductions and conclusions from the results acquired from the different processes. RSM creates contour plots that give a clear idea of the effects of the parameters on the outcome and can help us to optimize the results and avoid some critical points where the outcome can be largely outside of the requirements that we have settled for different studies. This method is one of the best to predict values in the welding field compared to other methods [35]. The response surfaces are plotted by maintaining the value of a factor at a level and variate the other factors to see the response of the outcome. The main objective of this study is to try to have a distance that is very close to 60.5mm because we used a 0.5mm spacer to have better welding results. According to Figure 2.7.4-1 for the distance d1 the best results would be acquired for a hold value of 1.25 for the amplitude are when the frequency is outside of the interval 250Hz and 450 Hz without giving an importance to the welding power value. The same goes for the value of the amplitude as it is not important if the frequency value is greater than 450Hz or smaller than 250 and that for a hold value of 2800kW of the power.

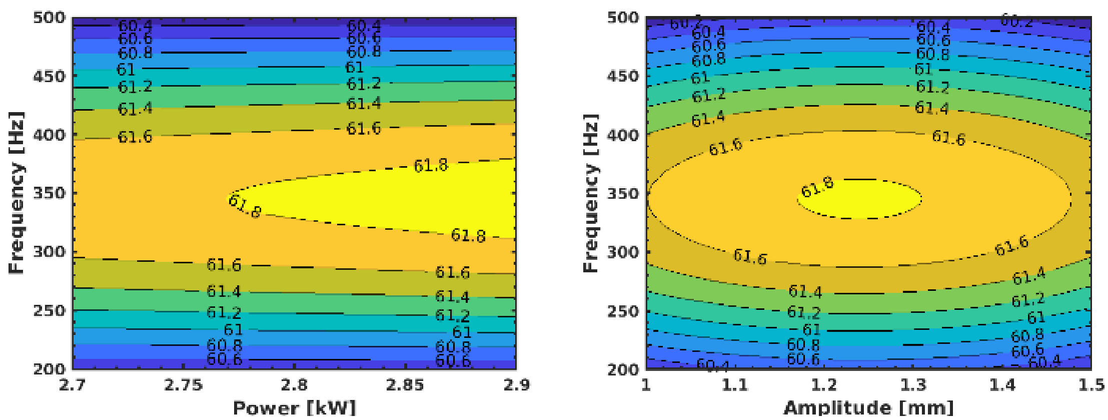

Figure 2.7.4-1: Response surface for d1

The exact same observation can be made for the surface response of the distance d2 and d3. In fact, for a hold value of 2800kW of the power there are critical values for the amplitude and the frequency that we should avoid getting the results we are aiming for. Those critical values are an amplitude level between 1.1 and 1.4 and a frequency level bounded by 250 and 450. Those observations can be seen in Figure 2.7.4-2 and Figure 2.7.4-3 below which represents the response surface for d2 and d3. This means that a higher frequency or a very low one can help us to have a better outcome for the distance and meet the requirements.

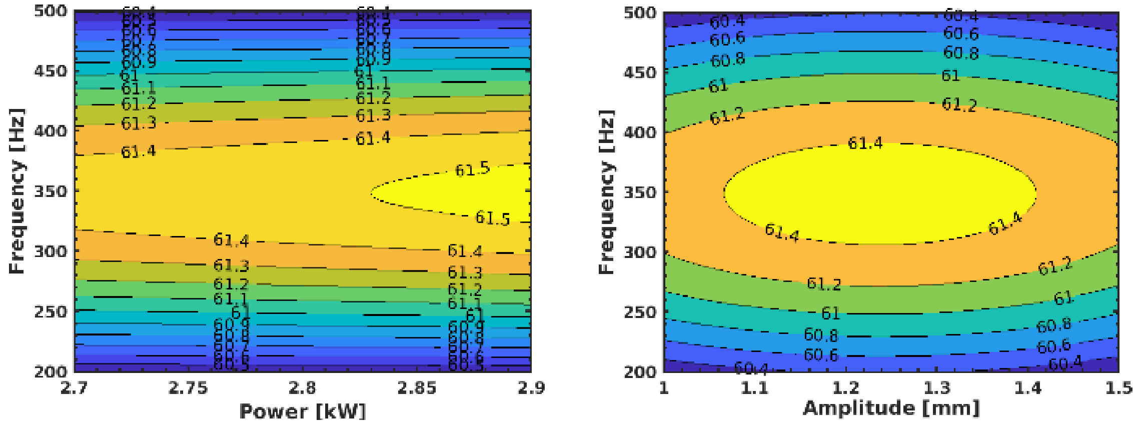

Figure 2.7.4-2: Response surface for d2

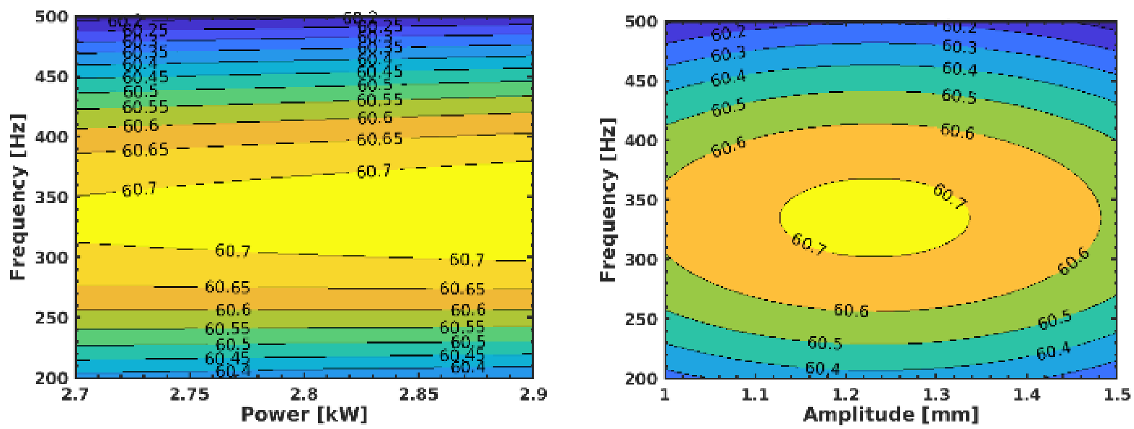

Figure 2.7.4-3: Response surface for d3

The last distance d4 has it different. It is clear that a variation in the first distances will also affect the last one the three factors should be taken into consideration in the observation of the response surface plots. In fact, from a first view the plots appear to be very different from the ones presented earlier. When the frequency is held at 350Hz, the combination amplitude and power don't play a big role as the value of the distance always meets the requirements and is always near our requirement value of 60.5. For A hold value of 1.25A for the amplitude the requirements are met when the frequency is greater for a power lower than 2820kW. For a higher power, the frequency can go down to 200Hz without exceeding the tolerance zone. Holding the value of the welding power to 2800kW opens the possibility for a lot of combination. In fact, as long as the value of the amplitude is near of 1.2 for a 200Hz frequency, the majority of the outcome for the distance meet the requirement. This can be presented in Figure 2.7.4-4 in the contour plots for d4.

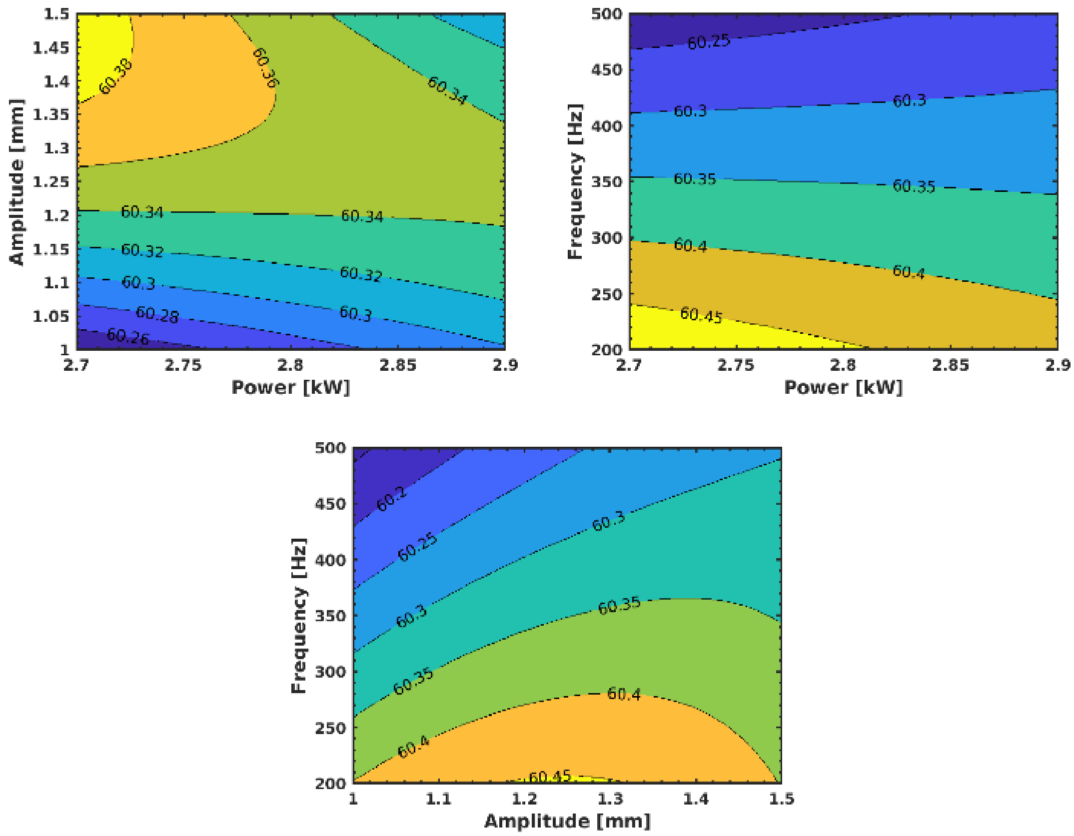

Figure 2.7.4-4: Response surface for d4

2.7.5 Discussion

The results acquired from the scan and the statistical analysis made in the previous sections show us a clear variation in the distances. This variation is also not equal for the four distances as it appears to be greater the further we move in the welding. In fact, it is commonly known for two pieces to move towards each other during the welding but, this movement can cause the rest of the pieces to tilt away from each other. This remark can also be seen in Figure 2.7.5 as the mean of the distances is presented. It is clear that d4 has a mean that exceeds the maximum value of the three first distances. This observation can be really powerful as we can be able to set a goal value for the distances before the welding and adapt the process of experiment to be able to get more precise values and more predictable ones. Using all those techniques and the information gathered earlier the outcome of the laser welding process for this aluminum alloy can be very predictable with a high reliability.

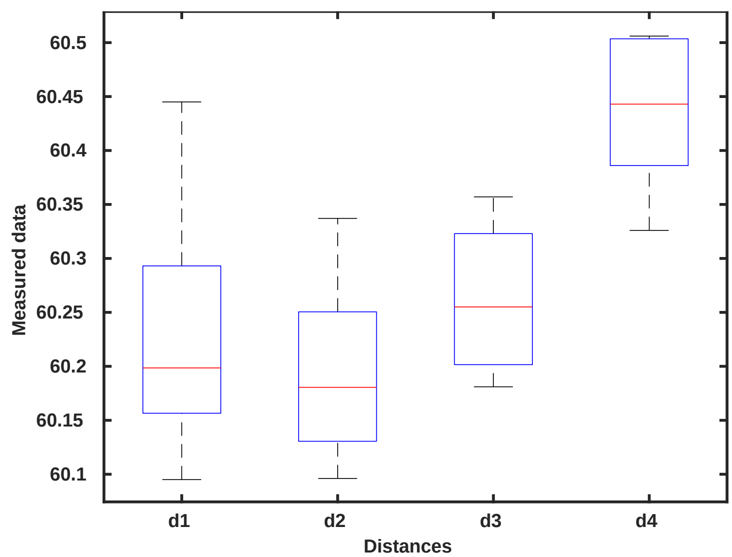

Figure 2.7.5: Mean comparison of the distances

2.8 Effect of the parameters on the angle

In the same vision of the study of the effects of the parameters, we had to discuss and calculate the variation of the angle $\alpha 1$ that we presented earlier in this study. This criteria represents the angle between the two welded parts. Studies showed that the laser welding process usually causes angular distortion on welded parts [36]. This angle distortion is crucial in many fields and cannot be omitted as some assemblies require extreme precision and a small variation of the plane surface can highly affect the outcome.

2.8.1 ANOVA results

As for the distances, we applied the ANOVA method on the results of the angle for our experiments to try to visualize the effects of the parameters on the angular distortion. The table below present us the variance analysis for the angle. The main factors for the angle are the interaction between the power of the welding, the amplitude, and the frequency. The term $P \times A \times F$ has a contribution of 56.60% on the outcome angle. The frequency has a 17.38% contribution, and the interaction amplitude-frequency sits just below with a 12.38 percentage. The contribution of the error is also small which leaves the majority of the variation of the outcome to the parameters of the experiment. The small p-value in this case always lower than 0.05 which shows that the analysis is reliable help us to omit the null hypothesis for the angle. The high F-value for the important contributors also implies that the relationship between output and input parameters is expressive. We can conclude by this analysis of variance that the parameters play an important role in the variation of the distances. A better visualization of the results found in this part will be found below on the model analysis and effects study.

Table 2.3.1: Analysis of variance for the angle

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
$\boldsymbol{F}$	1	0,27710	17,38%	0,8044	0,80441	12,23	0,040
$\boldsymbol{P \times F}$	1	0,02018	1,27%	0,8168	0,81682	12,41	0,039
$\boldsymbol{A \times F}$	1	0,19738	12,38%	0,8717	0,87166	13,25	0,036
$\boldsymbol{P \times A \times F}$	1	0,90267	56,60%	0,9027	0,90267	13,72	0,034
Error	3	0,19738	12,38%	0,1974	0,06579		
Total	7	1,59471	100,00%				

2.8.2 Model analysis

In the same optic as the work presented for the distances, we used the software Minitab™ to extract the regression equation from the ANOVA method to have a better understanding of the effects of the parameters on the distance and to be able to predict approximative results for future experiments. The alliance between parameters and outcome being proved in the previous section, the model needs to be quantified now. The regression equation for the angle α1 is presented below, and it appears that the three welding parameters play a role on this model. As we can see, the welding power, the frequency and the amplitude affect our model in different ways. An interaction between those parameters is also present

$$\alpha 1 = 180.774 + 0.119F - 0.000043\mathrm{PF} - 0.0971\mathrm{AF} + 0.000035\mathrm{PAF} \qquad (2.8.2)$$

For this model, the standard deviation has a value of 0.256 and the R-squared is high (0.876) which shows a good reliability of the model and prevent it from overfitting just like it was the case for the distances. The figure below presents us a quick comparison between the acquired data and the prediction values based on the model. In the case of the angle, we have an error that varies between 0.15 and 0.9 degree for a 0.53 mean. These values show that we have an interesting model to predict the future outcomes.

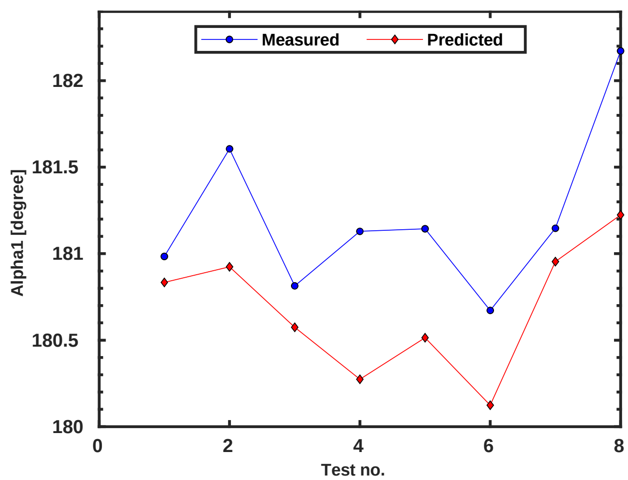

Figure 2.8.2: Measured data vs predicted value for the angle

2.8.3 Effect plots

The next step after the regression model is the presentation of the effects plots for the angle α1 to be able to visualize the variation of the outcome with the variation of the parameters. From the results shown in Table 4, the variation of the angle is very clear as all the parts knew an angle that gained at least one degree which shows us the importance of the parameters on the outcome. The figure shown below (Figure 4.3.1) present us the effect plot of the various parameters. From a first view it already appears that the effects of the parameters are different compared to the distances effects plots as all three parameters show a steep plot of effects. In fact, for a variation of 200 of the power of welding (from 2700kw to 2900kw) the angle increases by approximately 0.2 degree. The same observation can be made for the effect of the amplitude as the angle increases by a little bit over 0.2 degree in this case. The frequency remains again the most important factor, as it also appeared on the previous section for the distances, for an increase of 300Hz for the frequency, the value of the angle α1 rises by approximately 0.4 degree. This study shows that a positive variation of the parameters causes a positive variation of the outcome.

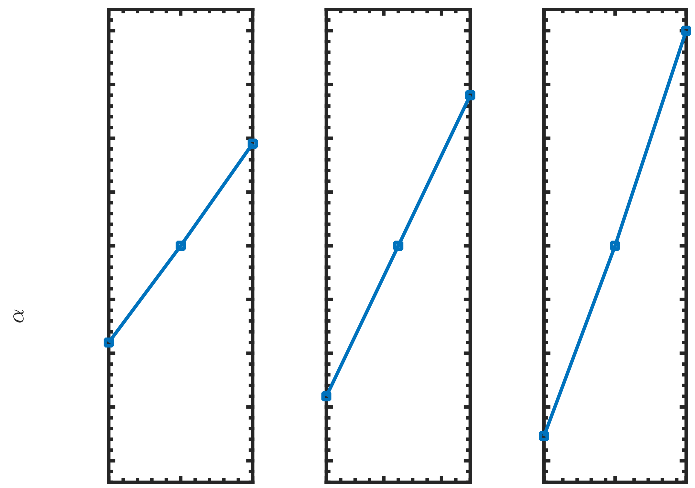

Figure 2.8.3: Effects plots for the angle

2.8.4 Response surface method

In this study, we also required the use of the response surface method to have a better visualization of the effects of the parameters on the outcome. The results presented in the previous sections showed that the effect of the parameters is different for the angle compared to the outcome found on the distances earlier. In fact, the three parameters amplitude, power and frequency play an important role in the variation of the angle as it appeared in the presentation of the model and the regression equation shown in the previous section. The response surface for the angle is a bit more complex than the ones presented for the distances as the three parameters are here way more effective on the outcome. This RSM is presented in Figure 2.8.4 below. The requirement for this study is an angle $\alpha 1$ really near 180 degrees to have a perfect welding. The hold values for the parameters are 350Hz, 2.8kW and 1.25mm for respectively the frequency, the power and the amplitude. From the contour plots we can see that for a hold value of 350Hz for the frequency we can get the needed results for a combination of high amplitude-low power or low amplitude-high power. On the other hand, for a hold value of 1.25 of the amplitude or 2800 of the power, a combination of high frequency with low value of the other parameter give an outcome that is included in the tolerance.

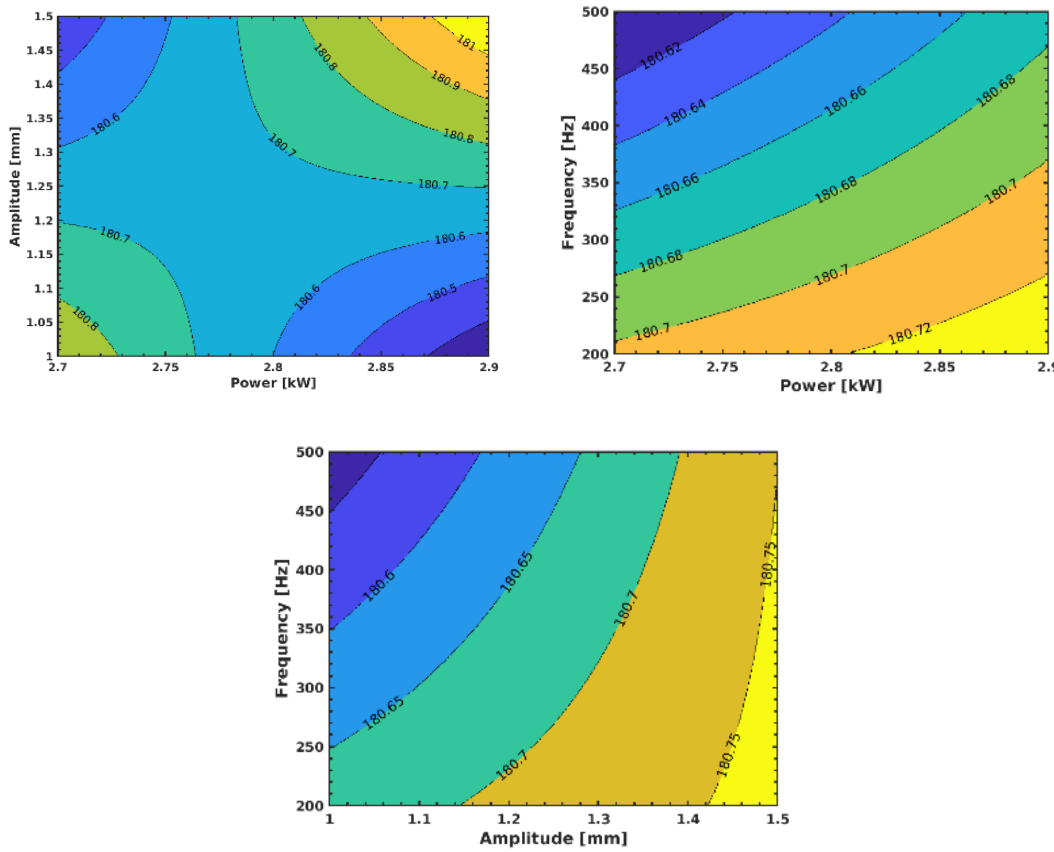

Figure 2.8.4: Response surface method of the angle

2.9 Conclusion

The main objective of this study was to be able to create a predictive model for the welding process of aluminium alloy 5052-H32. We performed welding test based on the Taguchi method for the design of the experiment and we used a CMM to inspect the welded parts. From the results it was clear that we had a variation in the distances and the angle. We then used the ANOVA method to be able to visualize and present the effects of the parameters on the outcome. We also created a model for each outcome to be able to understand previous experiments and predict future ones. The models presented had an absolute error value that didn't exceed 0.13 mm for the distances and 0.9 degree for the angle which show us the reliability and the strength of the models. The results found in this study are crucial in our exploration and research for the 4.0 maintenance. This study aims to be a step toward the predictive maintenance and open new possibilities for the future like its implementation with industry 4.0 and artificial intelligence.

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CHAPITRE 3
UNE NOUVELLE APPROCHE POUR MESURER LA PLANÉITÉ DES PIÈCES SOUDÉES AU LASER SUR MESURE EN UTILISANT DES TECHNIQUES DE BALAYAGE 3D

I. Houban[1], N. Barka[1] and S. S. Kanganroudi[1]

University of Quebec at Rimouski, Rimouski (Qc), Canada

3.1 **Résumé** en français du troisième article

Plus léger et plus résistant à la corrosion par rapport à d’autres alliages métalliques, l’utilisation d’un alliage d’aluminium permet de réduire la consommation d’énergie et de fournir un véhicule plus durable pour l’industrie automobile et même l’industrie navale où l’alliage d’aluminium 5052-H32 est présent dans différentes pièces. Mais le soudage de l'alliage d'aluminium reste un réel problème en raison de sa conductivité thermique élevée, de son faible point de fusion ainsi que de sa grande réflexivité. Cependant, une technique innovante telle que l'oscillation du faisceau laser est proposée pour surmonter ces difficultés en distribuant la grande quantité l'énergie du laser requise pour le soudage de l'aluminium et en limitant les dommages qui pourraient survenir. La puissance du laser, la vitesse et l'amplitude sont étudiées pour évaluer leurs effets sur la planéité à l'aide d'un plan factoriel complet à trois facteurs et à deux niveaux suivi d'une analyse de la variance (ANOVA). Le résultat révèle que l'amplitude possède l'effet le plus influent suivi de la fréquence, et finalement, la puissance du laser. Une augmentation de l'oscillation d'amplitude tend à pousser les pièces l’une loin de l’autre. Une interaction importante est trouvée entre la puissance du laser et le soudage dans les analyses statistique car plus la puissance est grande plus la planéité est importante. Une optimisation utilisant la méthode de surface de réponse à partir des paramètres de soudage a permis de déterminer que la meilleure soudure pouvait

être obtenue par une bonne combinaison des paramètres de soudage en faisant diminuer la puissance et augmenter la vitesse pour ne pas laisser au laser le temps de trop déformer la pièce.

Ce troisième article, intitulé « A new approach to measure flatness of tailor laser welded parts using 3D scanning techniques » fut essentiellement rédigé par son premier auteur Ilyasse Houban qui a également réalisé toutes les expériences et travaux de laboratoires requis pour l'acquisition des données dans les locaux du DMIG de l'Université du Québec à Rimouski, le soudage laser par contre a été fait grâce à l'aide du deuxième et troisième auteur. Le premier auteur a également écrit les parties concernant l'état de l'art ainsi que l'interprétation des résultats à travers des travaux d'inspection géométrique et de traitement de données qui ont abouti aux résultats finaux optimisés. Noureddine Barka est le second auteur de cet article. Il est à l'origine de ce projet de recherche en proposant l'approche et la méthodologie pour aborder la problématique. Il a également contribué à l'amélioration de la rédaction pour la version finale. Le troisième auteur de l'article est Sasan Sattarpanah Karganroudi qui apporté son expertise du domaine d'inspection et soudage laser.

3.2 Titre du troisième article

A new approach to measure flatness of tailor laser welded parts using 3D scanning techniques

3.3 Abstract

Laser welding, a critical joining technique for aluminum alloy, is widely used for fast and precise part welding, as the evolution of the automotive field and the aerospace one require more efficient results in this era. Regarding the importance of the welded parts and its performance, a precise part inspection is required to make sure that the welded pieces match the requirements and are in the tolerance zone. In this study, two same parts of aluminum 5052 H-32 are laser welded using different parameters to see their effect on the flatness. Then after welding, a geometric inspection is made by using a laser scanner that make it possible to acquire all the needed data from the different parts. The results are analyzed using Analysis of Variance (ANOVA) and Response Surface Methodology (RSM) to determine the main effect of process parameters, also the best combination of welding parameters that minimizes

the deviation and the flatness of the part. Results imply that a good joining of the parts must be achieved and the difference between the highest point and the lowest must be minimized. This study provides a good exploration and a complete process from laser welding to inspecting the effect of the different parameters of that joining technique.

3.4 Nomenclature

ANOVA: Analysis of variance

AA: Aluminium alloy

Adj MS: Adjusted mean square

Adj SS: Adjusted sum of squares

CAD: Computer aided design

CMM: Coordinate measuring machine

d: Distance

DF: Degree of freedom

f: Frequency

mm: Millimetre

Mg: Magnesium

MS: Mean square

P: Laser power

R-sq(adj): Adjusted coefficient of determination

R-sq(pred): Predicted coefficient of determination

R-sq: Coefficient of determination

S: Standard deviation

SS: Sum of squares

V: Welding speed

W: Watt

3.5 Introduction

First discovered in 1807, the 13rd element of the periodic table never stopped to amaze. In fact, it is one of the most used metals in industrial processes. Most of it goes into the transport field and the building one with respectively 36% and 26% of all its applications[1]. This high usage of it is mostly explained by the interesting properties of the aluminum in fact it has a good mechanical resistance, corrosion resistance combined with low density[2]. The characteristic properties of aluminum, high strength stiffness to weight ratio, good formability, good corrosion resistance, and recycling potential made it a perfect match to the need of the automotive for a fuel-efficient and long-lasting vehicle [3]. The combination of the aluminum with other materials leads to powerful alloys. Nowadays all components have higher requirements on the performance of materials [4] and to meet those requirements the materials are reinforced and casted with other materials to reach the appropriate properties. Many casting methods to create composite materials exist [5, 6] because the composite materials are a promising solution for improving the performance of the base material [7]. Those combinations open the possibility for the usage of aluminum alloys in many fields with different requirements. It is indeed used in marine, aircrafts, general sheet metal work, heat exchangers, fuel lines and tanks, flooring panels, streetlights, appliances, rivets and wire [8]. The aerospace field mainly uses the 5xxx aluminum alloy (magnesium as principal alloying element) and it is a work hardening alloy [9]. Being as promising of a material as it appears to be, we decided to take this study on sheets of this aluminum alloy. The properties of it also make it clear for our choice of material. Nonetheless, a part alone is not useful in the industrial field. In fact, the next step is the assembly and the aluminum alloy knows some difficulties and restraint at this level of production [10]. Many methods exist and were invented to respond to different needs of assembly, in our case and as it is for the airspace field we are looking for a permanent watertight and non-destructive assembly [11] as this process has a lot of impact on the product quality [12]. The welding method is one of the most commonly used assembly methods for the aluminum alloy and more precisely the laser welding one as the spot welding does not give satisfying results due to the low resistivity of aluminum or MIG which causes high thermal distortion [13]. The laser welding is a modern joining method that made its place very easily as it is one of the most efficient and reliable assembly methods. It is also so versatile as its parameters open many doors for its applications, a small change in the speed or the power of the welding can lead to very different outcomes [14]. It is in fact very different from other fusion welding techniques both from an operation and an equipment standing point. From its term, this method uses a laser beam to join parts together and for our experimentation we are going for a butt joint welding. Although it is very effective, the high reflexivity and the conductivity of the aluminum makes it a challenge to use this type of welding, as a lot of energy would be required due to the dissipation caused by the material properties [15, 16]. The introduction of the oscillation of the laser beam really changed the way laser welding has been used. This comes as a result of the limitation of the heat generated due to energy distribution [17] and a limitation of alloying elements loss[18].

The last step of the manufacturing process is nonetheless than the inspection and more precisely fin our case, the geometric inspection of the part. This step of a part life cycle makes it possible to compare the manufacturing result with its CAD model. It can be divided into two sections, contact inspection and non-contact one. Over the past few years, the digital data acquisition devices have been advancing drastically and rapidly such as 3D optic and laser scanners [19, 20] along with the computational calculation developments that made possible the use of Computer-Aided Inspection (CAI) methods. The 3D data acquisition devices make it possible to obtain a set of points, called point clouds, by scanning the surface of the parts during the process of inspection. From the point clouds obtained a scan mesh is generated by scanning the raw data (point clouds), and this process is possible due to mesh smoothing methods as presented by [21, 22]. The objective of the scan mesh is to represent the geometrical shape of the part in the most accurate way with the least required data volume which can be translated to the mesh size. Computer aided inspection methods help to make an automatic time-saving inspection by both applying tolerancing methods and computational meshing tools. Those methods make it possible to compare the Computer-Aided-Design (CAD) model and the scan mesh in a common coordinate system to define the geometrical deviations that appears on the surface of the parts during the manufacturing process. As we direct our work to the industry 4.0, we will be using a laser scanner with a software to process the point clouds, generate a mesh and compare it to the original CAD. The part used for this experimentation is an aluminum alloy 5052-H32 sheet with a very small thickness. This choice was made to match the parts used in the aerospace field.

In this research, an experimental method is adopted, and results are explored using ANOVA to analyze the effect of laser welding parameters on the deviation angle and different distances between features of 5052 H-32 alloy parts. This statistic approach is planned, to perform most precisely yet with the optimum number of tests. This proposed statistical approach is developed in progressive steps. The first step is to prepare an experimental plan and set a design of experimentation of the welding process to get the most interesting results. The second step is to take the welded parts to the metrology lab where we will geometrically inspect them using a laser scanner to extract all the data possible and needed for the ANOVA analysis which will be the last step. Based on ANOVA analysis, Response Surface Methodology (RSM) and main effects of parameters on each result are being extracted. The ANOVA method was chosen for this study as it is so powerful to predict future results and have a better understanding of past events [23] and the RSM is here to present a the relationship between the parameters and the outcome [24]. This study is executed to achieve an optimized combination for the laser welding of alloy 5052 H-32 and also to make it possible for the combination of laser welding with laser inspection, to the author knowledge no study had been found combining both of those techniques. The feasibility and effectiveness of the proposed approach led to an accurate and reliable statistical model for predicting the deviation caused by laser welding. This article is formed as follows: Section 3.6 presents the methodology of our experimental tests based on laser welding and its related parameters with a presentation of the metrology setup used. Results of experimentation, statistical and RSM analyses, and deviation discussions are then reported in section 3.7. In the end, section 3.8 presents conclusions and ideas for future works in this field.

3.6 Experiment procedure

3.6.1 Materials and laser welding process

The laser welding experiments in this study have been performed on aluminium alloy 5052 H-32 that is widely used in the automotive, the aerospace, and the naval industries. It is well known for its corrosion resistance against seawater and salt spray, a high fatigue strength and a good weldability. The chemical composition of aluminium alloy 5052 H-32 and its mechanical characteristics are presented in Tables 1 and 2 respectively. This is done to give a small idea of properties related to laser welding.

Table 3.6.1-1: Aluminum alloy 5052 H-32 chemical composition in wt% [25]

Component	**Al**	**Cr**	**Cu**	**Fe**	**Mg**	**Mn**	**Si**	**Zn**
Content (%)	95.7-97.7	0.15-0.35	0.1	0.4	2.2-2.8	0.1	0.25	0.1

Table 3.6.1-2: Mechanical and thermal properties of Al 5052 H-32[25]

Yield strength (MPa)	**Elongation at break (%)**	**Fatigue strength (MPa)**	**Melting point (°C)**	**Shear Modulus (GPa)**
241	10	131	607-649	25.9

The welding machine is composed by an IPG Photonics YLS-3000 laser source which is Nd:YAG laser with wave length of 1070nm and BIMO High YAG laser head giving a laser focus diameter of 0.45mm. All those welding devices are mounted on a FANUC robot (Figure 3.6.1) which is a mechanical arm because laser welding is a dangerous process that requires the use of an automated workstation [26]. You can also see in Figure 2.1.1 that we used aluminum discs on the parts for the clamping to avoid any deviation caused by the clamps as the force will be on the surface of the disc and not just the contact point between the clamp and the parts.

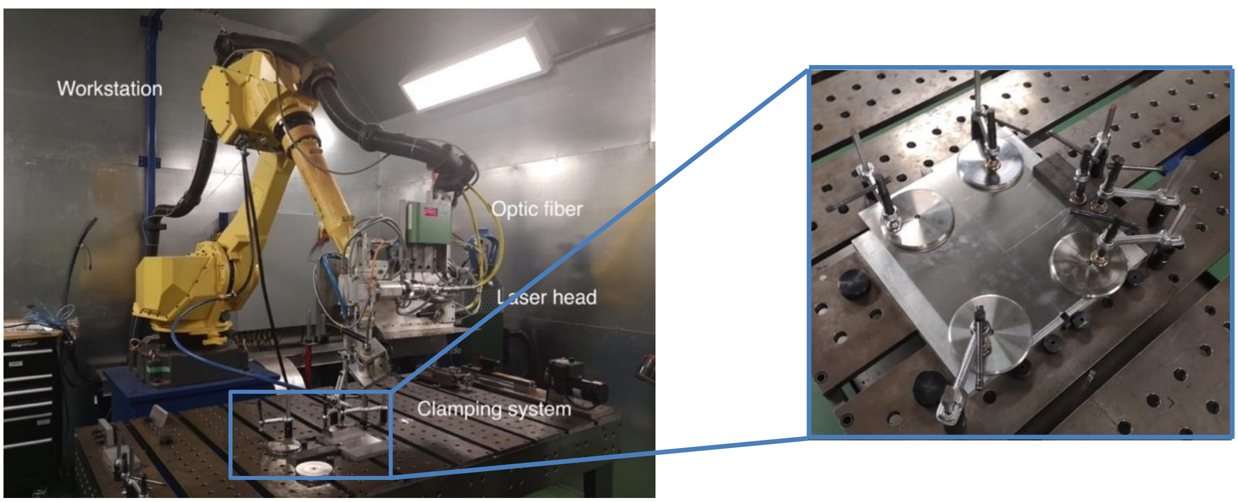

Figure 3.6.1-1: Laser welding machine & clamping system

All the part used in this experiment are made of the Al Alloy 5052 H-32 with identical geometry of 250 by 200 with very small thickness. Those dimensions were chosen to try to match the parts that are used for the aerospace field. Our objective in this study is to visualize and try to predict the flatness error caused by the laser welding process. After welding the parts together, we take them to our metrology lab to measure the different deviations and effects of the welding. To make a great geometric inspection that is a key step in our experiment, we used a non-contact laser scanner as shown in the figure below (Figure 2.1.2).

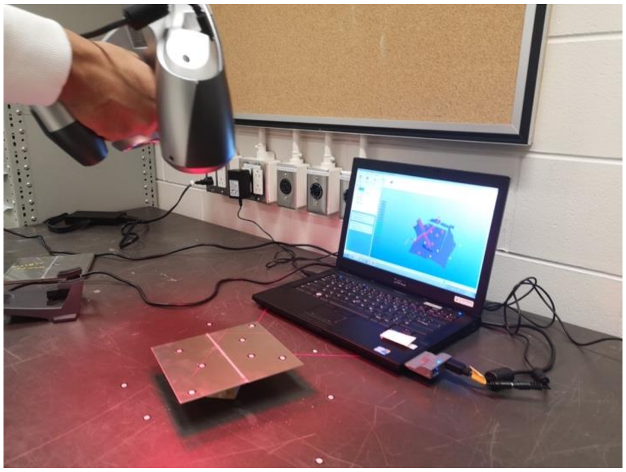

Figure 3.6.1-2: Laser inspection process

3.6.2 Design of experiment

The experiment process for the laser welding followed a pre-designed protocol that was created after some testing on some parts to get the best results. The design of experiment presented below in Table 3 takes as main parameters the power of the welding, the amplitude and the speed. Other parameters like the frequency or the focal diameter are set at one level. We should also note that the parts were all stabilized the same exact way so that the laser beam can hit the same spots for every test. The design of experiment chosen for this study was made following the Taguchi method. In fact, it is a factorial design of three parameters with two levels each which give us an 8 tests study. This factorial design of experiments helps a lot to get better results in fewer experiments [27]. The complete factorial design can also provide the effect of interaction between parameters which is very significant for this study as the considered parameters are related to the characteristics of the laser welding machine as described [28, 29].

Table 3.6.2: Design of experiment and flatness result

Test	Power (W)	Amplitude (mm)	Speed (mm/s)	Flatness error (mm)
1	2000	0.75	30	3.45
2	2000	0.75	40	2.56
3	2000	1	30	5.33
4	2000	1	40	4.82
5	2200	0.75	30	7.18
6	2200	0.75	40	6.41
7	2200	1	30	7.84
8	2200	1	40	6.54

The main objective of this study is to visualize and later be able to predict the flatness error of the parts after welding them. Following this vision, the welded parts are then transferred to the metrology laboratory where they will be scanned with a laser scanner that provide us with a cloud point of the parts. The cloud points are later transformed to a mesh that is also smoothen using a dedicated software before being ready to use and compared with the CAD model of the parts. The scan mesh and the CAD are then both loaded into *GOM Inspect*™ to inspect them and extract the results. The two meshes are aligned in a first step using different algorithms then the comparison of the surfaces is computed. Note that for this study we omitted 50mm in the length and in the width in this computation so that we can avoid taking in consideration the borders effect of the welding that can give us unreliable results. The flatness error for each test is presented in Table 3.6.2-1. Note that for this study we excluded 3mm from each side to avoid the borders effect of the laser scanning process.

From a first view the variation seems pretty important for each part. This opens up many fields of discussion to see how each parameter affects our outcome. A statistical analysis is made in the next section to visualize clearly the effects and represent the variations with plots and model equation to be able to predict future outcomes and give a better understanding of past ones.

3.7 Statistical analysis

Collecting the data from the outcome is actually only the first step of our study. In fact now, the task is to discover hidden patterns in this data to try to predict future outcomes. This all lies under the name of predictive maintenance. As it already appears, the flatness error is quite important but we cannot stop and rely all our study on that. From the different statistical methods that exists and from our goal for this study, we chose the ANOVA method.

3.7.1 ANOVA results

To get deep down into the relation between the variables within the experiment, we required the use of an ANOVA method which is as explained earlier related to the variance. And more precisely the stepwise method is the one used in this study using Minitab™. This method starts with an empty model or includes the terms we specified to include in the initial model or in every model. Then, Minitab™ adds or removes a term for each step. We can specify terms to include in the initial model or to force into every model. Minitab™ stops when all variables not in the model have p-values that are greater than the specified [30]. Using Minitab™, we performed a stepwise regression for the analysis of the variance, and we were able to extract the statistical table below. Our goal with this analysis is to compute and visualize the effects of the parameters on the flatness. Being the difference between the highest point and the lowest one, it is very clear from table 4 that the variation of the flatness is important and might be related to the parameters. The first step of this analysis is the ANOVA table that present the sources for each distances and those are the affecting parameters, The degrees of freedom (df) which is the number of independent variables in our regression model it's also the amount of information in our data. The sequential sums (Seq

SS) of squares are measures of variation for different components of the model it is also used to calculate the p-value for a term. It also depends on the order of the terms that are entered into the model. The contribution is as clear as the name and it displays the percentage that each source in the variance analysis table contribute to the total sequential sum of squares [30] . The adjusted sum of squares is the same as the sequential one, but the order is not important. Adjusted mean squares measure how much variation a term or a model explains, assuming that all other terms are in the model, regardless of the order they were entered. Unlike the adjusted sums of squares, the adjusted mean squares consider the degrees of freedom. The F-value is the test statistic used to determine whether the term is associated with the response. And The p-value is a probability that measures the evidence against the null hypothesis [31]. Lower probabilities provide stronger evidence against the null hypothesis in this case the null hypothesis would be that the flatness is null. The results of the variance analysis for the flatness of the parts in this study are presented in Table 5 below.

Table 3.7.1: ANOVA results

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-value	P-value
P	1	17,4345	74.05%	17.435	17.435	44.55	0.003
S	1	1,5051	6.40%	1.5051	1.5051	3.85	0.121
A	1	3,0381	12.90%	3.038	3.038	7.76	0.049
Error	4	1,565	6.65%	1.5625	0.3913		
Total	7	23,5430	100%				

From the table it is clear that the laser welding power plays a major goal in the outcome parameter. In fact, it has a contribution of 74.05%, higher than any other parameter. The P-value of the power is also very low (0.003) which assures us of the reliability of the study. Next to that, the amplitude contributes on the outcome with 12.9%, with a P-value that meets the requirement to omit the null hypothesis. The speed parameter has it a bit different as the contribution is a bit lower 6.4% and a P-value of 0.121. As this is an initial study and a discovery one, we are still taking into consideration the speed in our model. The error has 4 degrees of freedom and a contribution of 6.65%. The high F-value for the important contributors also implies that the relationship between output and input parameters is expressive. We can conclude by this analysis of variance that the parameters play an important role in the variation of the distances. A better visualization of the results found in this part will be found below on the model analysis and effects study.

3.7.2 Model presentation

The ANOVA analysis being such a powerful statistical method to analyze the data can also present us the regression equation for each distance. This kind of equation is used to find out the relationship between sets of data if it exists [32] and the existence of it has been proven in the analysis of variance in Table 3.7.1. The field of modelling is very wide and there are several ways to create models for phenomena or even series of experiments. For the collected data, the multiple linear regression was chosen because it is among the simplest in terms of calculation but presents a good reliability as shown by many researchers who applied it their works[33, 34]. Data that fits into an equation like the regression one is very helpful to make future prediction possible or even giving indications for past events. The multiple linear regression equations are composed of an output calculated from the input parameters with coefficients calculated by the last mean square method. The model obtained for this study considers three parameters, the laser power, the speed and the amplitude of the laser beam. The model will allow us to predict approximations for the variation in flatness for future experiments. The generated model is represented below:

$$F = -26{,}76 + 0{,}01476 \times P - 0{,}0867 \times S + 4{,}93 \times A \qquad (1)$$

From the equation it appears to be quite a simple model without interactions between the parameters and that is exactly what we were seeking in this paper. This model is an initial step in the way of predicting future results and have a better understanding of past applications of the laser welding process. We also present the R-squared and the standard deviation in Table 6 below to show the strength of the model found.

Table 3.7.2: R-squared & standard deviation table

Source	Standard deviation	R-squared	R-squared adjusted
Flatness	0.62555	93.35%	88.37%

Another important aspect of this model is its standard deviation and the R-squared. Those factors are the ones who can assure that our models are reliable or not. In fact the R-squared is a statistical measure that represents the proportion of the variance for a dependent variable that's explained by variables in the regression model [35]. The adjusted R-squared is a modified version of R-squared that has been adjusted for the number of predictors in our model. In our study the values of both of the R-squared and the adjusted R-squared are high. Those results show a good reliability of the model and prevent it from overfitting.

3.7.3 Main effects and RSM

To better visualize the effect of the parameters on the flatness of the parts and to give a better understanding of the results found on Table 3.7.2 after the analysis of the variance we required the use of effect plots on Minitab™. A main effects plot is a plot of the mean response values at each level of a design parameter or process variable. One can use this plot to compare the relative strength of the effects of various factors. The next figure (Figure 3.7.3-1) presents us an overview of the effect of the different parameters on the outcome of our study.

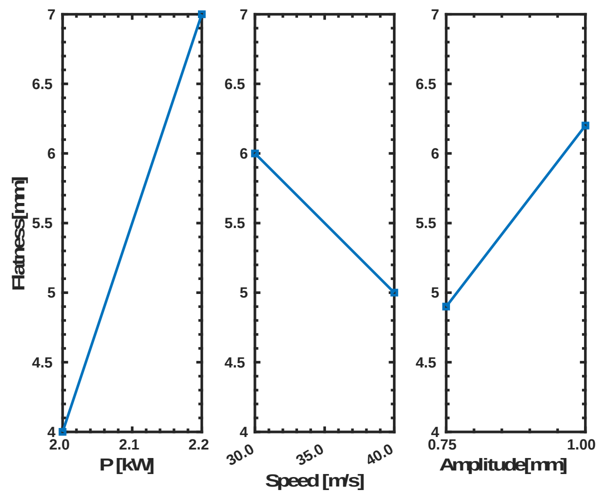

Figure 3.7.3-1: Effects plot of the flatness

The plots show a clear representation of the effects of the parameters on the flatness. The main observation we can make is that the power is the parameter with the most influence on the outcome. The flatness goes up from 4mm to 7mm for an increase of 200W of the laser welding power. The outcome follows also the amplitude. The increase of this parameter tends to increase the value of the flatness. In fact, for an amplitude of 0.75mm the outcome is at 4.9mm and it goes up to 6.2mm for an increase of 0.25mm of the amplitude. The speed of the laser welding process has it a bit different as the greater the speed, the lower the flatness. This can be explained by the fact that the laser beam doesn’t spend as much time on each part of the aluminum sheet which lowers the distribution of energy into the part. Number wise, the flatness goes down from 6mm to 5mm for a speed that goes up form 30mm/s to 40mm/s. Those plots and numbers can only strengthen our study as they came to confirm the results found on the statistical analysis.

Moving forward into the study, we required the use of the response surface method to have a better understanding of the outcome and prepare ourselves for future application of the laser welding process. RSM is used for the modeling and analysis of problems in which a response of interest is influenced by several variables, with the objective of optimizing this response, CCDs are among the principal RSMs used in experimental design [36]. The RSM is also presented in this study as it is a powerful tool to come out with deductions and conclusions from the results acquired from the different processes. RSM creates contour plots that give a clear idea of the effects of the parameters on the outcome and can help us to optimize the results and avoid some critical points where the outcome can be largely outside of the requirements that we have settled for different studies. This method is one of the best to predict values in the welding field compared to other methods [37]. The response surfaces are plotted by maintaining the value of a factor at a level and variate the other factors to see the response of the outcome. The main objective of laser welding process for this kind of parts is to lower the flatness as much as possible and this is what we will be looking for while studying the RSM of this paper. Note that for the hold value of each parameter we took the mean of it as we only have two levels for each parameter as a result of the application of the Taguchi method for the design of experiment and that is presented in the previous section.

The figure below (Figure 3.7.3-2) presents the different RSMs of this study. It is clear that the higher the amplitude and the welding power, the greater the flatness. Those results come to confirm the study down earlier. To get to a desired low flatness, the combination of high speed, low amplitude and low power is required. This can be explained by the fact that the higher the speed, the lower the distribution of the energy will be on the part. And a high power and amplitude means that more energy is generated and applied to the part and makes the deformation caused by the laser welding process higher.

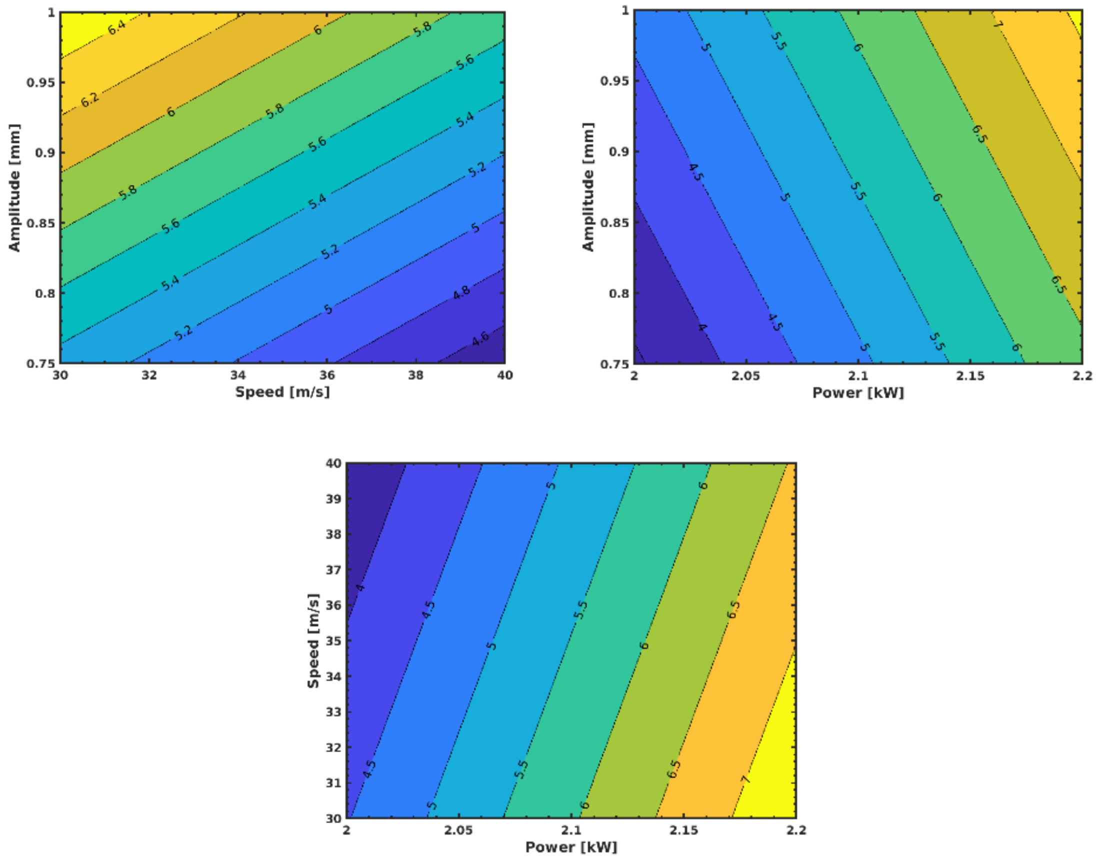

Figure 3.7.3-2: Response surface of the flatness

3.8 Conclusion

The main objective of this study was to be able to create a predictive model for the flatness variation of aluminum alloy parts that are laser welded. We performed welding test based on the Taguchi method for the design of the experiment and we used a laser scanner to inspect the welded parts. From the results it was clear that we had a variation in the distances and the angle. We then used the ANOVA method to be able to visualize and present the effects of the parameters on the outcome. We also created a model for each outcome to be able to understand previous experiments and predict future ones. From the statistical analysis, we found a strong model that seems reliable. This study is a step forward the predictive maintenance and opens new possibilities in laser welding process and laser inspection.

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CONCLUSION GÉNÉRALE

Pour améliorer les procédés de soudage laser et d'inspection géométrique des pièces, cette recherche propose de nouvelles approches combinant des ordinateurs et des analyses statistiques. En ce sens, des études approfondies ont été faites concernant les différentes techniques d'inspection géométrique et l'efficacité du soudage laser comme méthode d'assemblage. Pour y arriver, le premier objectif était principalement focalisé sur l'exploration des différentes méthodes d'inspection. Il était question de mettre en évidences les avancements et les travaux effectués dans ce domaine. Cette première étape avait pour but d'avoir une idée claire et nette des directions que nos études et nos recherches peuvent prendre. Le second objectif était destiné à voir l'effet des paramètres de soudages sur des alliages d'aluminium épais et inspecter cet assemblage grâce à un CMM. Pour cela, il était important de connaître l'effet des paramètres sur le procédé et de trouver un modèle de prédiction pour pouvoir améliorer le procédé. Les travaux d'optimisation ont permis de trouver les valeurs de paramètres qui permettent d'avoir la meilleure soudure avec les meilleures propriétés mécaniques. Le troisième objectif visait à étudier la planéité de plaques en alliage 5052-H32 suite à leur assemblage post-soudage et les inspecter avec un scanner laser. Pour atteindre tous ces objectifs, l'étude a été divisée en trois phases dont chacune avait pour dessein de faire avancer la recherche, pour accéder aux buts fixés liés aux problématiques. De telle manière que, les deux techniques d'inspection, avec contact et sans-contact, seront étudiées en les combinant chacune avec le soudage laser pour faire en sorte que notre étude touche le processus de fabrication/assemblage et celui de l'inspection/maintenance.

La première phase de cette étude avait pour but de regrouper tous les travaux précédents et les méthodes développées dans le domaine de l'inspection géométrique des pièces et cela sous forme d'une revue de littérature. Dans cette partie du mémoire, les différentes méthodes d'inspection, avec contact (CMM fixe) et sans-contact (scanner laser) sont présentées. Les différents avancements de ce domaine de maintenance et prévention sont aussi présents dans ce premier chapitre. L'implémentation des ordinateurs et de méthodes assistées par ordinateur fait aussi part de cette recherche. En effet, on peut trouver des parties dédiées à l'inspection 4.0, puis d'autres pour l'inspection assistée par ordinateur qui montrent comme ce domaine a évolué avec le temps pour répondre à des attentes élevées de la part des processus de fabrication et d'assemblage de pièces qui diffèrent d'un domaine à un autre. Cette révolution, étant l'une des plus importantes dans le monde de l'industrie, s'avère essentielle à prendre part dans notre recherche littéraire. Cette phase est essentielle dans notre travail de recherche car elle nous a permis de mieux diriger nos travaux et avoir une idée des résultats futurs que l'on peut avoir.

La seconde phase de l'étude avait pour but d'optimiser le soudage d'alliage d'aluminium 5052-H32 en vue de son inspection avec un CMM. Dans cette partie du mémoire, des plaques de 4,16 mm d'épaisseur avec des trous ont été soudées au laser suivant un plan d'expérience factoriel complet pour englober toutes les variations possibles des paramètres qui sont la puissance de soudage, l'amplitude ainsi que la fréquence et observer les effets des interactions. L'analyse des résultats sollicitent l'utilisation d'outils comme l'ANOVA qui a permis de déduire l'impact des paramètres sur la variation des distances et de l'angle suite à la soudure. Les résultats ont montré que l'amplitude est le paramètre le plus influent plus que la fréquence et la puissance du laser. Néanmoins, les analyses ont montré qu'il existe une interaction importante entre la fréquence et la puissance du faisceau. Une des manières de quantifier cette interaction est de voir son effet sur les distances entre les trous et l'angle entre les pièces assemblées. Une surface de réponse a donc été réalisée en tenant compte de ces déformations. L'optimisation a permis de conclure que pour avoir une bonne soudure sans causer trop de déformations, une interaction haute fréquence et basse puissance est nécessaire. En ce qui concerne l'amplitude, quand cette dernière est élevée on se doit d'avoir une basse puissance et vice-versa. Cette étude a permis de mettre en place un modèle de prévision et prévention du processus de soudage laser et son effet sur la variation des distances et de l'angle pour des pièces plutôt épaisses comme celles utilisées dans le domaine naval. Le modèle mis en place est plutôt robuste et précis comme le montre la comparaison des résultats réels avec les résultats prédits par le polynôme présenté dans ce chapitre.

La dernière phase de cette étude porte sur l'effet des paramètres de soudage sur la planéité de plaques en aluminium 5052-H32 suite à une inspection faite avec un scanner laser sans-contact. Dans cette partie, on a étudié les effets des paramètres tels que la vitesse de soudage, la puissance du laser et l'amplitude. Un plan d'expérience basé sur la méthode Taguchi a été établi donnant un plan factoriel pour l'expérience. Les résultats d'analyses montrent une grande influence de la puissance de soudage sur la planéité. L'étude montre aussi que pour avoir une bonne soudure sans trop de déformations, il faudrait baisser la valeur de la puissance pour une vitesse plus importante. Un modèle de prédiction de la planéité des pièces soudées a été développé pour approximer la valeur de cette sortie à partir des paramètres admis à l'aide de la méthode de régression. D'ailleurs, la méthode de la surface de réponse a montré plus en détail l'effet des paramètres sur la planéité des pièces. Les résultats ont conclu que les meilleurs paramètres de soudage au laser d'alliages 5052-H32 pour minimiser la planéité sont une puissance de 2100W, une amplitude de 0.8mm et une vitesse de 40mm/s.

Cette étude constitue une nouvelle découverte et propose de nouvelles approches dans le domaine du soudage laser d'alliage d'aluminium et leur inspection géométrique par un CMM fixe et un scanner laser. Une ouverture vers l'industrie 4.0 et les nouvelles technologies est aussi présentée. Les objectifs étant de combiner deux processus de fabrication, d'assemblage et d'inspection très précis et étudier le comportement d'alliage d'aluminium ont été atteints. Les recherches littéraires faites ont démontré qu'il n'existait pas encore de travaux ou de recherche combinant ces deux processus pour l'alliage d'aluminium d'où l'originalité du travail fait.

RECOMMANDATIONS POUR LES TRAVAUX FUTURS

Cette partie représente les horizons qui peuvent être explorés à partir des résultats de la recherche réalisée ainsi que les suggestions pour approfondir le sujet dans l'avenir :

- Transposer les méthodologies sur d'autres alliages d'aluminium et viser un domaine plus large pour l'utilisation de la technique.
- Coupler les méthodes d'inspection avec d'autres techniques d'assemblage et de fabrication.
- Viser l'inspection des pièces plus complexes ou plus grandes et qui sont utilisées dans d'autres domaines.
- Se diriger vers des inspections assistées par ordinateur automatisées pour économiser le temps et l'argent.
- Explorer les autres effets du soudage laser sur l'assemblage d'alliages d'aluminium.
- Mesurer les contraintes résiduelles dues au procédé de fabrication et d'assemblage en se basant sur les données de mesure.
- Implémentation de l'intelligence artificielle avec des méthodes de mesure.

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